DEPOSITION, REMOBILIZATION AND FLUID FLOW IN SEDIMENTARY BASINS – case studies in the NORTHERN NORTH SEA AND NIGERIA TRANSFORM MARGIN

A thesis submitted to The University of Manchester for the degree of Doctor of Philosophy in the Faculty of Engineering and Physical Sciences.

2014

OLUWATOBI OLOBAYO

SCHOOL OF EARTH, ATMOSPHERIC AND ENVIRONMENTAL SCIENCES
# TABLE OF CONTENTS

<table>
<thead>
<tr>
<th>Section</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>LIST OF CONTENTS</td>
<td>2</td>
</tr>
<tr>
<td>LIST OF FIGURES</td>
<td>6</td>
</tr>
<tr>
<td>LIST OF TABLES</td>
<td>12</td>
</tr>
<tr>
<td>LIST OF GRAPHS</td>
<td>14</td>
</tr>
<tr>
<td>ABSTRACT</td>
<td>15</td>
</tr>
<tr>
<td>DECLARATION</td>
<td>16</td>
</tr>
<tr>
<td>COPYRIGHT STATEMENT</td>
<td>17</td>
</tr>
<tr>
<td>THE AUTHOR</td>
<td>18</td>
</tr>
<tr>
<td>ACKNOWLEDGEMENTS</td>
<td>19</td>
</tr>
</tbody>
</table>

## CHAPTER 1. INTRODUCTION

1.1 Study Areas and Location
   1.1.1 The Northern North Sea Basin
   1.1.2 The Nigeria Transform Margin

1.2 Rationale

1.3 Aims and Objectives

1.4 Database and Methods
   1.4.1 Data
   1.4.2 Methods

1.5 Thesis synopsis

## CHAPTER 2. GEOLOGICAL SETTINGS AND REVIEW OF DEPOSITIONAL, REMOBLIZED AND FLUID FLOW FEATURES IN THE STUDY AREAS

2.1 Geological Setting
   2.1.1 The Northern North Sea
   2.1.2 Petroleum Systems
   2.1.3 The Nigeria Transform Margin

2.2 Review of Depositional, Soft-sediment Remobilization & Fluid Flow
   2.2.1 Mass Transport Deposits
   2.2.2 Sandstone Intrusion Complexes
   2.2.3 Other Fluid Flow Phenomena
      Silica Diagenetic Boundaries
      Pockmarks
      Pipes
      Gas-hydrates bottom simulating reflections
CHAPTER 3.  CENOZOIC SEDIMENTATION IN THE NORTHERN NORTH SEA USING 3D SEISMIC DATA  65

Abstract  65

3.1 Introduction  65
3.2 Geological Setting  68
3.3 Data and Methods  70
  3.3.1 Database  70
  3.3.2 Methods  72
3.4 Results  77
  3.4.1 BCU and Structural Elements of the Basin  77
  3.4.2 CSS0 – Cretaceous  79
  3.4.3 CSS1 – Paleocene to Early Eocene  82
  3.4.4 CSS2 – Eocene  87
  3.4.5 CSS3 – Oligocene Wedge  90
  3.4.6 CSS4 – Oligocene  92
  3.4.7 Middle Miocene Unconformity  94
  3.4.8 CSS5 – Lower Miocene  95
  3.4.9 CSS6 – Upper Miocene  97
  3.4.10 CSS7 – Upper Prograding Pliocene  98
  3.4.11 CSS8 – Uppermost Pliocene to Lower Pleistocene?  100
  3.4.12 CSS9 – Pleistocene  100
3.5 Discussion  104
  3.5.1 Cretaceous Unit  104
  3.5.2 Paleocene Unit  105
  3.5.3 Eocene Unit  107
  3.5.4 Oligocene Unit and MMU  109
  3.5.5 Miocene Unit  111
  3.5.6 Pliocene and Pleistocene Units  111
  3.5.7 Net Accumulation Rate  112
3.6 Conclusions  113
References  116

CHAPTER 4.  THE SAND INJECTITE STRATIGRAPHY IN THE NORTHERN NORTH SEA  122

Abstract  122

4.1 Introduction  123
  4.1.1 Mechanics of Sandstone Intrusions  127
  4.1.2 Petroleum Systems for Hydrocarbon E&P  129
4.2 Regional Setting  130
4.3 Database and Methods  132
  4.3.1 Database  132
  4.3.2 Methods  134
4.4 Observations and Results  139
  4.4.1 Polygonal Faults  139
  4.4.2 Temporal and Spatial Distribution of Clastic Intrusion Styles  141
    4.4.2.1 CSS0 (Cretaceous)  142
    4.4.2.2 CSS1  149
4.4.2.3 CSS2 (Eocene) 161
4.4.2.4 CSS4 (Oligocene) 166
4.4.2.5 CSS6 (Miocene) 178
4.4.2.6 CSS7 (Pliocene) 180

4.5 Discussion 184
4.5.1 Possible Interpretations of Amplitude Anomalies 184
4.5.2 Parent Sand Body and Feeder Systems 188
4.5.3 Sandstone Intrusions and Polygonal Faults 189
4.5.4 Sandstone Intrusions and Underlying Structures 190
4.5.5 Timing - Single or Multiple Episodic Events 192
4.5.6 Mechanism of Formation 194

4.6 Conclusions 199
References 202

CHAPTER 5. QUANTITATIVE ANALYSIS OF SANDSTONE INTRUSIONS, POLYGONAL FAULTS AND DIAGENETIC BOUNDARY IN THE NORTHERN NORTH SEA 211

Abstract 211

5.1 Background 212
5.2 Database and Methods 214
5.3 Quantitative measurements 214
5.3.1 Sandstone Intrusions 214
5.3.2 Polygonal Faults 221
5.3.3 Silica Diagenetic Boundary 224
5.4 Discussion 228
5.5 Conclusions 229
References 229

CHAPTER 6. 3D SEISMIC ANALYSIS OF CENOZOIC SLOPE DEPOSITS AND FLUID FLOW FEATURES ALONG THE NIGERIA TRANSFORM MARGIN 231

Abstract 231

6.1 Introduction 232
6.2 Geologic Setting and Petroleum System 235
6.3 Dataset and Methods 237
6.3.1 Dataset 237
6.3.2 Methods 237
6.4 Observations and Results 240
6.4.1 Sequence Stratigraphic Units 240
6.4.2 Seabed Morphology 244
6.4.3 Mass Transport Deposits (MTDs) 246
6.4.3.1 Headwall Domain 246
6.4.3.2 Translational Domain 246
6.4.3.3 Toe Domain 248
6.4.4 Deep-water Channels 249
6.4.4.1 Highly-sinusous Channels 249
### 6.4.4.2 Linear Channels

254

### 6.4.5 Sediment Waves

254

### 6.4.6 Fluid Flow Features

257

- **6.4.6.1** Pipes and High-amplitude Reflections
- **6.4.6.2** Pockmarks
- **6.4.6.3** Gas Hydrate BSR
- **6.4.6.4** Seafloor Mound
- **6.4.6.5** Polygonal Faults

257

264

265

268

### 6.5 Discussion

272

- **6.5.1** Mechanisms for MTD Formation
- **6.5.2** Controls on Fluid Flow Features and Distribution
- **6.5.3** Fluid Type, Source and Driving Mechanism
- **6.5.4** Implications

273

276

277

278

### 6.6 Conclusions

279

References

280

## CHAPTER 7. DISCUSSION AND CONCLUSIONS

285

### 7.1 Principal Findings

285

### 7.2 Discussion

288

- **7.2.1** Northern North Sea
  - **7.2.1.1** Origin of Amplitude Anomalies
  - **7.2.1.2** Possible Interpretations of Amplitude Anomalies
  - **7.2.1.3** Lithology of Amplitude Anomalies
  - **7.2.1.4** Parent Sand Body and Feeder Systems
  - **7.2.1.5** Timing of Emplacement and Implications
  - **7.2.1.6** Intrusions and Polygonal Fault Relationship
  - **7.2.1.7** Intrusions and Structural High Relationship
  - **7.2.1.8** Factors Facilitating Fluid Flow Phenomena

288

289

292

294

297

299

302

302

### 7.2.2 Nigeria Transform Margin

311

- **7.2.2.1** Mass Transport Deposits (MTDs)
- **7.2.2.2** Mechanism for Slope Failure
- **7.2.2.3** Seabed Fluid Flow Phenomena
- **7.2.2.4** Overburden Fluid Flow Phenomena
- **7.2.2.5** Major Controls on Fluid Flow Phenomena
- **7.2.2.6** Potential Fluid Type and Source
- **7.2.2.7** Origin of Fluid Flow and Driving Mechanism

311

313

315

317

320

321

322

### 7.3 Implications for Hydrocarbon Exploration and Production

322

### 7.4 Further Work and Recommendations

324

### 7.5 Conclusions

325

## REFERENCES (CHAPTERS 1, 2 & 7)

327

## APPENDIX

## FINAL WORD COUNT: 94,247
LIST OF FIGURES

CHAPTER 1.

Fig.1.1. World maps showing the two study areas 21
Fig.1.2. Location and structural map of the North Sea 22
Fig 1.3. Location map of the Nigeria Transform Margin 23
Fig.1.4. Regional seismic lines from the North Sea showing intrusions 25
Fig. 1.5. Schematic diagram showing soft-sediment remobilization 26
Fig.1.6a. Seismic and well data available for NNS studies 29
Fig.1.6b. Seismic profile showing seabed polarity from the NNS 30
Fig. 1.7a. Seismic and well data available for NTM studies 32
Fig. 1.7b. Seismic profile showing seabed polarity from the NTM 33
Fig. 1.8. Well to seismic tie of well 35/8-1 35
Fig. 1.9. Attributes to image intrusions in 2D, plan view and 3D 38
Fig. 1.10. Parameters measured for intrusions for analysis 39

CHAPTER 2.

Fig. 2.1. Regional seismic section through the North Sea 42
Fig. 2.2. Stratigraphic framework and petroleum systems from the NNS 44
Fig. 2.3. Petroleum system chart for the NNS 46
Fig. 2.4. Paleogeographic map of Africa and South America 47
Fig. 2.5. Petroleum system chart for the NTM 49
Fig. 2.6 Paleogene sandstone deposition in the NNS 50
Fig. 2.7 Three models suggested for sandstone occurrence 50
Fig. 2.8 Seismic, outcrop, core and log examples of sandstone intrusions 52
Fig. 2.9 Examples of other fluid flow features 53
Fig. 2.10 3D schematic diagram of MTD morphology 54
Fig. 2.11 3D diagram of common sandstone intrusion features 55
Fig. 2.12 Schematic diagram showing dykes, sills and extradite 58
Fig. 2.13 Schematic diagrams showing effect of liquefaction  60

CHAPTER 3.

Fig. 3.1. Location and structural map of the North Sea  67
Fig. 3.2. Simplified stratigraphic column  71
Fig. 3.3a Map showing previous work using 2D seismic  73
Fig. 3.3b Seismic and well data available for study  73
Fig. 3.4 SW-SE seismic, geoseismic and well log correlation profiles  78
Fig. 3.5 TWT structure maps of horizons  81
Fig. 3.6 TWT thickness maps of CSS units  84
Fig. 3.7 Seismic cross section across polygonal faults  85
Fig. 3.8 SW-NE seismic, geoseismic and well log correlation profiles  86
Fig. 3.9 Paleocene clinoforms geometries  87
Fig. 3.10 NW-SE seismic and geoseismic profiles  89
Fig. 3.11 Eocene depositional systems  91
Fig. 3.12 Well log correlation and seismic profile of Opal A-CT boundary  94
Fig. 3.13 Well log correlation and seismic profile of Oligocene sandstones  96
Fig. 3.14 NW-NE seismic and geoseismic profiles  99
Fig. 3.15 3D image of the mid-Miocene unconformity  101
Fig. 3.16a Pliocene clinoforms channels  103
Fig. 3.16b Horizon map showing iceberg scours in Pleistocene  103
Fig. 3.17 Composite TWT ms thickness maps  106
Fig. 3.18 Integrated map for all depocentres  108
Fig. 3.19 Simplified sandstone distribution maps  110
Fig. 3.20 Northern, Central and Southern profiles across the area  114

CHAPTER 4.

Fig. 4.1a. Location and structural map of the North Sea  124
Fig. 4.1b Models for sandstone occurrence in the North Sea  125
Fig. 4.1c Global distribution map of post-depositional features.  126
Fig. 4.2a  Schematic diagrams showing effect of liquefaction  
Fig. 4.2b  Petroleum System chart  
Fig. 4.3  Simplified stratigraphic column  
Fig. 4.4a  Seismic and well data used for study  
Fig. 4.4b  Recognition of sandstone injectites  
Fig. 4.4c  Parameters to measure conical sandstone intrusions  
Fig. 4.5  Seismic section and horizon maps of polygonal faults  
Fig. 4.6  Seismic cross section through polygonal faults  
Fig. 4.7  Mapped intrusions  
Fig. 4.8  Maximum amplitude maps  
Fig. 4.9  Outline of intrusions with BCU variance map  
Fig. 4.10  Simplified sand distribution maps  
Fig. 4.11  Paleocene mound  
Fig. 4.12  Seismic sections showing mounds  
Fig. 4.13  Wireline and core photos for Paleocene intrusions  
Fig. 4.14  Geometries of Eocene intrusions  
Fig. 4.15  Discordant amplitude anomalies  
Fig. 4.16  Well calibrated sections  
Fig. 4.17a  3D representation of a tripartite association  
Fig. 4.17b  Petrophysical analysis of well 35/8-2  
Fig. 4.18  Saucer-shaped intrusion and possible extrudite  
Fig. 4.19  Oligocene intrusions  
Fig. 4.20  Miocene intrusions  
Fig. 4.21  Seismic section above the Snorre Field  
Fig. 4.22  Estimating timing of emplacements for intrusions  
Fig. 4.23  Proposed model of sandstone intrusions in the NNS  
Fig. 4.24  Northern, Central and Southern profiles across the study area  

CHAPTER 5.  
Fig. 5.1  Global distribution map
Fig. 5.2 a  Map of study area  213
Fig. 5.2b  Seismic section and time slice through intrusions  213
Fig. 5.3  Measured parameters for intrusions  214
Fig. 5.4  Plots for Late Cretaceous-aged intrusions  215
Fig. 5.5  Plots for Middle Paleocene-aged intrusions  216
Fig. 5.6  Plots for Middle – Late Eocene-aged intrusions  217
Fig. 5.7  Plots for Middle Miocene-aged intrusions  218
Fig. 5.8  Plots for Tertiary intrusions  219
Fig. 5.9  Plots for all intrusions  220
Fig. 5.10  Characteristics of polygonal faults  221
Fig. 5.11  Dip populations of sandstone intrusions and polygonal faults  222
Fig. 5.12  Fault lengths vs orientation  223
Fig. 5.13  Well tie to show diagenetic boundary  224
Fig. 5.14  Seismic section across diagenetic boundary  225
Fig. 5.15  Concentration of opal CT shown from wells  226

CHAPTER 6.

Fig. 6.1a.  Gulf of Guinea Province map to show study area  234
Fig. 6.1b  Map of structural zones along WATM with study area  234
Fig. 6.2a  Paleogeographic map of Africa and South America  235
Fig. 6.2b  Petroleum system chart along the margin  237
Fig. 6.2c  Simplified stratigraphic column along the margin  238
Fig. 6.3  Seabed map showing extent of study area  239
Fig. 6.4  Seismic lines across the study area  241
Fig. 6.5  TWT thickness maps of the units  243
Fig. 6.6  Dip and variance attributes on the seabed  245
Fig. 6.7  Summary diagram of key components of MTDs  247
Fig. 6.8  Seafloor diagram to show MTD  250
Fig. 6.9  Seismic section and plan view of deformed blocks and ramps  251
Fig. 6.10  Schematic diagrams for MTD distribution  252
Fig. 6.11  Iso-proportional slices through channel complex  253
Fig. 6.12  TWT map and seismic section showing linear channels  255
Fig. 6.13  Sediment waves on the seabed  256
Fig. 6.14  Isolated pipes and pockmarks  258
Fig. 6.15  Stacked paleo pockmarks and fault-related pockmarks  260
Fig. 6.16  Channel-related pockmarks  262
Fig. 6.17  Elongated pockmarks  263
Fig. 6.18  Bottom Simulating Reflections  267
Fig. 6.19  Sea floor mound  269
Fig. 6.20  Polygonal faults  271
Fig. 6.21  Summary diagram of all features in the NTM  272
Fig. 6.22  Schematic representation of fluid flow features  274

CHAPTER 7.
Fig. 7.1.  Summary diagram of fluid flow products  287
Fig. 7.2.  Three models of sandstone occurrence with examples from study  290
Fig. 7.3  Simplified depositional sand distribution and intrusions  296
Fig. 7.4  Criteria for estimating timing of emplacement  298
Fig. 7.5  Single vs. Multiple emplacements  300
Fig. 7.6  Schematic diagrams illustrating intrusion emplacement  310
Fig. 7.7  Summary diagram of key components of MTDs on the NTM  312
Fig. 7.8  Evolution and distribution of MTDs along the NTM  316
Fig. 7.9  Schematic diagrams of distributions of MTDs and fluid flow  318
# LIST OF TABLES

## CHAPTER 1.

| Tab. 1.1 | Key seismic parameters for CSS units from the NNS | 30 |
| Tab. 1.2 | Key seismic parameters for CSS units from the NTM | 31 |
| Tab. 1.3 | Summary table for seismic data parameters from both areas | 32 |
| Tab. 1.4 | List of wells used for the NNS study | 33 |
| Tab. 1.5 | Key seismic characters and brief descriptions | 37 |

## CHAPTER 3.

| Tab.3.1 | Key parameters for CSS units from seismic data | 72 |
| Tab.3.2 | Summary of CSS units and surface description | 75 |
| Tab.3.3 | Estimated net sediment accumulation rates | 76 |

## CHAPTER 4.

| Tab. 4.1 | Key parameters for CSS units from seismic data | 134 |
| Tab. 4.2 | Summary of polygonal faults and other studies | 141 |
| Tab. 4.3 | Summary of geometric characteristics of intrusions | 142 |
| Tab. 4.3 | Summary of sandstone intrusions parameters in study area | 187 |

## CHAPTER 5.

| Tab. 5.1 | Summary table of intrusions, faults and diagenetic boundaries | 227 |
| Tab. 5.2 | Clay mineralogy of Cenozoic and Tertiary rocks | 228 |
CHAPTER 6.

| Tab. 6.1 | Key seismic data parameters | 239 |
| Tab. 6.2 | Summary of polygonal faults in NTM and other studies | 270 |
| Tab. 6.3 | Estimated net sediment accumulation rates | 275 |

CHAPTER 7.

| Tab. 7.1 | Summary of sandstone intrusions parameters and other studies | 289 |
| Tab. 7.2 | Polygonal fault characteristics from the study and other studies | 293 |
| Tab. 7.3 | Summary of parameters across opal A-CT boundaries | 262 |
LIST OF GRAPHS

CHAPTER 3.

Graph 3.1 Estimated sediment accumulate rate 113

CHAPTER 4.

Graph 4.1 Dip angles of polygonal faults and intrusions 191

CHAPTER 6.

Graph 6.1 Estimated sediment accumulation rate 276

CHAPTER 7.

Graph 7.1 Dip angles of polygonal faults and intrusions 301
Graph 7.2 Estimated sediment accumulation rate 316
ABSTRACT

Deposition, Remobilization and Fluid Flow in Sedimentary Basins – case studies in the Northern North Sea and Nigeria Transform Margin

Oluwatobi Olobayo

A thesis submitted to The University of Manchester for the degree of Doctor of Philosophy in the Faculty of Engineering and Physical Sciences

December 2014

Soft-sediment remobilization and fluid flow processes and their products such as sand injectites, mud volcanoes, pipes, pockmarks and authigenic carbonates constitute a key, but under-appreciated component of sedimentary basins. The structures are evidence of and provide focused fluid pathways bypassing the stratigraphic and structural framework and thus have numerous implications for hydrocarbon exploration and production by influencing sediment and fluid distributions. Recent advances in subsurface imaging using high-resolution 3D seismic data, integrated with well data, geochemical data and outcrop data have greatly improved the understanding of subsurface sediment remobilization and fluid flow processes in sedimentary basins.

This study presents substantial new results from the description, analysis and interpretation of products of subsurface remobilization processes and fluid flow based on all available data from the Northern North Sea and the Nigeria Transform Margin. The studied intervals, which encompass the entire Cenozoic and Cretaceous succession, have undergone repeated, large-scale remobilization and deformation of sediments through time. The North Sea is the archetype Giant Injected Sand Province (GISP) with kilometre-scale sandstone intrusions observed within multiple stratigraphic intervals, but this is the first time the northern North Sea has been systematically studied on a regional scale. Seismic-scale sandstone intrusions are well documented along the Atlantic Margin from the South Viking Graben, Outer Moray Firth, Norwegian-Danish Basin, Faroe-Shetland Basin and Barent Sea but primarily emplaced during one or two episodes. Results from the NNS show evidence for five major episodes of emplacement. These sandstones, believed to be sourced from different stratigraphic levels, have intruded thick polygonally-faulted, diatomaceous and smectite-rich mudstones; probably facilitated by hydrocarbons and diagenetically-released water in spatio-temporally varying proportions.

The Cenozoic section of the Nigeria Transform Margin comprises up to 2 km of sediments, including recurrent mass transport deposits ranging between a few to tens of kilometres in length and constituting up to 25 % of the stratigraphic section. A series of fluid flow features such as pockmarks, pipes, bottom simulating reflections, polygonal faults and mound have been interpreted on the seabed and in the overburden; all of which provide evidence of focused fluid movement in the subsurface becoming more abundant towards the Niger Delta.

Our study provides details on the geometries, scale, spatial distribution, potential causative mechanisms and implications of these soft-sediment remobilized and fluid flow products; as well as their relationships with other depositional and structural elements within the basin. It also reveals the extent by which sedimentary basins can be affected by these processes and therefore be incorporated into present stratigraphic frameworks and improve reservoir models.
DECLARATION

I hereby declare that no portion of the work referred to in this thesis has been submitted of an application for another degree or qualification of this or any university or other institute of learning.

Oluwatobi Olobayo
i. The author of this thesis (including any appendices and/or schedules to this thesis) owns certain copyright or related rights in it (the “Copyright”) and she has given The University of Manchester certain rights to use such Copyright, including for administrative purposes.

ii. Copies of this thesis, either in full or in extracts and whether in hard or electronic copy, may be made only in accordance with the Copyright, Designs and Patents Act 1988 (as amended) and regulations issued under it or, where appropriate, in accordance with licensing agreements which the University has from time to time. This page must form part of any such copies made.

iii. The ownership of certain Copyright, patents, designs, trademarks and other intellectual property (the “Intellectual Property”) and any reproductions of copyright works in the thesis, for example graphs and tables (“Reproductions”), which may be described in this thesis, may not be owned by the author and may be owned by third parties. Such Intellectual Property and Reproductions cannot and must not be made available for use without the prior written permission of the owner(s) of the relevant Intellectual Property and/or Reproductions.

iv. Further information on the conditions under which disclosure, publication and commercialisation of this thesis, the Copyright and any Intellectual Property and/or Reproductions described in it may take place is available in the University IP Policy (see http://documents.manchester.ac.uk/DocuInfo.aspx?DocID=487), in any relevant Thesis restriction declarations deposited in the University Library, The University Library’s regulations (see http://www.manchester.ac.uk/library/aboutus/regulations) and in The University’s policy on Presentation of Theses.
I hold a BSc in Geology (with Second Class Upper Division – 2:1) from Kogi State University, Nigeria (2005) and an MSc in Petroleum Geoscience (with distinction) from The University of Manchester, United Kingdom (2009). Prior to my second degree, I worked two years with ExxonMobil Nigeria as an intern and contract geologist where I developed reasonable geoscience skills in seismic and well interpretations. During the PhD, I had the opportunity to work with Tullow Oil Norway where I worked on a ‘sand injectite’ prospect around the Troll area, which was useful for my research. During my PhD, I have gained experience working on sand injectites in the North Sea and a wide range of sedimentary and non-intrusive fluid flow features along the Nigeria Transform Margin.
I give all glory and gratitude to the Almighty God for seeing me through this project.

I will like to specially thank my supervisor, Dr. Mads Huuse for the support and passion he showed during the course of the project. I appreciate how much he believed in me and the opportunities I had through him. I will also like to thank Dr. Christopher Jackson for his constructive comments and reviews. It all made it a better project.

I wish to thank Richard Lamb (PGS) for facilitating access to 3D seismic data used and to TGSNOPEC for providing the 2D lines.

I owe so much gratitude to Petroleum Technology Development Fund (PTDF), Nigerian Government for providing full funding.

I appreciate all my close friends and colleagues; Munira Raji, Dr Benjamin, Dr Atunima, Dr Sharples, Georgina Heldreich, Rashad Gulmammadov and Rachel Lamb who helped me through. It was more fun and bearing with you all.

Finally, I thank my father and mother, Oba Dr. and Olori MFS Olobayo for being the most supportive parents; and to all my siblings, Yetunde, Bimbo, Segun, Muyiwa, Tunde and Toyosi. Thank you all for your prayers. To my partner Temi. Sulaiman, thank you for your love and support. To Prince Shola Akanmode and Rear Admiral Ajayi. Thank you so much.
Chapter 1

1 INTRODUCTION

1.1 STUDY AREAS AND LOCATION

The two study areas investigated during this research encompasses a stratigraphic succession, over 5 km thick, along the Atlantic margin (Fig. 1.1). The study areas include (1) the North Sea, a failed rift system and (2) the Nigeria Transform Margin, located in the Dahomey-Benin basin as part of the east-west aligned, open-water sedimentary basins that formed during the rifting between the African and South American plates (Figs. 1.2 & 1.3) (Ahmadi et al., 2003; Greenhalgh et al., 2011). The present-day structural and stratigraphic configuration of both study areas were formed in response to Late Jurassic to Early Cretaceous rifting and transform tectonism respectively; and therefore have undergone complex tectonic histories (Zanella et al., 2003; Brownfield & Charpentier 2006). The Cenozoic succession in both study areas is made up 2 km-thick sediments, significantly dominated by siliciclastic, deep-water deposits and have undergone large-scale, sediment deformation/remobilization and fluid flow. These post-depositional processes constitute a significant aspect of the basin evolution. Improvement in three-dimensional seismic reflection imaging in the last few decades, have boosted interpretations of geological features associated with original and post-depositional processes both in the sub-surface and on the present day seafloor (Nissen et al., 1999; Posamentier & Kolla 2003; Cartwright 2007). The understanding of these geological processes and their resultant products has been significantly enhanced by the integration of 3D seismic studies with well data and outcrop studies.

The research has focused on the Cenozoic interval for both study areas but included the Cretaceous sections in order to understand the structural elements of the basins. Though the North Sea and Nigeria Transform Margin vary in basin evolution, sedimentation, tectonism, climatic conditions and exploration history, both show similarities in post-depositional processes and fluid-flow products. Both study areas are mature hydrocarbon provinces but are at different levels of hydrocarbon exploration, production and development. The Northern North Sea is covered by continuous 3D seismic data and penetrated by hundreds of boreholes through decades of exploration; however, the Nigeria Transform Margin is still considered to be in infancy stage with regards to hydrocarbon exploration and production, which was stimulated by exploration successes in surrounding basins along the margin. Exploration has focused on the Mesozoic succession in both areas.

1.1.1 The Northern North Sea Basin

The North Sea basin is one of the most petroliferous hydrocarbon basins in the world and has been well explored for decades (Ahmadi et al., 2003). The study area is located between 60-62° latitude and 1-5° longitude in the northern part of the North Sea and encompasses the North Viking Graben.
Fig. 1.1 (a) Map of the world ocean floor and (b) Total sediment thickness of the world’s oceans and marginal seas showing location of the two study areas. 1 is the Northern North Sea and 2 is the Nigeria Transform Margin. Both images from http://www.ngdc.noaa.gov website.

and part of the Sogn Graben (Fig.1.2). It is bounded to the east by the Norwegian coastline, Shetland Isles to the west, North Atlantic in the north and South Viking Graben in the south. The North Sea Basin houses the best and well documented seismic examples of remobilized and sandstone injectites in the world; most of which are associated with hydrocarbon producing reservoirs in the Paleogene succession (Huuse et al, 2009, AAPG) (Figs. 1.2, 1.4 & Appendix 1.1). Seismic and well data utilised for on-going investigation are available through continuous discovery.
of these unusual sandstone bodies at shallower intervals within the basin when drilling for much deeper targets; mainly low-stand fans and channels (Dixon et al., 1995; Lonergan et al., 2000; Duranti et al., 2003; Huuse & Cartwright 2007; Huuse et al., 2010; Morton et al., 2014). Success has been limited to the Outer Moray Firth and South Viking Graben, while the Northern North Sea has proven less prospective even with the presence of similar features (Fig. 1.2).

Fig. 1.2 Structural map of the North Sea basin showing major structures such as the triple arm, highs, sub-basins, terraces, platforms, faults and surrounding landmasses (modified from Fraser et al., 2003). Location of study area is shown in the red outline. MB-Magnus Basin, ESB-East Shetland Basin, ESP-East Shetland Platform, TS-Tampen Spur, SG-Sogn Graben, MT-Maloy Terrace, UT-Uer Terrace, LT-Lomre Terrace, HP-Horda Platform, OFZ-Øygarden Fault Zone, SB-Stord Basin, FGS-Fladen Ground Spur, UH-Utsira High, WGG-Witch Ground Graben, OMF-Outer Moray Firth, IMF-Inner Moray Firth, RFH-Ringkøbing Fyn-High, MNSH-Mid North Sea High. Also included on the map are locations of some hydrocarbon producing fields/discoveries. Yellow numbered squares represents fields associated with remobilised/injected sands (1-Kraken, 2-Jotun, 3-Grane, 4-Mariner, 5-Leadon, 6-Volund, 7-Gryphon, 8-Harding, 9-Balder, 10-Sleipner, 11-Alba, 12-Chestnut, 13-Forties, 14-catcher, 15-Cecile, 16-Siri, 17-Nini). Yellow stars show locations of previous work done in the area that are related to post-depositional products or soft-sediment deformation. Inset shows present day bathymetry of the North Sea. Black and red outline show location of the whole the North Sea and study area respectively.
1.1.2 The Nigeria Transform Margin

The study area is located in the Dahomey-Benin basin and bounded by the Gulf of Guinea in the south, the Hihon and Fifa Fields in the west, Aje Field to the north and western Niger Delta to the west (Fig. 1.3). The study focused on the post-transform/post-rift section bounded at the base by the Late Albian unconformity and top by the present day seabed (Brownfield & Charpentier 2006).

Fig. 1.3 (a) Gulf of Guinea Province (7183) with location of oil and gas fields (b) map showing the structural zones along the West African transform Margin. Study area covers OPL blocks 312, 313 and 314 as show in red. Yellow and blue boxes represent location of soft-sediment deformation features and fluid flow pipes by Davies 2003 (WND) & Løseth et al., 2011 (END) respectively. Location of surrounding fields and discoveries also shown. Inset shows location with the Atlantic (Redrawn from Brownfield & Charpentier 2007; Techlink, PGS 2006)
Although, hydrocarbon exploration activities started in the basin much earlier following discovery of bitumen and tar sands in Late Cretaceous outcrops, this did not yield desired commercial accumulation along the African Equatorial conjugate margin (Greenhalgh et al., 2011). However, continuous exploration with better resolved seismic data and data gathered from initial drilled wells revealed the presence of Cretaceous petroleum plays along the margin. The studied interval forms the thick overburden above Cretaceous Fans which form the major targets for exploration along the margin (Appendix 1.2 & 1.3).

1.2 RATIONALE

Soft sediment deformation comprises all processes that result in the re-deposition or remobilization of sediment in the sub-surface (Van Rensbergen et al., 2003). Products of these geological processes are classified into organised forms such as subsurface sandstone remobilization and injection, mud volcanoes, salt bodies and fluid flow products (Huuse et al., 2010); as well as more disorganised forms such as mass transport deposits (Fig. 1.5). They have been documented from the two study areas and other hydrocarbon basins in the world (Appendix 1; Huuse et al., 2010). Understanding these products is important as they have major implications for hydrocarbon exploration and production in sedimentary basins. They are often associated with over pressure conditions in the sub-surface and significant sediment and fluid movements.

The North Sea Basin as a whole is a Large Sandstone Intrusion Province (LISP); with Faroe-Shetland Basin and San Joaquin Basin containing kilometre-scaled sandstone injectites, which have have intruded into background mudstone successions over a geologic period geologic period of time (Cartwright et al., 2010). Sandstones are commonly believed to be deposited by gravity-flow processes in the form of low-stand fans and channels (Den Hartog Jager et al., 1993; Posamentier & Kolla 2003); but detailed investigation using improved seismic imaging, integrated with well data and outcrop studies, have revealed unusual geometries that are difficult to unravel by conventional depositional processes (Dixon et al., 1995). The northern part of the North Sea is very distinct such that sandstones belonging to the Late Cretaceous to Early Pliocene interval show evidence of intense sub-surface remobilization, injection and extrusion. Most of these sand bodies are believed to be deposited from the basin margins during fluctuations in sea level (Den Hartog Jager et al., 1993; Rundberg 1991; Jordt et al., 1995; 2000; Martinsen et al., 1999; Anell et al., 2011). It is therefore very important to ascertain the extent to which these deep-water depositional sandstones have been affected by wholesale remobilization and injection through hundreds of metres of shale mudstones, as their presence may signify a breach in the sealing capacity of the mudstone (Cartwright et al., 2007). While sand injection appears to have enhanced prospectivity in the Paleogene, deep-water succession of the Outer Moray Firth and South Viking Graben; they appear to have compromised prospectivity in the Northern North Sea (Fig. 1.2). Therefore, it is important to
Fig. 1.4 Regional seismic cross sections across the North Sea basin to show stratigraphic and geological occurrence of sandstone intrusions (Huuse et al., 2009). Location of black circles and ages are shown in the inset figure.
incorporate them into the existing Cenozoic stratigraphic framework for the development of accurate reservoir models in the area and beyond.

Moreover, it is important to document their occurrence, lateral and vertical distribution, geometries, dimensions and implications for hydrocarbon exploration and production in the area as they constitute a large part of the basin stratigraphy which has not been previously accounted for on a basin scale. In spite of intense studies of these features that span a period of over a decade, some questions still remain unanswered such as timing, parent bodies, fluid budget and driving mechanisms. This reveals the level of their complexity.

**Fig. 1.5** Schematic diagram to illustrate occurrence of active and buried, large-scale soft sediment remobilization and fluid flow products on a typical continental margin (Modified from Huuse et al., 2010)

Soft-sediment deformation features in form of hummocks and depressions formed as a result of fluidized sediment flows were observed on the western margin of the Niger Delta basin (Fig. 1.3b) (Davies 2003). A range of other fluid flow phenomena such as pockmarks, pipes, bottom simulating reflections (BSRs) and mud volcanoes have also been observed in the Niger Delta basin close to the studied site of the Nigeria Transform Margin (Figs. 1.3b, 1.5) (Graue 2000; Cunningham & Lindholm 2000; Løseth et al., 2001, 2011; Judd & Hovland 2007). Seismic data from the margin allowed mapping of some of these fluid-flow related features on the present day seabed and in the sub-surface. Understanding fluid flow phenomena has important implications for hydrocarbon exploration and production as this could provide useful insights into the occurrence of
active petroleum systems, help to locate underlying hydrocarbon traps, and could represent evidence of seal failures and potential geohazards (Heggeland 1998; Gay et al., 2006; Cartwright et al., 2008; Løseth et al., 2009; Huuse et al., 2010; Andresen 2012).

An important part of the study is the identification of several layers of mass transport deposits (MTDs) in the Cenozoic succession; which is indicative of repeated slope failure along the margin (Posamentier & Martinsen 2011). MTDs have been recognised worldwide in sedimentary basins and constitute major geohazards; therefore, mapping their spatial distribution is useful for pre-drilling analysis before placement of infrastructures (Shipp et al., 2011).

The two study areas are characterised by large-scale, soft-sediment remobilization and distribution; a phenomena that has major implications for hydrocarbon exploration and production activities (Van Rensbergen et al., 2003; Huuse et al., 2010). Other fluid flow phenomena documented in the study areas include polygonal faults, in both areas and silica diagenetic transformation in the Northern North Sea.

1.3 AIMS AND OBJECTIVES

The thesis examines depositional and soft-sediment deformation and fluid-flow phenomena in the Cenozoic intervals of the Northern North Sea and along the Nigeria Transform Margin (Figs. 1.2 & 1.3). Multiple emplacements of sandstone intrusions and extrusions and mass transport deposits form the main features observed in both basins. These soft-sediment deformation products occur at a scale of tens to thousands of metres. The main aim of the study is to:

- Understand the causes of soft-sediment remobilization, fluid flow phenomena and their resultant effects in sedimentary basins

To achieve the aim in both study areas, the following specific objectives are outlined;

- Review the regional stratigraphic framework of both the Northern North Sea and the Nigeria Transform Margin with reference to previous studies
- Interpret key seismic horizons and define sequences delineated by these horizons

Northern North Sea

- Identify, map and document the presence of sandstone intrusions and extrusions across the area
- Map the distribution of these post-depositional sandstones both laterally and vertically throughout the studied interval
• Investigate timing of emplacement of intrusions to determine whether they formed as single or multiple events in the basin and their driving mechanisms
• Map depositional sandstone bodies in the form of channels and fans that could be potential parent bodies for observed intrusions
• Define the extent of polygonal fault systems and their relationship with sandstone intrusions
• Map the extent of opal A to opal CT diagenetic transformation zone across the area and assess any genetic link between the process and sandstone intrusions
• Quantitatively Document the dimensions of sandstone intrusions such as dip angles, width and height of intrusions and polygonal fault dips
• Investigate the implication of wholesale remobilization, injection and extrusion of sands within the area with respect to hydrocarbon exploration and production

Nigeria Transform Margin
• Identify and document the occurrence and spatial distribution of mass transport deposits within the post-transform interval along the margin
• Identify, map and document the occurrence of present-day seabed and overburden fluid flow phenomena observed in the area. These includes pockmarks, pipes, bottom simulating reflectors (BSRs), seabed mound, furrows and polygonal faults
• Define relationships between fluid flow phenomena and depositional (deep-water channels) or tectonic (faults) products
• Identify potential triggering mechanisms for repeated occurrence of mass transport deposits in the area
• Identify and document the implications of repeated mass transport deposits and fluid flow features in the area with respect to hydrocarbon exploration and production

The outcome of this study shows that both study areas are characterised by processes and products of large-scale sediment deformation and fluid flow that should be incorporated into the present stratigraphic framework and evolution history for generating accurate geologic and reservoir models in both in sedimentary basins.

1.4 DATABASE AND METHODS

1.4.1 Data

Varieties of datasets were available for each of the study areas and details of which are presented below (Figs. 1.6 & 1.7). Additional description of the datasets will be discussed under specific chapters in the thesis.
1.4.1.1 Seismic data

The study in the Northern North Sea was carried out mainly by the use of a 3D MegaSurvey created by merging a large number of legacy 3D subset volumes provided by PGS. The 3D seismic has an areal coverage of 29,000 km$^2$ in the northern part of the North Sea basin and covers the whole of quadrant 34 and 35 and part of quadrants 29, 30, 31, 32, 33, and 36 (Fig. 1.6a). 2D seismic lines were also provided by TGSNOPEC and were useful for regional correlation and to fill up gaps within 3D seismic volume (Fig. 1.6a). Seismic data was processed in zero-phase with reverse polarity based on European polarity convention such that a downward increase in impedance represents negative amplitude (trough or red reflection) (Fig. 1.6b). A change in polarity is observed locally in the area. Dominant frequency ($\text{df}$) was estimated for each interval and used with the interval velocities from wells to calculate horizontal ($\lambda/2$) and vertical resolutions ($\lambda/4$) (Tab. 1.1.). Frequencies and interval velocities vary across the study area. The 3D seismic survey has a bin spacing (inline and crossline spacing) of 50 m x 50 m with a vertical sample interval of 4 ms two-way-time (TWT).

![Fig. 1.6a Seismic and well data used for study to show extent of 3D MegaSurvey (courtesy of PGS); with a time slice @ -2300ms. Green lines show some 2D lines (TGSNOPEC) used to complement gaps in the 3D seismic volume. Black circles represent well locations. Irregular black outlines are hydrocarbon producing fields]
Seismic data quality is good to moderate but quality deteriorates towards the western part of the study area due to the chaotic nature of the seismic which made mapping very challenging.

Table 1.1 Frequencies, velocities and vertical resolution estimated for each CSS unit from the Northern North Sea

<table>
<thead>
<tr>
<th>CSS UNITS</th>
<th>FREQUENCY (hz)</th>
<th>VELOCITIES (km/s)</th>
<th>HORIZONTAL RESOLUTION (m)</th>
<th>VERTICAL RESOLUTION (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>CSS0</td>
<td>40</td>
<td>2.840</td>
<td>35</td>
<td>18</td>
</tr>
<tr>
<td>CSS1</td>
<td>30</td>
<td>2.300</td>
<td>38</td>
<td>19</td>
</tr>
<tr>
<td>CSS2</td>
<td>35</td>
<td>2.130</td>
<td>30</td>
<td>15</td>
</tr>
<tr>
<td>CSS3</td>
<td>60</td>
<td>1.74</td>
<td>15</td>
<td>7</td>
</tr>
<tr>
<td>CSS4</td>
<td>40</td>
<td>2.05</td>
<td>26</td>
<td>13</td>
</tr>
<tr>
<td>CSS5</td>
<td>30</td>
<td>2.17</td>
<td>36</td>
<td>18</td>
</tr>
<tr>
<td>CSS6</td>
<td>40</td>
<td>2.12</td>
<td>27</td>
<td>13</td>
</tr>
<tr>
<td>CSS7</td>
<td>55</td>
<td>2.10</td>
<td>27</td>
<td>13</td>
</tr>
<tr>
<td>CSS8/9</td>
<td>50</td>
<td>2</td>
<td>19</td>
<td>10</td>
</tr>
</tbody>
</table>

For study on the Nigeria Transform Margin, a 2,845 km² of GeoStreamer, 3D high-resolution seismic data was also provided by PGS (Fig. 1.7a). Seismic data covers Oil Prospecting Licence (OPL) 312, 313 and 314 within the Gulf of Guinea (Fig. 1.3a). The seismic data was processed in zero-phase with normal SEG polarity such that a downward increase in acoustic impedance is represented by positive amplitude (red peaks = hard reflections) (Fig. 1.7b). The dominant frequency (df) for the whole volume is up to 50 hz and horizontal and vertical resolution are up to 20 and 10 metres respectively; assuming an average velocity of 2000 m/s (Tab. 1.2). 3D seismic
data is pre-stack time migrated with a bin size (inline and crossline spacing) of 12.5 m x 12.5 m. Water depth ranges between 1500 and 3800 ms and seismic data goes down to six seconds TWT. Data quality is great but disturbed below the channel complex in the eastern part of the study area and often chaotic due to the presence of large mass transport complexes. A summary table for the seismic data from both study areas is shown in table 1.3.

**Table 1.2** Frequencies, velocities and vertical resolution for each CSS unit from the Nigeria Transform Margin

<table>
<thead>
<tr>
<th>SEISMIC UNITS</th>
<th>FREQUENCY (hz)</th>
<th>INTERVAL VELOCITY (km/s)</th>
<th>HORIZONTAL RESOLUTION (m)</th>
<th>VERTICAL RESOLUTION (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>SU1</td>
<td>25</td>
<td>2</td>
<td>42</td>
<td>21</td>
</tr>
<tr>
<td>SU2</td>
<td>48</td>
<td>2</td>
<td>21</td>
<td>10</td>
</tr>
<tr>
<td>SU3</td>
<td>30</td>
<td>2</td>
<td>33</td>
<td>17</td>
</tr>
<tr>
<td>SU4</td>
<td>40</td>
<td>2</td>
<td>25</td>
<td>13</td>
</tr>
<tr>
<td>SU5</td>
<td>50</td>
<td>2</td>
<td>20</td>
<td>10</td>
</tr>
</tbody>
</table>

**1.4.1.2 Well data**

Hundreds of wells cover the Northern North Sea and include wireline logs such as gamma ray, density, neutron, sonic, resistivity and other logs (Tab. 1.4). Most of the wells targeted Jurassic-aged reservoirs with only few that penetrated features of interest. Table 1.4 shows a list of selected wells used to carry out analysis in the Northern North Sea. The selection of wells was based mainly on getting a good correlation across the whole area and those wells that penetrated depositional and post-depositional features of interest (Fig. 1.6a). Wells were useful for horizon interpretation and lithology delineation across the basin.

Checkshot data was also available for some of the wells and used to establish time-to-depth relationship especially for thickness estimations in metres across the basin. Completion logs and well reports that are publicly available on the Norwegian Petroleum Directorate website (NPD.NO) were also useful for this research. Biostratigraphic information from a few wells (29/6-1, 30/6-2, 35/8-1 and 35/8-2) available on npd.no website were also useful during the course of the study. Additional well information was available from the TGS Facies map browser.
Fig. 1.7a TWT structure map of the seabed showing extent of 3D seismic data used for study in the Nigeria Transform Margin. Study area was divided into 2 areas for ease of description and discussion based on distribution of mass transport deposits and fluid flow features observed in the area.

Table 1.3 Summary table to show details from 3D seismic data available for both study areas

<table>
<thead>
<tr>
<th>STUDY AREA</th>
<th>3D SEISMIC SURVEY (Km²)</th>
<th>DATA INTERVAL (TWT sec)</th>
<th>WATER DEPTH (ms)</th>
<th>INTERVAL VELOCITY (km/s)</th>
<th>DOMINANT FREQUENCY (hz)</th>
<th>HORIZONTAL RESOLUTION (m)</th>
<th>VERTICAL RESOLUTION (m)</th>
<th>BIN SPACING (m)</th>
<th>SEISMIC DATA POLARITY</th>
</tr>
</thead>
<tbody>
<tr>
<td>Northern North Sea</td>
<td>29,000</td>
<td>6</td>
<td>110 – 475</td>
<td>1.74 – 2.84</td>
<td>35 – 50</td>
<td>15 – 38</td>
<td>7 – 19</td>
<td>50 x 50</td>
<td>SEG reverse</td>
</tr>
<tr>
<td>Nigeria Transform Margin</td>
<td>2,845</td>
<td>6</td>
<td>1500 – 3800</td>
<td>2</td>
<td>25 – 50</td>
<td>21 – 42</td>
<td>10 – 21</td>
<td>12.5 x 12.5</td>
<td>SEG normal</td>
</tr>
</tbody>
</table>
Fig. 1.7b Seabed polarity from the Nigeria Transform Margin (NTM)

No well data was available for the Nigeria Transform Margin. Stratigraphic picks were obtained from PGS website for the Aje Field located north of the study area (Appendix 1.2 & 1.3). These picks were carried through the entire study area guided by reflection continuity and terminations based on seismic stratigraphic techniques of Mitchum et al., (1977). Other horizons were also mapped strictly based on reflection continuity and seismic facies change across intervals. The lack of well data made it difficult to constrain lithology across the area.

Table 1.4 Wells selected from each quadrant in the Northern North Sea used to carry out analysis

<table>
<thead>
<tr>
<th>QUADRANTS</th>
<th>FIELDS/DISCOVERIES</th>
<th>WELLS USED</th>
</tr>
</thead>
<tbody>
<tr>
<td>29</td>
<td>Martin Lange</td>
<td>29/6-1</td>
</tr>
<tr>
<td>30</td>
<td></td>
<td>30/2-2, 30/3-3, 30/3-9, 30/4-1, 30/6-5</td>
</tr>
<tr>
<td>31</td>
<td>Troll</td>
<td>31/2-1, 31/2-2, 31/2-5, 31/2-19S, 31/3-1, 31/3-4, 31/4-3,</td>
</tr>
<tr>
<td>32</td>
<td></td>
<td>32/4-1</td>
</tr>
<tr>
<td>33</td>
<td></td>
<td>33/5-2, 33/6-2</td>
</tr>
<tr>
<td>34</td>
<td>Snorre</td>
<td>34/2-4, 34/4-5, 34/4-7, 34/7-1, 34/7-9, 34/8-3A, 34/10-2, 34/10-19, 34/10-23, 34/10-30, 34/10-32, 34/10-36</td>
</tr>
<tr>
<td>35</td>
<td>Vega, Fram, Agat</td>
<td>35/3-1, 35/3-2, 35/3-3, 35/3-4, 35/3-5, 35/4-1, 35/7-3, 35/9-3/4T2, 35/8-1, 35/8-2, 35/8-3, 35/8-5S, 35/9-3, 35/9-5, 35/10-1, 35/10-2, 35/10-3, 35/11-1, 35/11-2, 35/11-3S, 35/11-5, 35/11-6, 35/11-8S, 35/11-11, 35/12-1, 35/12-2, 35/12-3S,</td>
</tr>
<tr>
<td>36</td>
<td></td>
<td>36/1-2, 36/4-1, 36/6-2S, 36/7-1, 36/7-3</td>
</tr>
</tbody>
</table>
1.4.2 Methods

A series of interpretation techniques were applied in the course of the research and discussed below. Additional methodologies for specific chapters are discussed under each chapter.

Synthetic seismograms were generated for well to seismic calibration to accurately relate formation tops in wells to reflections in seismic. Density and sonic logs were used to calculate the acoustic impedance at different stratigraphic layers. This was in turn used to generate the reflection coefficient, which was convolved with an extractive wavelet from the seismic volume to produce a synthetic seismogram (Fig. 1.8). All well logs used were exported from a project in Kingdom Suite and imported into Petrel for interpretation.

Key horizons tied from wells were used in conjunction with time significant boundaries identified from reflection terminations (onlaps, offlaps, toplaps, truncations and downlaps) based on seismic stratigraphic techniques of Mitchum et al., (1977) (Tab. 1.5). These horizons were mapped using 2D and 3D tracking in Schlumberger Petrel software across the entire study area to create time structure maps.

In the Northern North Sea, 12 major horizons (H) were mapped from the Base Cretaceous Unconformity up to the present day seabed using the 3D MegaSurvey (Tab. 1.5). 10 main Cenozoic stratigraphic sequences (CSS0 – CSS9) were defined based on the stratigraphic framework of Jordt et al., (1995, 2000) and unit characteristics are summarized in table 1.5. For the purpose of clarity and ease of description, the area was divided into 4 segments; NE, SE, SW and NW respectively based on major fields in the area such as NE - Agat; NW – Snorre, SE – Troll and SW – Oseberg fields (Fig. 1.6a).

6 major horizons were mapped for the Nigeria Transform Margin (NTM). These horizons were matched from nearby Aje Field located in the northern part of the study area (Appendix 1.2 & 1.3). Horizons divide the post-transform succession into 5 seismic units (SU1 – SU5) (Chapter 2). Several other horizons were produced from horizon stacking in Paleoscan. For ease of description, the NTM was divided into 2 areas; 1 and 2 based on approximate limit of mass transport deposits and fluid flow phenomena (Fig. 1.7a).

TWT structure maps were used to generate thickness maps between surfaces. Results from these maps provided an insight into understanding the basin fill through time. Seismic attributes were extracted on single or dual horizons and on the entire volume to image features of interest such as depositional elements and fluid flow phenomena. Attributes include root mean square (RMS), maximum amplitude, dip, azimuth, variance and instantaneous value in petrel and opendtect software. These attributes have great potential to highlight subtle depositional elements such as channels and fans; and fluid flow phenomena such as sandstone injectites, pockmarks, pipes and polygonal faults.
Fig. 1.8 Synthetic seismogram of well 35/8-1. Panel 3 shows the gamma ray log with the yellow indicating intervals with sandstones. Panel 4 shows density (black) and sonic log (blue). Panel 5 and 7 shows reflection coefficient and generated synthetic seismogram respectively. Panels 6 and 8 represent traces extracted from seismic volume closest to the well used for the ties.

A significant part of the study was to map sandstone intrusions and extrusions in the Northern North Sea (NNS). These post-depositional sandstones are manifested as high-amplitude, discordant or concordant anomalies that crosscut hundreds of metres of mudstone intervals (Fig. 1.9). Some of the anomalies were penetrated by boreholes to make lithological interpretations. Mapping of these features was carried out line-by-line using 2D tracking and manual interpretation in petrel (Huuse & Mickelson 2004, Shoulder et al., 2007; Jackson et al., 2010). This was only achievable where significant contrast existed between the sandstone injectite and encasing mudstone (Huuse et al., 2004). Maximum amplitude extraction was utilized to determine their spatial and lateral distribution. Most of these features in the NNS have very complex geometries and cannot be picked; in such cases, we relied only on the distribution to show their occurrence. Quantitative analysis was carried out to measure dip angle, upper width, lower width and height of the sandstone injectites (Fig. 1.10). This was very useful in comparing sandstone injectites from each of the units in the study area and with other basins. The quantitative parameters were graphically presented to highlight comparisons and investigate any relationships.
<table>
<thead>
<tr>
<th>SEISMIC UNIT</th>
<th>INTERNAL FACIES DESCRIPTION</th>
<th>SEISMIC SURFACES</th>
<th>SURFACE DESCRIPTION</th>
<th>KEY SEISMIC CHARACTER</th>
</tr>
</thead>
<tbody>
<tr>
<td>CSS9</td>
<td>Low angle prograding reflections in the west, more continuous/parallel in other parts of the basin. High amplitude, possibly gas clouds or gas pockets are randomly observed</td>
<td>H10-Base Pleistocene unc</td>
<td>Hard reflection, fairly parallel in most parts of the basin, lacks major topography</td>
<td></td>
</tr>
<tr>
<td>CSS8</td>
<td>Medium angle prograding reflections, as observed in CSS9, similar internal reflection, restricted to the north western margin of the area.</td>
<td>H9-Late Pliocene - Lower base Pleistocene unc</td>
<td>High amplitude reflection restricted to the NW of the area and merges with H10 to form a composite unconformity in the basin centre</td>
<td></td>
</tr>
<tr>
<td>CSS7</td>
<td>High angle prograding reflections, described as clinoforms, low-mod amplitude. Unit down laps onto underlying surface in a NW direction</td>
<td>H8-Base Pliocene surface</td>
<td>Considerably continuous surface with variable amplitude. Mounded in the western margin and forms the down lap surface for the prograding clinoforms</td>
<td></td>
</tr>
<tr>
<td>CSS6</td>
<td>High-mod-Low amplitude reflections. Mounded geometry and highly affected by underlying discordant high amplitude facies</td>
<td>H7-Mid Miocene Unconformity</td>
<td>High amplitude surface. Continuous in most part of the basin but severely affected by underlying injected facies. A very important erosional break in the area</td>
<td></td>
</tr>
<tr>
<td>CSS5</td>
<td>Parallel reflections, often affected by polygonal faulting. Transparent and low amplitude. Conformable with underlying reflections</td>
<td>H6-Base Miocene surface</td>
<td>Continuous reflection. Offset by series of polygonal faults emanating from underlying units</td>
<td></td>
</tr>
<tr>
<td>CSS4</td>
<td>Variable amplitude character. Upper part fairly continuous and parallel when not affected by injected sand facies, offsetted by numerous polygonal faulting. Onlaps onto the Intra Neogene unconformity in the E. Lower part is characterised by transparent facies and pinches eastwards. The units are separated by the H5-Opal A-CT boundary, a non-stratigraphic surface</td>
<td>H5-Opal A-CT boundary, H4-Intra Oligocene unc, H3-Eocene-Oligocene surface</td>
<td>Diagenetic surface, cuts across the CSS4 high amplitude reflection. Very high amplitude inclined surface. Top of Oligocene wedge. Often offset by polygonal faults. Poorly expressed in the western margin</td>
<td></td>
</tr>
<tr>
<td>SEISMIC UNIT</td>
<td>INTERNAL FACIES DESCRIPTION</td>
<td>SEISMIC SURFACES</td>
<td>SURFACE DESCRIPTION</td>
<td>KEY SEISMIC CHARACTER</td>
</tr>
<tr>
<td>-------------</td>
<td>-----------------------------</td>
<td>------------------</td>
<td>---------------------</td>
<td>----------------------</td>
</tr>
<tr>
<td>CSS3</td>
<td>Low-transparent semi-continuous amplitude reflections. Lower part is affected by polygonal faults. Forms a wedge and pinches out towards the basin. Truncated by the H11</td>
<td>H4-Intra Oligocene unc</td>
<td>Very high amplitude inclined surface. Overlying surface for the Oligocene wedge (CSS3). Forms the onlap surface for the upper unit of CSS4</td>
<td></td>
</tr>
<tr>
<td>CSS2</td>
<td>Intensely disturbed by chaotic and remobilized/injected facies. Low-transparent reflections, high amplitude discordant anomalies within background strata. Truncated by H11 along the eastern margin</td>
<td>H3-Eocene-Oligocene surface</td>
<td>Often offset by polygonal faults. Moderate high amplitude reflection. Poorly expressed in the western margin</td>
<td></td>
</tr>
<tr>
<td>CSS1</td>
<td>Variable internal seismic character. Low-med, semi continuous reflections, prograding clinoforms in the sw part (Donorch delta). High amplitude anomalies observed in the se part. Locally affected by polygonal faults. Uniform thickness</td>
<td>H2-Top Balder surface</td>
<td>High amplitude reflection. Regional extensive and formed from volcanic activity. Affected by polygonal faults in the basin centre</td>
<td></td>
</tr>
<tr>
<td>CSS0</td>
<td>Low-transparent semicontinuous amplitude reflections. Variable thickness and offset by major Mesozoic faults. Occasionally, reflections are parallel and very continuous.</td>
<td>H1-Base Tertiary surface</td>
<td>Conformable with the H2 and occur also regionally. High amplitude, continuous and sometimes offset by polygonal faults. Base of the Cenozoic succession</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>H0-Base Cretaceous Unconformity</td>
<td>Regional and major regional unconformity. High amplitude and continuous. Surface is offset by underlying faults.</td>
<td></td>
</tr>
</tbody>
</table>

**Tab. 1.5** Key seismic characters of mapped surfaces and seismic units with brief descriptions of each
Fig. 1.9 Different attributes used to image conical intrusions in cross section, plan view and 3D in Opendtect. These characteristics are used to identify sandstone injectites.
Along the NTM, mass transport deposits constitute a significant portion of the interval of interest and their distribution was represented by mapping the base of the failed sediments and extracting a series of attributes on the top and base horizons which were mapped. MTDs are easily recognised within seismic by their chaotic character. Pockmarks and pipes were identified from original seismic volumes and time slices through the features. RGB frequency decomposition and iso-proportional slicing, using Geoteric software, was also used for imaging of deep-water depositional products such as channel-systems and lobes. The technique was based on slicing the interval of interest into horizons and zones which follow the general stratigraphic architecture of the unit constrained by upper and lower bounding horizons.

The Northern North Sea and Nigeria Transform Margin are pervasively deformed by small, normal faults that have polygonal geometry in plan view. These faults were best imaged using horizon mapping and time slices through variance and ant-tracking volumes (Cartwright 1994). Fault population statistics such as length, azimuth, throw and dips were measured. Results obtained were used to make graphical plots to investigate any relationships between the parameters. Rose diagrams were also generated to show fault orientations.

\[ \text{Fig. 1.10 Parameters measured for conical sandstone intrusions (not drawn to scale)} \]
1.5 THESIS SYNOPSIS

The thesis is written as an alternative format presented in seven (7) chapters, which includes papers to be submitted to peer-reviewed journals.

**Chapter 1** Introductory chapter consisting of location of study, rationale, aims and specific objectives, dataset available for the study areas and methods adopted to achieve the objectives.

**Chapter 2** Review of depositional and fluid-flow features in both basins and their geologic settings.

**Chapters 3 – 6** Research papers based on results from the entire study to be submitted to peer-reviewed journals.

**Chapter 7** Synthesis chapter that summarises and integrates all the results and findings from the research study. It also includes conclusions and recommendation for future work

---

**Paper 1**

**Title:** Cenozoic Sedimentation in the Northern North Sea using 3D Seismic Data

To be submitted to *Basin Research*

**Authors:** Oluwatobi Olobayo¹, Mads Huuse¹, and Christopher Aiden-Lee Jackson²

¹ *Basin Studies and Petroleum Geoscience Research Group, SEAES, University of Manchester, Williamson Building, Oxford Road, Manchester M13 9PL, United Kingdom*

² *Basins Research Group (BRG), Department of Earth Sciences and Engineering, Imperial College, London, SW7 2BP, United Kingdom*

---

**Paper 2**

**Title:** The Sand Injectite Stratigraphy of the Northern North Sea

To be submitted to *Basin Research*

**Authors:** Oluwatobi Olobayo¹, Mads Huuse¹, and Christopher Aiden-Lee Jackson²

¹ *Basin Studies and Petroleum Geoscience Research Group, SEAES, University of Manchester, Williamson Building, Oxford Road, Manchester M13 9PL, United Kingdom.*

² *Basins Research Group (BRG), Department of Earth Sciences and Engineering, Imperial College, London, SW7 2BP, United Kingdom*
Paper 3

Title: Quantitative Analysis of Sandstone Intrusions, Polygonal Faults and Silica Diagenetic Boundary in the Northern North Sea

To be submitted to Basin Research

Authors: Oluwatobi Olobayo¹, Mads Huuse¹, and Christopher Aiden-Lee Jackson²

¹ Basin Studies and Petroleum Geoscience Research Group, SEAES, University of Manchester, Williamson Building, Oxford Road, Manchester M13 9PL, United Kingdom.

² Basins Research Group (BRG), Department of Earth Sciences and Engineering, Imperial College, London, SW7 2BP, United Kingdom

---

Paper 4

Title: 3D Seismic Analysis of Cenozoic Slope Deposits and Fluid-Flow Features along the Nigeria Transform Margin

To be submitted to Geosphere

Authors: Oluwatobi Olobayo¹, Mads Huuse¹, and Christopher Aiden-Lee Jackson²

¹ Basin Studies and Petroleum Geoscience Research Group, SEAES, University of Manchester, Williamson Building, Oxford Road, Manchester M13 9PL, United Kingdom.

² Basins Research Group (BRG), Department of Earth Sciences and Engineering, Imperial College, London, SW7 2BP, United Kingdom
2 GEOLOGICAL SETTINGS AND REVIEW OF DEPOSITIONAL, REMOBILIZED AND FLUID FLOW FEATURES IN THE STUDY AREAS

2.1 GEOLOGICAL SETTING

2.1.1 Northern North Sea

The Cenozoic North Sea Basin formed as a thermal sag basin above pre-existing, rift-related structures, associated with extensional events during the last two phases of riftting in the Permo-Triassic, and the Late Jurassic-to-Early Cretaceous (Fig. 2.1) (Ziegler 1990; Fossen et al., 2010). The last two phases form the framework in which the present-day basin configuration is built on (Kyrkjebø et al. 2001; Zanella et al. 2003). Each phase was followed by thermal relaxation and subsidence (Ziegler 1990; Rundberg 1991; Faleide et al., 2002). Subsidence was greatest in the Viking Graben, Central Graben and the Sogn Graben, with sediment thickness of ≥ 2300 metres, characterized by mainly clastic sedimentation of fine-grained, hemipelagic mudstones, smectitic and siliceous mudstones (Anell et al. 2011). Coarser sediments were supplied into the basin during uplifts along the Shetland platform and Norwegian mainland in form of large fans and channel-lobes (Rundberg 1991; Den Hartog Jager et al., 1993; Jordt et al., 1995; 2000; Martinsen et al., 1999; Huuse & Mickelson 2004; Anell et al., 2011; Goledowski et al., 2012). They formed the main sediment sources in the Tertiary.

Fig. 2.1 Seismic section through the North Sea showing Cenozoic sequences (coloured) above rift-related, Mesozoic sequences. Study area is located within the Norwegian sector of the North Sea basin (Den Hartog Jager et al., 1993). Length of seismic line approximately 310 km
Based on Isaksen & Tonstad (1989), the Cretaceous stratigraphy is divided into Cromer Knoll and Shetland groups, composed mainly of thick mudstones in the study area, but very thin or almost absent over the Troll fault blocks (Fig. 3.4). Large slope fan, channels and terminal fans belonging to the Kyrre Formation in the Upper Cretaceous were mapped along the Maløy slope (Jackson et al., 2008, 2010). The overlying Cenozoic interval is divided into three main groups: Rogaland, Hordaland and Nordland groups. Uplifts along the basin margins, which were related to break-up of North Atlantic resulted in deposition of clastic sediments, inform of channels and sand-rich fans into the basin from the Shetland platform and west of Norway (Ahmadi et al., 2003; Huuse & Mickelson 2004; Brunstadt et al., 2009). This was followed by deposition of ash-rich, tuffaceous deposits during the Late Paleocene to Early Eocene, as a result of separation of Norway and Greenland that formed the Balder Formation (a regional marker horizon across the North Sea). This marks the top of the Rogaland Group (Fig. 3.2) (Jones et al., 2003; Jordt et al., 1995, 2000; Anell et al., 2011).

The Hordaland Group comprises of siliciclastic sediments, bounded above and below by the mid-Miocene unconformity and the Top Balder Formation, respectively (Fig. 3). Deepening of the basin occurred in Paleocene till Eocene time and a regional transgression covered the underlying tuffaceous sediments by depositing low-permeability, deep marine muds (Kyrkjebo et al. 2001; Ahmadi et al., 2003). Deposition within the basin at this time was characterised by fine-grained, smectite-rich mudstones and coarser-grained, siliceous-rich mudstones in the Eocene and Oligocene intervals, respectively (Rundberg 1991, Thyberg et al., 1999, 2000). These include large sandstone units deposited by gravity currents along the eastern basin margin (Rundberg 1991; Jordt et al., 2000; Faleide et al., 2002; Martinsen et al., 2005). Along the adjacent margin of the basin to the west, large, sand-rich systems were also supplied into the basin from the Shetlands in the Early Eocene times. These sandstones form the sandstone of the Frigg Field.

The Eocene-Oligocene transition records significant events globally; these include change from greenhouse to icehouse conditions, reduction in water bottom temperature, global mass extinction, faunal and mineralogical changes from smectite-rich to silica-rich sediments (Rundberg 1991; Zachos 2001; Miller et al., 2005; Rundberg & Eidvin 2005). The Eocene and Oligocene deep-marine, Horda and Lark Formation, respectively comprises three sandstone members namely; Frigg, Grid and Skade members (Isaksen & Tonstad 1989, Jordt et al., 1995, 2000). Detailed mineralogical and geochemical studies by Rundberg (1991) showed the boundary represents (a) a transition from very fine grained, greenish, Eocene mudstones to brownish, coarser-grained, Oligocene mudstones; (b) decrease in smectite and increase in kaolinite and illite and (c) an increase in biogenic silica sediments.

Fine-grained sedimentation dominated during the Oligocene, but thick-bedded, sandstone bodies, belonging to the Skade Formations were locally deposited (Isaksen & Tonstad 1989, Jordt et al., 1995, 2000). More recent studies on the Skade sandstones have, however, dated them as Lower Miocene rather than Oligocene (Rundberg & Eidvin 2005, Eidvin & Rundberg 2007). No formal name has been assigned to the Oligocene sandstones, which is probably the age equivalent to the Belton sands in the UK sector. Deposition of biogenic sediment also had a major influence on the
Fig. 2.2 Stratigraphic framework for the Northern North Sea and Nigeria Transform Margin including soft-sediment remobilization and fluid-flow phenomena and petroleum systems (partly modified from Jordt et al., 1995, 2000; Borsato et al., PGS; Kubala et al., 2003; Schlakker et al., 2012; Olobayo et al., 2015)
stratigraphy of the Oligocene mudstones, as sediment underwent diagenetic transformation after they were deposited, altering their mineralogical composition, porosity and possibly permeability (Rundberg 1991; Thyberg et al., 1999; Rundberg & Eidvin 2005, Davies et al., 2006).

The mid-Miocene unconformity (MMU) represents a period of significant erosion in the North Sea and separates the Hordaland from the Nordland Group with a time-gap of ~15 ma (Isaksen & Tonstad 1989; Martinsen et al., 1999; Galloway et al., 1993; 2002; Rundberg & Eidvin 2005; Løseth et al., 2013). It is occasionally mounded in the study area. All sediments deposited after the erosion were classified under the Nordland Group (Fig. 3.2). The MMU in the northern North Sea is often overlain by the Utsira Formation, which is Late Miocene or Early Pliocene in age (Isaksen & Tonstad 1989; Martinsen et al., 1999; Galloway 2002; Rundberg & Eidvin 2005). Utsira Formation is sandstone dominated and while some workers believed it was formed in marine shelf or shallow marine environment (Isaksen & Tonstad 1989; Rundberg 1991; Martinsen et al., 1999; Galloway 2002), others favoured a more submarine deposition (Gregersen 1997).

The Utsira Formation is overlain by westwardly-prograding, Pliocene-age clinoforms sourced from the Norwegian mainland (Jordt et al., 2000). Jordt et al., (2000) and Eidvin & Rundberg (2001) related the thick wedges created by Pliocene clinoforms to increased accommodation during major sea-level rise or significant subsidence within the basin; although no record of sea-level increase during this period (Miller et al., 2005). The clinoforms are truncated at their tops by the regional Pleistocene unconformity, formed from grounding ice sheets and mapable across the entire area. The Pleistocene unit is composed of mudstones interbedded with sandstones and glacial tills to glacial marine sediments (Faleide et al., 2002; Gregersen et al., 2007).

2.1.2 Petroleum Systems

The North Sea basin is one of the most petrolierous basins in the world with an active petroleum system throughout the Cenozoic (Huuse & Mickelson 2004). The primary source rock for oil in the North Sea is the Late Jurassic Kimmeridge Clay Formation (Late Oxfordian to Ryazanian in age) in the UK sector, an age equivalent of the Draupne Formation in the Norwegian sector (Kubala et al., 2003). Other potential source rocks include the Heather Formation and Middle Jurassic coal-bearing rocks of the Brent Group. These formations generated gas in the North Sea with limited potential for oil (Coward et al., 2003; Kubala et al., 2003). In the North Viking Graben, reservoirs are mostly Middle to Late Jurassic, shallow marine sandstones and sourced from either the Draupne, or the Heather Formations for oil and from the Brent Group for gas (Kubala et al., 2003).

Maturity for oil generation in the North Viking Graben was reached in the Late Cretaceous with peak maturation since the mid-Paleogene (~54 Ma) and maturation for gas generation since the Late Neogene (~14 Ma). Active generation continues till present day (Kubala et al., 2003). Main traps include series of horst-graben and fault-related structures formed during the rifting. These
structures form the giant hydrocarbon fields in the North Sea, such as Troll, Snorre, Stratfjord and Gullfaks (Fraser et al., 2003).

These faults are often suggested to have provided secondary migration pathways for hydrocarbon from Jurassic into shallower sections in the Frigg Field (South Viking Graben) and other Early Paleogene reservoirs (Kubala et al., 2003); however, in the North Viking Graben, there is paucity of such commercial hydrocarbon accumulations (Fig. 1.2). Although Paleogene-aged sandstones are emplaced within thick, low permeability mudstones in the northern North Sea, they are often close to normally pressured, with the sand bodies in pressure communication over large areas and often connected to large aquifers (Moss et al., 2003; Huuse & Mickelson 2004). This large, cross-strata connectivity has been explained by the presence of numerous sandstone intrusions and polygonal faults within the Paleogene succession (Huuse & Mickelson 2004).

![Petroleum system chart for the North Viking Graben in the North Sea. Also shown are timing for sandstone injectite emplacement in the study area (modified from Kubala et al., 2003; Schlakker et al., 2012)](image)

**Fig. 2.3** Petroleum system chart for the North Viking Graben in the North Sea. Also shown are timing for sandstone injectite emplacement in the study area (modified from Kubala et al., 2003; Schlakker et al., 2012)

2.1.3 The Nigeria Transform Margin - Geology and petroleum systems

The study area is located within the Dahomey-Benin basin and forms part of the east-west aligned basins within the Gulf of Guinea that consists of Cote d'Ivoire, Ghana, Togo, Benin and western part of Nigeria coast (Fig. 1.3a) (Brownfield & Charpentier 2006). These basins were initiated during the rifting between the African and South American plates, which began in the Late Jurassic and characterized by, transform and wrench faults that formed during the separation (Fig. 2.4) (Greenhalgh et al., 2011).
The Nigerian Transform Margin and the other basins within the Gulf of Guinea are in contrast to passive-margin basins, such as the Lower Congo and Angola basins, mainly based on influence of transform tectonics and absence of salt tectonics (MacGregor et al., 2003). Basin evolution along the margins underwent complex tectonic history and occurred in three phases, which were separated by major unconformities. They include: pre-transform or pre-rift (Late Proterozoic to Late Jurassic), syn-transform or syn-rift (Late Jurassic to Early Cretaceous) and post-transform or post-rift (Late Cretaceous to Holocene) (Brownfield & Charpentier 2006).

At the end of Late Jurassic to Early Cretaceous time, the basin was characterized by transform and block faulting above regionally, extensive Paleozoic basin that formed during separation of North America from Europe and Africa, which started in the Late Permian to Early Triassic time (Ziegler 1988). Thick continental crust of the African and South American continental plates began to breakup in the Early Albian time and formed the sedimentary basins separated by transform faults (Blarez & Mascle 1988). Culmination of transform tectonism in the mid to Late Albian time coincided with initial breakup of oceanic crust along the continents and formed the Gulf of Guinea. The Gulf of Guinea was formed initially as an anoxic oceanic basin but had become a completely oxic seaway at the beginning of Campanian (Fig. 2.4) (Brownfield & Charpentier 2006).

The stratigraphic section of the basin was also divided based on the three stages of evolution, which includes: Precambrian to Lower Cretaceous rocks for pre-transform, Lower Cretaceous to Late Albian rocks for syn-transform and the Cenomanian to Holocene rocks representing the post-transform stage (Fig. 6.2c) (Brownfield & Charpentier 2006). The studied interval belongs to the post-transform succession bounded at the base and top by the Top Albian unconformity and
present day seabed, respectively (Fig. 2.2). The former marked the end of the syn-transform phase followed by thermal subsidence that continued till present day (Greenhalgh et al., 2011). In the mid-Late Cretaceous, deeply incised canyons were eroded into the shelf during relative sea-level fall, such that sediments were transported into the basin creating large turbidite fans, which form the main reservoir targets along the transform margin (Brownfield & Charpentier 2006; Greenhalgh et al., 2011). These sandstones were deposited within the Araromi and Agwu Shale Formation, which could have formed the source rocks and seals for the reservoirs (Fig. 6.2c) (Borsato et al., PGS). Non-marine to marginal marine conditions prevailed during the middle Cretaceous and expected to contain gas-prone source rocks (MacGregor 2003; Brownfield & Charpentier 2006). Sediments deposited during the Late Cretaceous in the basin were divided into two main stratigraphic units: the Abeokuta and Araromi Formations (Obaje 2009). Sandstone belonging to the former of these two formed the reservoir sands for the Aje and Seme Fields in Nigeria and Benin, respectively (Fig. 6.2c).

Tertiary rocks unconformably overlie Cretaceous rocks and comprise of Paleocene to Eocene marine shales belonging to the Imo Shale Formations interbedded with the Ameki Formation sandstones in the study area (Fig. 6.2c). A major Oligocene-Miocene unconformity separated the Early Tertiary succession from Miocene marine rocks (Brownfield & Charpentier 2006; Borsato et al., PGS).

All the east-west trending basins on both sides of the equatorial transform margins have similar structural and stratigraphic features. Exploration activities in the basins have increased significantly in the last few years due to successes from recent discoveries in Cretaceous fans, such as the world-class Jubilee Field, Venus and Odum Fields (Brownfield & Charpentier 2006). Although, exploration started in the area much earlier following discovery of bitumen and tar sands in Late Cretaceous outcrops along the African Equatorial conjugate margin, this did not yield desired commercial accumulations (Greenhalgh et al., 2011). However, continuous exploration with the use of better resolved seismic data and data gathered from initial wells revealed presence of two main petroleum plays, which includes the older, syn-transform Aptian-Albian Fields such as Hihon, Fifa, Tano and the younger, post-transform Upper Cretaceous Fields such as Aje, Panthere, Belier (Fig. 6.2c) (Greenhalgh et al., 2011).

Hydrocarbon generation in the Cretaceous source rocks started in the Late Miocene in the Dahomey-Benin basin and continues till present day, though this began much earlier in the other nearby basins (MacGregor 2003; Brownfield & Charpentier 2006).
2.2 REVIEW OF DEPOSITIONAL, SOFT-SEDIMENT REMOBILIZATION AND FLUID FLOW FEATURES

Submarine fans and channel systems constitute successful reservoirs for hydrocarbon exploration and production in the Paleogene and Eocene intervals of the North Sea basin (Fig. 2.6) (Den Hartog Jager et al., 1993; Ahmadi et al., 2003). Increasing interest in deep-water systems facilitated acquisition of better seismic data integrated with well data and outcrop studies to better understand their architecture and other products associated with them.

Most sandstone in the North Sea, Gulf of Guinea and other parts of the world are commonly believed to have been deposited by gravity-flow processes creating large, deep-water channel lobes and low-stand fans (Fig. 2.6) (Den Hartog Jager et al., 1993; Ahmadi et al., 2003; Hamberg et al., 2005; Martinsen et al., 2005; Dmitrieva et al., 2012). However, detailed investigation using better resolved seismic data with careful integration with well data and outcrop studies have revealed unusual geometries that are difficult to unravel by normal depositional, gravity-driven processes (Dixon et al., 1995; Duranti et al., 2002). It is believed that these originally deposited sandstones have been subject to sub-surface remobilization and injection resulting in modifications to their geometries. The products of the post-depositional processes are classified as remobilized, injected or extruded sandstones (Fig. 2.7) (Lonergan et al., 2000; Huuse et al., 2009 AAPG; Huuse et al., 2012).
Fig. 2.6 Paleogene sandstones in the North Sea interpreted as low-stand fans, mounded fans and isolated channel complexes (Den Hartog Jager et al., 1993)

Fig. 2.7 Three (3) models suggested for occurrence of sandstone in the North Sea Basin. They include the depositional model through gravity-driven processes; remobilized – in-situ remobilization of sandstones after deposition and Injected model – due to part or whole injection of the sandstones. When sands reach the seabed, extrudites are formed (partly modified from Huuse et al., 2009, AAPG)

This phenomenon was first recognised in Californian outcrop in the early 90’s (Newsome 1903; Jenkins 1930), but received little or no attention until recently in the last two decades, when their impact on hydrocarbon exploration and production in North Sea basin was realised (Lonergan et al., 2000; Hurst & Cartwright 2007). Sandstone intrusions and extrusions, as they are sometimes referred to, form part of the subsurface sediment remobilization and fluid-flow products in sedimentary basins described by Huuse et al., (2010), and they have been grouped into
sandstone intrusion and extrusion complexes, mud volcano systems and focused fluid flow pipes based on geological processes that formed them (Figs. 2.7, 2.8, 2.9). They are collectively classified as fluid flow features, as their formation involve significant volume of fluid (pore water or hydrocarbon) to be added to the sediment facilitated either by internally, or externally driven mechanism (Løseth et al., 2003, 2009; Cartwright 2007; Andresen 2012). They are widely recognised in seismic, outcrops, cores and well logs in several sedimentary basins world-wide (Appendix 1.1). They are also classified under products of soft-sediment remobilization (Van Rensbergen 2003), which also includes mass transport deposits and other fluid flow products (Frey Martinez et al., 2011).

Other fluid flow phenomena include pockmarks, gas chimneys, gas hydrate BSRs, diagenetic boundaries, gas hydrate pingoes, carbonate mounds and polygonal faults; typically manifested on seismic data as amplitude anomalies (Shipley et al., 1979; Hovland & Judd 1988; Cartwright 1994; 2007; Rensbergen et al., 2003; Davies et al., 2006; Judd & Hovland 2007; Gay et al., 2007; Løseth et al., 2009; 2011; Huuse et al., 2010; Andresen 2012; Serie et al., 2012). Over the years, these fluid flow features have been classified into various groups based on geometries, geological processes, lithology, fluid type, fluid flow direction and mechanism of emplacement, such as subsurface sediment remobilization, focused fluid flow and stratigraphic/lateral fluid flow (Andresen 2012). They have long-term impacts on fluid flow and their presence signifies a breach in the sealing capacity of the host rock (Cartwright 2007; Løseth et al., 2009; Huuse et al., 2010).

Some of the soft-sediment remobilization and fluid flow phenomena mentioned above are commonly observed in the both study areas and will be discussed briefly in the following subsections.

### 2.2.1 Mass Transport Deposits

Mass transport deposits (MTDs) form when shear stress oriented down the slope overcomes shear strength of the slope materials causing failure, such that large amount of sediments are transported down the slope (Zhu et al., 2011). They occur on the slope and basin-floor settings and occur as creep, slide, slump, and debris flows (Posamentier & Martinsen 2011). Several mechanisms have been invoked for causing slope failure and they include sediment loading, slope progradation, seafloor slope gradient, gas hydrate dissolution, presence of gas in sediments, earthquake shaking, sea level changes and opal A to CT conversion (Davies & Clark 2006; Garziglia et al., 2008; Shipp et al., 2011). MTDs are often represented as transparent chaotic facies on seismic data and have been recognised from outcrop and core data across the globe, ranging from few metres to hundreds of kilometres in length e.g the Storegga slide, offshore Norway, which is one of the largest MTDs in the world (Posamentier & Martinsen 2011). Several authors have investigated the interplay between mass transport deposits and turbidite systems, which makes them important components of deep-water settings as regarding hydrocarbon exploration and production.
Fig. 2.8 Seismic: Volund (Szrawarska et al. 2010), Tampen Spur (Huuse & Mickelson 2004), Danica (Szrawarska et al. 2010), Faroe Shetland (Shoulders et al. 2004), Alba (Huuse et al. 2007), Gamma (Huuse et al. 2007), Ulsira high (Briedis & Wild 2010); Sin Canyon (Andresen et al. 2009). Outcrops: Helmsdale NE Scotland, Moreno Shale Pancoche, Tumey hills San Joaquin, (Huuse et al. 2004, Santa Cruz (Thompson et al. 2007), Southeast Frances, (Panze et al. 2007). Well logs: Volund (De Boer et al. 2007). Cores: Jolund (Guargena et al. 2007) & Baldar (Briedis et al. 2007). Compiled by Oluwatobi Olobayo, First year Transfer Report 2012.
Figures 2.9 Mud Volcanoes: Seismic: Voring plateau Norway (Huuse et al. 2010), Eastern offshore Trinidad (Deville et al. 2010), Outcrops: Lusi east Java Indonesia (Google images), Norris Geyser basin Wyoming (Huuse et al. 2010).

Focused Fluid Flow Pipes: Seismic: Offshore Nigeria (Loseth et al. 2010), Offshore Namibia (Moss & Cartwright 2010), Outcrops: Caramel Fm Utah, (Felice 2010); Caramel Fm Utah (Chan et al. 2007), Kodachrome basin, Utah (Google images). Compiled by Oluwatobi Olobayo, First year Transfer Report 2012
(Nelson et al., 2011; Dykstra et al., 2014). Internal and external morphology of MTDs are often grouped under 3 main domains: headwall, translational and toe domain, each of which consists of component that can provide information of the direction of failure and evolution of the mass transport deposit (Fig. 2.10) (Bull et al., 2009).

![3D schematic diagram of the morphology of MTD showing the 3 domains and individual component (Bull et al., 2009).](image)

### 2.2.2 Sandstone intrusion complexes

We refer to remobilized, injected and extrusion sandstones as sandstone intrusion complexes when describing all three of them together in the rest of the chapter to avoid ambiguity, but will stick to individual terminology when describing each of them. As mentioned earlier, sandstone injectites were first recognised from outcrops as back as the early 19th century (Newsome 1903; Jenkins 1930) but were not encountered again till the late sixties and early eighties in sub-surface cores from the Balder and Alba Fields, respectively (Braccini et al., 2008). These unconventional sandstones were considered as geological oddities and completely ignored within the reservoirs (Hurst & Cartwright 2007; Braccini et al., 2008). However, continuous encounter in cores from sandstone reservoirs and improvement in subsurface imaging from high-quality 3D seismic data revealed seismic-scale injectites, and after which their implications on petroleum systems was recognized. Ever since, their awareness within Paleogene sandstones in the North Sea have grown following successes from major hydrocarbon fields, such as Alba, Balder, Leadon, Volund, Chestnut (Fig. 1.2) (Lonergan et al., 2000; Huuse et al., 2004; Hurst & Cartwright 2007).

In seismic data, sandstone intrusion complexes are represented as high-amplitude, anomalous reflections, often referred to as dykes, when discordant to background stratigraphy and sills, when concordant with back ground strata similar to those observed in igneous environment (Fig. 2.11)
(Shoulders & Cartwright 2004; Braccini et al., 2008; Polteau et al., 2008). They form a wide range of geometries, such as wing-like, crestal, conical, saucer-shaped and often described as V, U or W-shape, though more complex geometries occur in the sub-surface (Cartwright et al., 2008; Jackson 2007; Andresen et al., 2009; Huuse et al., 2010; Hurst et al., 2011; Safronova et al., 2012). In plan view, they often form circular to elliptical geometries (Fig. 1.9). Steep-sided mounds with discordant margins and single mounds have also been described in literature, forming sand extrudites or sand volcanoes (Fig. 2.11). These geometries have also been observed in outcrops around the world (Vigorito et al., 2008).

![Fig. 2.11 3D diagram of common sandstone intrusion features (Braccini et al., 2008)](image)

### 2.2.2.1 Processes and Mechanics of sandstone intrusions

Sandstone intrusion complexes have been observed recognised in a wide range of environments, such as lacustrine, deltaic, fluvial, aeolian, offshore shallow marine, but they are more prone in deep-water settings (Fig. 1.1) (Jolly & Lonergan 2002). Their occurrence in deep-water settings has been attributed to prevalence of loosed, unconsolidated sands within low permeable, fine-grained mudstone socks, sufficient fluid to entrain the sands, presence of excessive overpressure and triggering mechanisms; all of which form the main pre-requisite needed for their formation (Lonergan et al., 2000). Based on the extensive literature of occurrence of sandstone intrusions, they are also more commonly documented in tectonically active, mud-dominated sedimentary
basins with high sedimentation rates; such that tectonic stresses applied on the sediments generates differential pressure between the pore fluid in the sub-surface and the seabed or shallower aquifer (Jolly & Lonergan 2002; Huuse et al., 2010).

In a tectonically quiet basin that is not subjected to any applied stress, such that the dominant compressive stress is vertical (as a result of gravitational loading), for a sandstone dyke to propagate, the fluid pressure \( P_f \) must exceed the horizontal stress or minimum principal stress \( (\sigma_h) \) and the tensile strength of the host sediment, parallel to the bedding \( (T_h) \).

\[
P_f > \sigma_h + T_h
\]

And for a sill to form, the fluid pressure \( P_f \) must exceed the vertical stress or maximum principal stress \( (\sigma_v) \) and the tensile strength of the host sediment, perpendicular to the bedding \( (T_v) \) (Lonergan et al., 2000).

\[
P_f > \sigma_v + T_v
\]

This suggests that that geometry of a sandstone intrusion forming either as a sill, or dyke depends mainly on the fluid pressure, maximum or minimum principal stress, tensile strength of the host sediment, as well as the burial depth in the simplest case, where the basin is not subjected to any form of tectonic stress.

Sandstone intrusions are considered as typical examples of natural mode I hydraulic fractures (Jolly & Lonergan 2002) and processes at which these, occurs can be divided into three phases, which will be summarized below (1) overpressure build-up, (2) seal failure and (3) fluidization.

**Overpressure**

Overpressure or excess fluid pressure is achieved when the pore fluid pressure with a sealed system is greater than hydrostatic pressure at a given depth (Maltman 1994; Swarbrick & Osborne 1998). Overpressure can occur within the parent sand body, sealed in a low-permeability mudstone unit, such that the surrounding mudstones prevent normal expulsion of pore fluids from the pore spaces in the sand body. The weight of the overburden is partly supported by the excess pore fluid pressure causing the sand body to be underconsolidated, and the rest part is sustained by the effective stress, termed as the effective stress, \( \sigma^1 \) which is overburden or lithostatic pressure - fluid pressure

\[
\sigma^1 = \sigma_{Lith} - P_f
\]
Graph 2.1 illustrates behaviour of a sand body before and after overpressure. During early burial, the system is unsealed and the fluid pressure within the sediments follows the hydrostatic gradient, but with subsequent burial and partial or total sealing of the system, fluid pressure reaches the minimum horizontal stress and moves away from hydrostatic gradient towards lithostatic gradient instead. This happens at the onset of overpressure and overpressure continues to build up, leading to the seal failure and sandstone dyke formation (Figs. 2.12) (Lonergan et al., 2000; Jolly & Lonergan 2002).

Graph 2.1 Simplified pressure vs depth for a sedimentary succession and relationship between hydrostatic gradient, overburden load, pore fluid pressure, overpressure and effective stress (Jolly & Lonergan 2002)

The sandstone dyke continues to propagate until the pore fluid pressure parallels the maximum vertical stress and a sill is formed (Lonergan et al., 2000). At shallow depth or near the surface, overburden load is very small and not likely to reach minimum horizontal stress required for dyke formation, therefore favours formation of sills instead. This suggests that in areas where sills dominate, it is fair to assume intrusion occurred at shallower depth with small overburden load or stress (Jolly & Lonergan 2002). In some cases, where sufficient fluid and unconsolidated sands are still available, the entrained sands can reach the surface or paleo-seabed, forming a sand extrudite or sand volcano (Figs. 2.11, 2.12) (Jolly & Lonergan 2002; Hurst et al., 2011).
Overpressure can be generated by a variety of mechanisms and can occur either slowly, or instantaneously over a period of time (Osborne & Swarbrick 1997; Jolly & Lonergan 2002). Some of these mechanisms include: disequilibrium compaction, due to rapid burial of sediments (Osborne & Swarbrick 1997), lateral transfer of pressure (Yardley & Swarbrick 2000; Reilly & Flemings 2010), hydrocarbon generation and migration of basinal fluids (Osborne & Swarbrick 1997; Jolly & Lonergan 2002), drop in water-table (Hermanrud et al., 2012); tectonism, due to basin inversion (Cartwright 2010) and silica diagenetic transformation (Davies et al., 2006). They are collectively referred to as ‘priming mechanisms’, making the sandstones susceptible to subsequent remobilization (Huuse et al., 2010). They will be discussed more under chapter 4.

**Liquefaction**

The state at which overpressure is generated is known as liquefaction and the resultant remobilization of the entrained sediment in a fluid medium is defined as fluidization (Obermeier 1996). Based on his definitions, **liquefaction** is the conversion of sediments from solid to liquid state, as a result of pore pressure increase. Allen (1984) also defined liquefaction as the...
breakdown of sediment, such that the grains are separated and no longer supported by them, but by the pore fluid (Fig. 2.13). During liquefaction, i.e. increase in pore fluid pressure; the effective stress within the sediment is reduced to zero, as the fluid pressure is greater than the minimum principal stress, resulting in generation of fracture networks (Jolly & Lonergan 2002; Hurst et al., 2011).

Earthquakes have been proposed to trigger remobilization and injection of unconsolidated sand by a process known as shear-induced liquefaction or dynamic liquefaction, such that seismic waves propagate into the subsurface and the shearing motion produced by it breaks grain to grain contacts within the sand causing significant increase in fluid pressure beyond or close to lithostatic (Fig. 2.13) (Obermeier 1996, 1989; Cartwright 2010). Near-surface liquefaction of unconsolidated sands by seismic shaking, proposed by Obermeier (1989), could not be conceived when the parent body is deeply buried, due to high effective confining stress or increase in resistance to shear stress with depth (Jolly & Lonergan 2002; Cartwright 2010).

**Seal failure**

When rocks are subjected to stress, they react in different ways, depending on the type of rock, applied stress and stress direction. As mentioned earlier, sandstone dyke is an example of a natural hydraulic fracture, which propagates and is subsequently filled with sand (Cosgrove 1995; Jolly & Lonergan 2002).

For the host rock to fracture, it must be cohesive and the tensile strength (T) of the rock must be overcome while being subjected to some form of stress (at the least vertical stress). The deeper the rock, the more cohesive it will be, due to compaction and porosity loss with increased burial. The host rock for the parent bodies of sandstone intrusions and the intrusion themselves are often fine-grained sediments with very low-permeability (mostly mudstones) that have been sufficiently buried to generate overpressure high enough to fracture the sedimentary strata; such that the fracture networks created are exploited by unconsolidated sands (Fig. 2.12) (Lonergan et al., 2000; Jolly & Lonergan 2002; Hurst et al., 2011; Andresen & Clausen 2014). Presence of sandstone intrusions and other fluid flow phenomena, such as pockmarks and pipes are evidence of failure in the sealing system (Løseth et al., 2008; Judd & Hovland 2007; Cartwright 2010).

**Fluidization**

The final phase described under processes and mechanics of sandstone intrusions is the actual fluidization of the sand into the open fracture networks and this is simply defined as suspension of sediment grains by drag forces as a result of upward migration of fluid (Di Felice 1995; Hurst et al., 2011). It is the ability of fluid to lift cohesionless sediments and the process at which unconsolidated sands are carried from their source or parent sand body into fracture networks (Fig. 2.13) (Obermeier 1996; Duranti & Hurst 2004). Sandstone intrusions play significant role in hydrocarbon migration in the North Sea, as most fields affected by remobilization and injection of
sand have shown they often act as foci for fluid migration (Huuse et al., 2003). This discovery was based on seismic and carbon/oxygen stable isotope data from some North Sea fields.

Fluidization occurs when movement of pore fluid exceeds the minimum fluidization velocity (Obermeier 1996; Hurst et al., 2011). Certain parameters considered in the process include grain size, cementation effect, relative density, fluid velocity and viscosity (Huuse et al., 2010). It is often believed that fine or medium grained sandstones are the easiest and most common to fluidize, due to their low minimum fluidization velocity; however, larger grained sandstones could also be entrained in a pseudo-fluid state, made up of smaller grained sandstones and fluid (De Felice 2010). Fluidization requires significant volume of fluid (hydrocarbon or water) either produced from pore water within the sediments, or introduced from an external source (Lonergan et al., 2000; Van Rensbergen 2003; Huuse et al., 2010; Szarawarska et al., 2010). Most especially in large sandstone intrusion provinces, such as the North Sea, Faroe-Shetland and San Joaquin basins, additional fluid migrating from deeper part of the basin into the parent body may have contributed greatly to drive remobilization and injection of sands (Lonergan et al., 2000; Wild & Briedis 2010; Huuse et al., 2010). In the simplest of term, in order for grains to move, a differential pressure gradient must be generated across the unit; as such the force carrying the grain (drag force) must be greater than the weight of the grains (Jolly & Lonergan 2002). This is often achieved either by an internal, or external factor to trigger it.

Fig. 2.13 Schematic diagrams showing effect of liquefaction and fluidization of sand from depositional parent body during burial (Hurst et al., 2011)
2.2.2.2 Triggering mechanisms for sandstone intrusions

Several authors have investigated different triggering mechanisms for formation of sandstone intrusion complexes, but exact mechanism that initiated actual remobilization and injection are still speculative (Davies et al., 2006). Triggering mechanism could be either internally or externally-driven and almost a century of research have identified the following main triggers: seismic waves from large magnitude earthquakes (Huuse & Mickelson 2004; Cartwright 2010), lateral pressure transfer resulting in post-depositional tilting and migration of water and/or hydrocarbon into sealed sand bodies (Jolly & Lonergan 2002; Cartwright 2010), differential compaction (Jackson 2007; Sapronova et al., 2012), bolide impact (Cartwright 2010), influx of fluid from deeper part of the basin (hydrocarbon or water), tectonic activity (Huuse et al., 2010) and silica diagenetic transformation (Davies et al., 2006). Some have been widely accepted as more plausible than others and this would likely depend on the scale of remobilization. In large-scale intrusion provinces, shearing induced liquefaction by propagation of seismic waves and lateral pressure transfer seem to be the most conceivable mechanisms (Cartwright 2010). Some of these will be discussed in details in chapter 4.

Sandstone intrusions have not been recognised on the Nigeria Transform Margin in the course of this project, but previous studies have shown presence of similar features in form of alternating hummocky and depression structures above a buried, deep-water channel, located in the eastern part of the study area (Fig. 1.3b) (Davies 2003) and from the Lower Congo basin (Monnier et al., 2012).

2.2.3 Other fluid flow phenomena

2.2.3.1 Polygonal faults

Polygonal faults have been well studied in the North Sea basin and described as extensive array of non-tectonic faults formed from de-watering of fine-grained rocks especially mudstones during early burial (Cartwright 1994; 2007; Lonergan et al., 1998; Goulty et al., 2001). They are often recognised in layers or tiers and derive their distinct name from their planview geometry when imaged from time or horizon slices, taken from the original seismic or an attribute volume. Ever since their recognition in the Tertiary rocks in the North Sea, they have been documented in other sedimentary basins in the world (Appendix 1.1; Cartwright 2011).

Polygonal faults are pervasive in the study area from the Early Cretaceous to Miocene interval, made up of ~ 2.5 km thick of clastic sediments. They are often basin-scale with their formation linked to overpressure, layer-bound volumetric compaction and silica diagenesis at shallow burial (Cartwright 2011). Although, polygonal faults are commonly formed within fine-grained mudstones,
they have been observed in sandstone reservoir of Ormen Lange gas Field in Norway (Stuevold et al., 2003). Introduction of coarser-grained material such as sandstone can impede further propagation of polygonal faults and, as such useful in determining presence of deep-water sandstone facies within the emplaced unit (Cartwright 1994; 2011; Lonergan et al, 1998). This was also confirmed from a recent study where propagation of polygonal faults terminated above a slope fan along the Maløy Slope, offshore Norway (Jackson et al., 2014).

2.2.3.2 Silica diagenetic boundaries

This includes the conversion of sediments rich in biogenic silica (Opal A – amorphous) to crystalline silica (Opal CT – crystobalite and tridymite) by a process of dissolution and re-precipitation (Rundberg 1991; Thyberg et al., 1999; Davies & Cartwright 2002). The process results in the alteration of both physical and chemical properties of the rock; controlled by temperature, pore chemistry, presence of clays and carbonate minerals (Davies & Cartwright 2002). Silica diagenetic transformation causes abrupt collapse of pore framework, up to 30% of porosity loss, significant expulsion of water, rapid sediment compaction, generation of abnormally high pore pressure etc. and based on this, have been suggested to have facilitated formation of sandstone intrusions, pockmarks, slope marine failures and polygonal faults (Davies et al., 2006; Davies & Clark 2006; Cartwright 2007, 2011; Huuse et al., 2010).

The boundary is often represented by a strong, hard event that crosscuts background stratal reflections. The hard event corresponds to an increase in acoustic impedance produced from a downward increase in density and sonic at the reflection interface (Rundberg 1991; Davies & Cartwright, 2002).

In the northern North Sea, scanning electron microscopy (SEM) and x-ray diffraction (XRD) analysis revealed evidence of diagenetic transformation in Paleocene, Eocene and Oligocene intervals; same units where sandstone intrusions and polygonal faults are present (Rundberg 1991) (Chapter 5). This co-occurrence of silica diagenetic transformation boundaries have also been recognised in other basins in the world both on seismic data, in outcrops and IODP drill sites (Fig. 1.1). In some cases, a further transformation from opal CT to quartz phase or opal A to opal A’ have also been documented (Thyberg et al., 1999).

2.2.3.3 Pockmarks

Pockmarks are seafloor expressions of vertically focused fluid flow phenomena and often give indication of presence of an active petroleum system (Hovland & Judd 1988, Heggeland 1989; Judd & Hovland 2007; Cartwright 2007). They could be present day or paleo-pockmarks and are often associated with biogenic or thermogenic sources or both (Gay et al., 2006). They are
characterised as circular to elliptical depressions on the seabed when imaged on seismic data, side scan sonars and backscatter data (Fig 2.8) (Hovland & Judd 1988). Other geometries have also been observed across different sedimentary basins (Andresen et al., 2008).

Ever since their first recognition on the Scotian shelf by King & MacLean (1970), they have been documented in numerous basins in the world and are the most recognised fluid flow phenomena in sedimentary basins (Judd & Hovland 2007; Huuse et al., 2010). Seabed and paleo-pockmarks are often related to pipes, chimneys, tectonic faults, polygonal faults and channels, which represent conduits for upward fluid migration resulting into creation of pockmarks (Gay et al., 2007).

### 2.2.3.4 Pipes

Pipes are characterised as cylindrical, long and vertical columns, high amplitude or low amplitude anomalies associated with fluid migration from an underlying source similar to pockmarks (Løseth et al., 2009, 2011; Cartwright et al., 2007; Andresen 2012). In most cases, they terminate as pockmarks or craters on the seabed and are observed in seismic data and outcrops (Fig. 2.9) (Løseth et al., 2011). Løseth et al., (2011) mapped several vertical pipes below seafloor craters in the Niger Delta and attributed their origin to expulsion of gas from underlying sandstone reservoir (Figs. 1.3b & 2.9). In time slice, they are circular to elliptical in geometry and sizes range from tens of metres to hundreds of metres.

Presence of pipes suggests a breach in the sealing unit, as such provides evidence of possible underlying active petroleum system (Gay et al., 2007; Cartwright et al., 2007; Løseth et al., 2009). Pipes are also well recognised globally in sedimentary basins and have been observed on the Nigeria Transform Margin below seabed pockmarks.

### 2.2.3.5 Gas-hydrates bottom simulating reflections

Bottom simulating reflections (BSRs) are recognised from seismic data as continuous or discontinuous reflections with negative seabed polarity, often present in deep-water settings and associated with low temperature and high pressure (Shipley et al., 1979). Although they primarily track the seabed reflection, BSRs crosscut the surrounding reflections. They are often associated with gas hydrates (ice-like crystals) and represent the bottom of a gas hydrate stability zone (GHSZ) (Hovland 2005; Gay et al., 2007; Serie et al., 2012). The negative acoustic response is formed from contrast between over lying; high-velocity gas hydrate zone and underlying; low-velocity free gas-saturated sediments (Gay et al., 2003; Berndt et al., 2004).

Numerous gas hydrates have been documented on the continental margin in Nigeria and extend down to southern Angola (Cunningham & Lindholm 2000). Distribution of gas-hydrate related BSRs could indicate the extent of amount of gas hydrates present in the area though this is not always
true, as there are known areas where BSRs are present with no gas hydrate and vice versa (Hovland 2005). BSRs are often observed with other fluid flow products such as pockmarks, pipes, gas hydrate pingoes and often thought to be genetically related (Cunningham & Lindholm 2000; Hovland 2005; Gay et al., 2006a; Sultan et al., 2010; Serie et al., 2012).
3 CENOZOIC SEDIMENTATION IN THE NORTHERN NORTH SEA USING 3D SEISMIC DATA

ABSTRACT

This study presents a 3-D seismic analysis from the Northern North Sea between latitudes 60-62° and longitudes 1-5° over an area of 29,000 Km². The North Sea Basin as a whole is a rift-related basin with a complete record of Cenozoic sedimentation deposited on pre-existing, Mesozoic rift structures. Based on integration of 3D and 2D seismic as well as well log data, we have studied the entire Cenozoic succession encompassing the Cretaceous interval to review existing tectono-stratigraphic frameworks of the area. The studied interval is bounded at the base and top by the base Cretaceous unconformity and the present day seabed respectively, with sediment thickness reaching up to 5500 ms TWT in the deepest part of the basin. We divide the entire study interval into 10 major sequences separated by key unconformities and surfaces and observe changes in depocentres, sediment source, sedimentation rates, out build directions and sediment characteristics of the basin through time. These changes have primarily been attributed to well-known controlling factors which include tectonics, eustatic and climatic processes; however this study highlights on a regional scale the influence of post-depositional processes such as sandstone remobilization, polygonal faulting and silica diagenetic transformation as part of the factors responsible for basin evolution.

Our results include the presence of sandstone bodies at multiple stratigraphic levels with unusual geometries that cannot be unravelled by normal depositional processes. The results also include the seismic and well log characteristics of a newly-studied Eocene-aged depositional fan system along the eastern basin margin, which shows evidence of post-depositional modifications and other depositional sandstone systems. Documentation of the high-angled, Paleocene clinoforms along the eastern part of the basin reflecting greater sediment input from the Norwegian mainland than previously thought.

The study also presents the seismic and well log character of the opal A to opal CT boundary on a regional scale and propose that this should be treated as a diagenetic surface rather than a sequence boundary that separates the Oligocene interval as previously thought. The entire studied interval is polygonally faulted from Early Cretaceous to Miocene times.
3.1 INTRODUCTION

The North Sea Basin is one of the most petroliferous and intensely-studied basins in the world. The regional stratigraphy, structural, sedimentation, depositional and climatic processes have been well documented by previous works (Isaksen & Tonstad 1989; Ziegler 1990; Rundberg 1991; Martinsen et al. 1999; Jordt et al., 1995, 2000; Faleide et al., 2002; Huuse 2002; Ahmadi et al., 2003; Rundberg & Eidvin 2005; Anell et al., 2011; Goledowski et al., 2012). Factors controlling sedimentation have been attributed to interplay between tectonics, subsidence, climatic, eustatic processes (Huuse & Clausen 2001; Faleide et al., 2002) and the significance of each of these processes is still under debate. Recent studies using higher improved seismic, well and outcrop data have revealed the importance of post-depositional remobilization, injection and extrusion of sands into surrounding mudstones (Huuse & Mickelson 2004; Davies et al., 2006; Huuse 2008; Løseth et al., 2012) and their resultant influence on the present basin configuration. Some authors have also interpreted mud mobilization in the area (Løseth et al., 2003; Jackson & Stoddart 2006).

A number of sequence stratigraphic and litho-stratigraphic frameworks have been established over the years for the Cenozoic succession of the North Sea (Galloway 1993; Rundberg 1991; Martinsen et al., 1999; Jordt et al., 1995, 2000; Rundberg & Eidvin 2005; Anell et al., 2011). In this study we adopted the CSS classification of Jordt et al., 1995, 2000 to divide the entire Cenozoic into 10 sequences bounded by the base Cretaceous unconformity and present day seabed. We considered the effect of post-depositional remobilization and injection across the sequences; these processes have altered the original stratigraphic configuration and sedimentary architecture of the basin thereby redistributing sands through hundred metres of thick mudstone units. Our belief is that these post-depositional products may have been previously misinterpreted as depositional sandstones in the form of low-stand fans, channel and lobe complexes (Den Hartog Jager et al., 1993).

The aim of this study is to provide the first analysis of the Cenozoic succession of the Northern North Sea based on continuous basin-scale 3D seismic data. Previous interpretations and analysis have been based on relatively widely spaced 2D seismic lines or relatively small 3D seismic volumes. We provide in this paper; first, a comprehensive and detailed description of the seismic units from Cretaceous time to present day using regional 3D seismic volume and full integration with well data to review the stratigraphic framework of the Cenozoic North Sea basin of 50 x 50 m resolution; second, differentiate depositional sandstone systems from remobilized and injected sandstones from Cretaceous to Pliocene based on seismic characteristics and well log calibration; third, to present results from detailed investigation of a newly studied Eocene-age depositional fan system (Fan B) along the eastern part of the basin; fourth, present occurrence of multi-tiers of layer-bound polygonal faulting from Cretaceous to Miocene, as most studies on polygonal faults have been interval constrained; fifth, document the seismic expression of the Opal A-CT-Quartz diagenetic boundaries on a regional scale with the present day boundary located within Oligocene
sediments as a diagenetic rather than stratigraphic surface as previously thought thereby proposing a single unit for Oligocene interval (CSS4).

Fig. 3.1 (a) Structural map of the North Sea basin showing major structures such as the triple arm, highs, sub-basins, terraces, platforms, faults and surrounding landmasses (modified from Fraser et al., 2003). Location of study area is shown in the red outline. Acronyms as in Figure 1.2. Also included on the map are locations of some hydrocarbon producing fields/discoveries. Yellow numbered squares represents fields associated with remobilised/injected sands (as in fig.1.2). Yellow stars show locations of previous work done in the area related to post-depositional products or soft-sediment deformation. Inset: present day bathymetry of the North Sea.

The vast majority of petroleum exploration focus in the Northern North Sea is concentrated on the Mesozoic succession with giant discoveries such as Troll, Statfjord, Snorre and Gullfaks (Fig. 3.1). A number of wells penetrated brine-filled reservoir sandstones in the Tertiary interval. Recently there has been increasing interest in the overlying Cenozoic succession and only one well till date
encountered commercial accumulation of hydrocarbon unlike in other parts of the North Sea Basin. Despite a recent increase in interest in the overlying Cenozoic succession only one well, to date, targeting this area has encountered a commercial accumulation of hydrocarbon, unlike in other parts of the North Sea Basin. Our 3D chronostrat framework for depositional vs remobilized sandstones will be instrumental in understanding basin filling and implications on hydrocarbon exploration and production.

3.2 GEOLOGICAL SETTING

The study area is located in the Northern North Sea (Norwegian sector) between 60-62° latitude and 1-5° longitude (Fig. 3.1). It is bounded by the Norwegian coastline to the east, the Shetland Isles to the west, North Atlantic in the north and to the south by the South Viking Graben. It extends about 50 km away from the Norwegian coastline. The Cenozoic North Sea basin formed as a thermal sag depocentre above pre-existing, rift-related structures associated with extensional events during the last two phases of the rifting in the Permo-Triassic, and the Late Jurassic-to-Early Cretaceous (Ziegler 1990; Fossen et al. 2010; Kyrkjebø et al. 2004; Zanella et al. 2003). Each phase was followed by thermal relaxation and subsidence (Ziegler 1990; Rundberg 1991; Faleide et al. 2002). Subsidence was greatest in the Viking Graben, Central Graben and the Sogn Graben, with sediment thickness ≥ 2300 metres, dominated by hemipelagic, smectitic and siliceous mudstones (Anell et al. 2011).

The overall stratigraphy of the Cenozoic interval of the Northern North Sea has been divided into three lithostatic groups: the Rogaland, Hordaland and Nordland groups composed of mainly siliciclastic sediments such as mudstones, sandstones, siltstones and limestone nodules (Fig. 3.2) (Isaksen & Tonstad 1989). The Rogaland Group encapsulates the Paleocene (?) deposits and is dominated by hemipelagic mudstones belonging to the Vale, Lista and Sele formations, with localised deposits of deep-water facies belonging to the Egga and Sotra sandstone members (Brunstad et al., 2009). During the Early Paleocene, uplift of the basin margins resulted in an influx of siliciclastic sediments into the basin and deposition of submarine fans and channel-lobes (Ahmadi et al., 2003). The Shetland Platform, the Scottish and the Norwegian landmass were the main sources at this time (Jordt et al. 1995, 2000; Ahmadi et al. 2003; Anell et al. 2011). By the late Paleocene, volcanic activity related to the separation of Norway and Greenland gave rise to ash-rich tuffaceous deposits of the Balder Formation which extended into the early Eocene and marks the top of the Rogaland group (Fig. 3.2) (Isaksen & Tonstad 1989; Rundberg 1991; Ahmadi et al., 2003; Jordt et al., 1995, 2000; Anell et al., 2011). The Balder Formation extends over large areas and forms a key regional stratigraphic marker in the North Sea ideal for correlations. It is represented as a high-amplitude reflection in seismic and produces a downward decrease on the gamma ray log (Isaksen & Tonstad 1989). Subsidence was continuous throughout the Paleocene and into the Eocene, and a regional transgression, occurred in the Early Eocene, which covered
the tuffaceous sediments depositing low permeability, deep marine muds above in the Top Balder formation (Kyrkjebø et al. 2001; Ahmadi et al., 2003).

The Hordaland Group comprised of sediments bounded above and below by the mid-Miocene unconformity and the Top Balder Formation respectively. At the onset of the Eocene after the deposition of the Balder Formation, clastic sediments were deposited in the basin as a result of uplift from the Shetland and Norwegian landmasses. This includes large sandstone units deposited by gravity currents along the eastern basin margin (Rundberg 1991; Jordt et al., 2000; Faleide et al., 2002; Martinsen et al., 2005). This unit is ascribed to the Frigg sandstones (Isaksen & Tonstad 1989). Along the adjacent margin of the basin on the west, sand-rich systems were also supplied from the Shetlands to the east and forms part of the Frigg field dated to the Early Eocene.

Globally, the Eocene-Oligocene transition records significant events which occurred during this period such as; the major global transition from greenhouse to icehouse conditions; reduction in water bottom temperature; global mass extinction and related faunal change (Fig. 3.2) (Rundberg 1991; Zachos 2001; Miller et al., 2005; Rundberg & Eidvin 2005). Based on detailed mineralogical and geochemical studies by Rundberg 1991, the boundary represents; (a) transition from very fine grained, greenish, Eocene mudstones to brownish, coarser-grained, Oligocene mudstones; (b) decrease in smectite and increase in kaolinite and illite and (c) an increase in biogenic silica sediments. Tectonic inversion linked to initial opening of the North Atlantic and collision between the African and European plates in the Alpine orogeny occurred across the North Sea (Ziegler 1990, Ahmadi et al. 2003). However due to the distance from the centre of collision inversion was not as dominant in the Northern North Sea as compared to the rest of the basin. Very fine-grained sedimentation dominated during the Oligocene but coarse-grained, thick sandstone bodies, belonging to the Skade Formations were deposited locally into the basin from the western margin (Fig. 3.2) (Isaken & Tonstad 1989, Jordt et al., 1995, 2000). More recent studies on these Skade sandstones have however dated them as lower Miocene rather than Oligocene (Rundberg & Eidvin 2005, Eidvin & Rundberg 2007). No formal name has been assigned to the Oligocene sandstones and may be equivalent to the Belton sands in the UK (Ahmadi et al., 2003). Deposition of biogenic sediment also had a major influence on the stratigraphy of the Oligocene succession because these units underwent subsequent transformation that has implications for not only the mineralogical composition of the mudstones but also on the porosity and possibly permeability of the sediments in this interval (Rundberg 1991; Thyberg et al., 1999; Rundberg & Eidvin 2005; Davies et al., 2006).

The mid-Miocene unconformity (MMU) represents a period of significant erosion in the North Sea and separates the Hordaland from the Nordland Group with a time-gap of ~ 15 ma (Fig. 3.2) (Isaksen & Tonstad 1989; Martinsen et al., 1999; Galloway 2002; Rundberg & Eidvin 2005; Løseth et al., 2013). It is occasionally mounded in the Northern North Sea due to effect of underlying units (Løseth et al., 2013). All sediments deposited after the erosion were classified under the Nordland Group. The MMU in the Northern North Sea is often overlain by the Utsira Formation, which is Late Miocene or Early Pliocene in age (Isaksen & Tonstad 1989; Martinsen et al., 1999; Galloway 2002;
Rundberg & Eidvin 2005). The Utsira Formation is sandstone dominated and while some researchers believe it was formed in marine shelf or shallow marine environment (Isaksen & Tonstad 1989; Rundberg 1991; Martinsen et al., 1999; Galloway 2002), others favour a deeper submarine deposition (Gregersen et al., 1997; Gregersen 1998) (Fig. 3.2).

Overlying the Utsira Formation is the thick, Pliocene-age, westwardly-prograding clinoforms sourced from the Norwegian mainland (Jordt et al., 2000). Jordt et al., (2000) and Eidvin & Rundberg (2001), related the thick Pliocene wedges to indications of accommodation increase during a major sea-level rise or significant subsidence within the basin, although sea-level reconstructions do not record significant increase during the this period (Miller et al., 2005). The clinoforms are truncated at their tops by the regional Pleistocene unconformity formed from grounding ice sheets and mapable across the entire area (Fig. 3.2). The Pleistocene unit is composed of mudstones interbedded with sandstones and glacial tills to glacial marine sediments (Faleide et al., 2002; Gregersen et al., 2007).

3.3 DATA AND METHODS

3.3.1 Database

Previous studies of the area were based on 2D seismic and small 3D seismic volumes (Fig. 3.3). The dataset available comprises a subset of the Northern North Sea 3D seismic Megasurvey (courtesy of PGS) created by merging a large number of legacy 3D surveys that covers an area of 29,000 km$^2$ as well as38,000 km of 2D seismic reflection profiles from TGSNOPEC and over 50 wells with wireline logs (Fig. 3.3). A time-to-depth relationship was established from the check shot data, which made it possible to estimate thicknesses in metres. Completion logs, biostratigraphic data and well reports of some wells were available from the Norwegian Petroleum Directorate website (www.npd.no). The 3D seismic volume covers the whole of quadrants 34 and 35 but only parts of quadrants 30, 31, 32, 33, and 36 (Fig. 3.3b). The seismic data is time-migrated data and extends down to 6 seconds TWT, providing a full representation of the entire Cenozoic and incorporating most of the Mesozoic interval. Seismic data was processed in zero-phase with a reverse polarity such that a downward increase in impedance represents negative amplitude (trough or red reflection) based on European polarity convention. Seismic data quality is good to moderate but quality deteriorates towards the western part of the study area, which made mapping very challenging. The dominant frequency ($df$) and velocity ($V$) for each of the CSS units was extracted from the seismic volume and well data respectively and used to calculate the horizontal ($\lambda/2$) and vertical resolutions ($\lambda/4$) as values are expected to change across the basin (Tab. 3.1). Bin spacing is 50 x 50 metres and the vertical sample interval is 4 ms. Age determination was based on biostratigraphic information available in select wells from NPD and from previous studies in the area.
Fig. 3.2. A simplified stratigraphic column of the studied interval (Modified after Rundberg 1989; Jordt et al., 1995, 2000; Brundstadt et al., 2009; Anell et al., 2011; International Chronostratigraphic Chart 2014). Horizons and units mapped in this study are also shown. Other features shown include: Multiple levels of injected, remobilized and extruded sandstones, opal A - CT transformations and polygonal faults.
Chapter 3

Tab. 3.1 showing key parameters such as frequency, velocity, horizontal and vertical resolution from the seismic data for each of the CSS units.

3.3.2 Methods

Time-significant surfaces were identified based on reflection terminations (onlaps, offlaps, toplaps, truncations, downlaps) using seismic stratigraphic techniques of Mitchum et al., (1977) and surfaces from Sr isotope stratigraphic analysis of Rundberg & Smalley 1989. 12 major and 2 minor surfaces were mapped from the Base Cretaceous Unconformity to the present day seabed using the 3D MegaSurvey (Tab. 3.2). The surfaces divided the studied interval into 10 Cenozoic stratigraphic sequence (CSS) based on stratigraphic framework of Jordt et al., (1995 & 2000) with slight modification to CSS4 (Figs. 3.2 & 3.3). In this study, surfaces are represented as H – horizons. Well data was also used to identify and correlate to surfaces of interest as well as to provide lithological information within individual sequences. The location of some of the wells used in the study is shown in figure 3.3b.

Surfaces which represent the time structure maps were used to generate TWT thickness maps to identify main depocentres within the units. Attribute maps such as root mean square (RMS) amplitude, maximum amplitudes, amplitude variance, dip angle and ant-tracking were also generated from the time structure maps and original seismic volume. RGB frequency decomposition using GeoTeric software was used for imaging of deep-water depositional products such as channel-systems and lobes. Results from these maps provided insight into reconstructing a three-dimensional picture of the Cenozoic succession of the Northern North Sea. Gaps within the 3D seismic volume were filled using the 2D seismic lines. For the purpose of clarity and ease of description, the area was divided into 4 segments based on major fields in the area – NE (Agat),

<table>
<thead>
<tr>
<th>CSS UNITS</th>
<th>FREQUENCY (HZ)</th>
<th>VELOCITIES (KM/S)</th>
<th>HORIZONTAL RESOLUTION (M)</th>
<th>VERTICAL RESOLUTION (M)</th>
</tr>
</thead>
<tbody>
<tr>
<td>CSS0</td>
<td>40</td>
<td>2.840</td>
<td>35</td>
<td>18</td>
</tr>
<tr>
<td>CSS1</td>
<td>30</td>
<td>2.300</td>
<td>38</td>
<td>19</td>
</tr>
<tr>
<td>CSS2</td>
<td>35</td>
<td>2.130</td>
<td>30</td>
<td>15</td>
</tr>
<tr>
<td>CSS3</td>
<td>60</td>
<td>1.74</td>
<td>15</td>
<td>7</td>
</tr>
<tr>
<td>CSS4</td>
<td>40</td>
<td>2.05</td>
<td>26</td>
<td>13</td>
</tr>
<tr>
<td>CSS5</td>
<td>30</td>
<td>2.17</td>
<td>36</td>
<td>18</td>
</tr>
<tr>
<td>CSS6</td>
<td>40</td>
<td>2.12</td>
<td>27</td>
<td>13</td>
</tr>
<tr>
<td>CSS7</td>
<td>55</td>
<td>2.10</td>
<td>27</td>
<td>13</td>
</tr>
<tr>
<td>CSS8/9</td>
<td>50</td>
<td>2</td>
<td>19</td>
<td>10</td>
</tr>
</tbody>
</table>
**Fig. 3.3 (a)** Map showing the location of the present study area (red) in the Northern North Sea with respect to previous regional studies. Areas are represented by different colours. Note these other studies were carried out using 2D seismic lines. Surrounding landmasses are shown.

**Fig. 3.4** Seismic and well data used for study. Red outline represents extent of 3D MegaSurvey (courtesy of PGS); with a time slice at -2300ms. Green lines show 2D lines (TGSNOPEC). Black dots show selection of key well locations. Regional transects used in figures are represented as black lines. Irregular outlines are Mesozoic hydrocarbon producing fields (With exception of from the Peon discovery – 35/2-1)
<table>
<thead>
<tr>
<th>SEISMIC UNIT</th>
<th>INTERNAL FACIES DESCRIPTION</th>
<th>SEISMIC SURFACES</th>
<th>SURFACE DESCRIPTION</th>
<th>KEY SEISMIC CHARACTER</th>
</tr>
</thead>
<tbody>
<tr>
<td>CSS9</td>
<td>Low angle prograding reflections in the west, more continuous/parallel in other parts of the basin. High amplitude, possibly gas clouds or gas pockets are randomly observed</td>
<td>H11-Seabed</td>
<td>Hard reflection, fairly parallel in most parts of the basin, lacks major topography</td>
<td><img src="image1" alt="Diagram" /></td>
</tr>
<tr>
<td></td>
<td></td>
<td>H10-Base Pleistocene unc</td>
<td>High amplitude reflection, regionally extensive major unconformity. Underlying units truncate against it along the eastern margin.</td>
<td><img src="image2" alt="Diagram" /></td>
</tr>
<tr>
<td>CSS8</td>
<td>Medium angle prograding reflections, as observed in CSS9, similar internal reflection, restricted to the north western margin of the area.</td>
<td>H9-Late Pliocene - Lower base Pleistocene unc</td>
<td>High amplitude reflection restricted to the NW of the area and merges with H10 to form a composite unconformity in the basin centre.</td>
<td><img src="image3" alt="Diagram" /></td>
</tr>
<tr>
<td>CSS7</td>
<td>High angle prograding reflections, described as cliniforms, low-mod amplitude. Unit down laps onto underlying surface in a NW direction</td>
<td>H8-BasePliocene surface</td>
<td>Considerably continuous surface with variable amplitude. Mounded in the western margin and forms the down lap surface for the prograding cliniforms.</td>
<td><img src="image4" alt="Diagram" /></td>
</tr>
<tr>
<td>CSS6</td>
<td>High-mod-Low amplitude reflections, Mounded geometry and highly affected by underlying discordant high amplitude facies</td>
<td>H7-Mid-Miocene Unconformity</td>
<td>High amplitude surface. Continuous in most part of the basin but severely affected by underlying injected facies. A very important erosional break in the area.</td>
<td><img src="image5" alt="Diagram" /></td>
</tr>
<tr>
<td>CSS5</td>
<td>Parallel reflections, often affected by polygonal faulting. Transparent and low amplitude. Conformable with underlying reflections</td>
<td>H6-Base Miocene surface</td>
<td>Continuous reflection. Offsetted by series of polygonal faults emanating from underlying units.</td>
<td><img src="image6" alt="Diagram" /></td>
</tr>
<tr>
<td>CSS4</td>
<td>Variable amplitude character. Upper part fairly continuous and parallel when not affected by injected sand facies, offsetted by numerous polygonal faulting. Onlaps onto the Intra Neogene unconformity in the E. Lower part is characterised by transparent facies and pinches eastwards. The units are separated by the H5-Opal A-CT boundary, a non-stratigraphic surface</td>
<td>H5-Opal A-CT boundary</td>
<td>Diagenetic surface, cuts across the CSS4 high amplitude reflection</td>
<td><img src="image7" alt="Diagram" /></td>
</tr>
<tr>
<td></td>
<td></td>
<td>H4-Intra Oligocene unc</td>
<td>Very high amplitude inclined surface. Top of Oligocene wedge.</td>
<td><img src="image8" alt="Diagram" /></td>
</tr>
<tr>
<td></td>
<td></td>
<td>H3-Eocene-Oligocene surface</td>
<td>Often offsetted by polygonal faults. Mod-high amplitude reflection. Poorly expressed in the western margin.</td>
<td><img src="image9" alt="Diagram" /></td>
</tr>
<tr>
<td>SEISMIC UNIT</td>
<td>INTERNAL FACIES DESCRIPTION</td>
<td>SEISMIC SURFACES</td>
<td>SURFACE DESCRIPTION</td>
<td>KEY SEISMIC CHARACTER</td>
</tr>
<tr>
<td>--------------</td>
<td>-----------------------------</td>
<td>------------------</td>
<td>---------------------</td>
<td>-----------------------</td>
</tr>
<tr>
<td>CSS3</td>
<td>Low - transparent semi-continuous amplitude reflections. Lower part is affected by polygonal faults. Forms a wedge and pinches out towards the basin. Truncated by the H11</td>
<td>H4-Intra Oligocene unc</td>
<td>Very high amplitude inclined surface. Overlying surface for the Oligocene wedge (CSS3). Forms the onlap surface for the upper unit of CSS4</td>
<td></td>
</tr>
<tr>
<td>CSS2</td>
<td>Intensely disturbed by chaotic and remobilized/injected facies. Low - transparent reflections. High amplitude discordant anomalies within background strata. Truncated by H11 along the eastern margin</td>
<td>H3-Eocene-Oligocene surface</td>
<td>Often offsetted by polygonal faults. Moderate high amplitude reflection. Poorly expressed in the western margin</td>
<td></td>
</tr>
<tr>
<td>CSS1</td>
<td>Variable internal seismic character. Low-med, semi-continuous reflections. Prograding clinoforms in the sw part (Donorich delta). High amplitude anomalies observed in the se part. Locally affected by polygonal faults. Uniform thickness</td>
<td>H2-Top Balder surface</td>
<td>High amplitude reflection. Regional extensive and formed from volcanic activity. Affected by polygonal faults in the basin centre</td>
<td></td>
</tr>
<tr>
<td>CSS0</td>
<td>Low-transparent semicontinuous amplitude reflections. Variable thickness and offset by major Mesozoic faults. Occasionally, reflections are parallel and very continuous.</td>
<td>H1-Base Tertiary surface</td>
<td>Conformable with the H2 and occur also regionally. High amplitude, continuous and sometimes offsetted by polygonal faults. Base of the Cenozoic succession</td>
<td></td>
</tr>
</tbody>
</table>

**Tab. 3.2.** Mapped units and surfaces with brief descriptions for each one. Key seismic characters cropped from the entire data to show significant terminations and internal characters of the units. Truncations used to define surfaces are represented in black arrows based on sequence stratigraphic techniques (Mitchum et al., 1977).
SE (Troll), SW (Oseberg) and NW (Snorre) (Fig. 3.3).

Net sediment accumulation rate in the Northern North Sea from Cretaceous to Pleistocene was estimated (Tab. 3.3) using simple calculation adopted from Jordt et al., (2000) (Formula 3.1) and a representative graph was plotted (Graph 1). Parameters used were obtained from the available data and previous studies. Results are based on estimates and don't account for compaction, burial, remobilization and erosion.

\[ S = \frac{TWT}{2} \times V \times D^{-1} \]

**Formula 3.1:** From Jordt et al (2000) where \( S \): net accumulation rate, \( TWT \): two way time, \( V \): interval velocity and \( D \): duration.

High-amplitude, discordant and in some cases concordant anomalies were calibrated, where well data was available, to anomalous sandstone emplaced within units of predominantly mudstone hundreds of metres thick. These features were mapped and differentiated from depositional systems across the area. Time and horizon slices were used to identify polygonal fault networks in the area. Ant-tracking and variance attributes on sub-volumes revealed their polygonal geometry. Fault population statistics such as length, azimuth, throw and dips were also calculated.

**Tab. 3.3** showing calculated minimum, mean and maximum net accumulation rates within the CSS units mapped in the study area. Thickness values were extracted from TWT ms maps. The duration is taken from the international chronostratigraphic chart for Aug. 2012 (www.stratigraphy.org) except for where red fonts are used and durations were calculated from Jordt et al., 2000. Net Accumulation Rate = \( S = \frac{TWT \times V}{2D} \). Velocity is calculated from well data. These are only estimated values, compaction and erosion are not taken into account.

<table>
<thead>
<tr>
<th>CSS UNITS</th>
<th>SERIES</th>
<th>DURATION (Ma)</th>
<th>THICKNESS (ms)</th>
<th>VELOCITY (Km/s)</th>
<th>NET ACC. RATE (m/Ma)</th>
</tr>
</thead>
<tbody>
<tr>
<td>CSS0</td>
<td>Cretaceous</td>
<td>79</td>
<td>500</td>
<td>2.84</td>
<td>8.99</td>
</tr>
<tr>
<td>CSS1</td>
<td>Paleocene-Early Eocene</td>
<td>10</td>
<td>200</td>
<td>2.3</td>
<td>23</td>
</tr>
<tr>
<td>CSS2</td>
<td>Eocene</td>
<td>22.1</td>
<td>500</td>
<td>2.13</td>
<td>4.82</td>
</tr>
<tr>
<td>CSS3&amp;4</td>
<td>Oligocene</td>
<td>10.9</td>
<td>100</td>
<td>2.05</td>
<td>9.40</td>
</tr>
<tr>
<td>CSS5</td>
<td>Lower Miocene</td>
<td>3</td>
<td>50</td>
<td>2.17</td>
<td>18.08</td>
</tr>
<tr>
<td>CSS6</td>
<td>Upper Miocene-Lower Pliocene</td>
<td>9</td>
<td>100</td>
<td>2.12</td>
<td>11.78</td>
</tr>
<tr>
<td>CSS7</td>
<td>Pleistocene</td>
<td>2.4</td>
<td>100</td>
<td>2.10</td>
<td>43.75</td>
</tr>
<tr>
<td>CSS8&amp;9</td>
<td>Pleistocene</td>
<td>2.6</td>
<td>50</td>
<td>2</td>
<td>19.23</td>
</tr>
</tbody>
</table>

76
3.4 RESULTS

Although the North Sea basin has been extensively studied using 2D seismic profiles, we present the findings from our interpretation based on 3D seismic volume integrated with well log data (Figs. 3.3a & b). 12 major seismic surfaces were identified based on reflection terminations and seismic facie changes to provide new and additional insights into individual unit in the study area (Fig.3. 5 & Tab. 3.2). This section documents the seismic stratigraphic framework of the entire Cenozoic interval incorporated with the Cretaceous succession, 145 – 0 Ma (Fig. 6) to highlight observations and results, which includes structural elements, thicknesses, major depocentres, sediment input directions, sediment sources and controlling factors on the present basin configuration.

### 3.4.1 Base Cretaceous Unit (H0) and structural elements of the basin

The Base Cretaceous Unconformity (BCU) or H0 as described in this paper is represented by a high-amplitude, continuous reflection across the area and usually characterised by a blue peak (soft kick). Local changes in amplitude strength and polarity of the reflection occur above structural high areas and fault planes (Tab. 3.2). These disturbances could be related to lithological changes, seismic artefacts or fluid effect along the faults. The BCU is easily recognized based on changes in seismic facies and tectonic style; and marks the transition between the faulted, graben-style, syn-rift succession to post-rift succession (Kyrkjebø et al., 2004), although offset locally by underlying Mesozoic faults that propagate into the CSS0 unit (Fig. 3.4). Stratal terminations are clearly observed against the BCU and occasionally over structural highs the unconformity merges with other overlying reflections (Tab. 3.2 & Fig. 3.4).

Two-way time (TWT) structure and amplitude variance attribute maps of the unconformity clearly reveals the structural elements and basin geometry by highlighting structurally high areas from low areas (Fig. 3.5a & b). Subsurface depths of up to 1250 ms TWT (1775 m) are observed on structurally high areas such as the Horda platform which deepens abruptly towards the basin centre to about 4000 ms TWT (5680 m) and 6250 ms TWT (8875 m) within the North Viking and Sogn Grabens respectively using the seismic velocity estimated for the unit (Tab. 3.1). The maps also reveal relay fault zones, fault linkage systems and graben step overs linked to underlying faulting and rifting (Fig. 3.5b) (Fossen et al., 2010). The faults are dominantly normal with NNE-SSW orientation across the basin forming series of half-graben structures. The southeastern part of the area is more tectonically active with a series of faults above the Horda Platform (Fig. 3.5b & d). These areas have thought to have undergone severe local uplift and erosion of underlying sediments (Ahmadi et al., 2003; Kyrkjebø et al., 2004; Fossen et al., 2010).
Fig. 3.11 (a&b) SW-SE seismic and geoseismic profiles with wells across the southern part of the area. The CSS4 is subdivided into upper and lower units by the Opal A/CT diagenetic horizon (H5). Unit is intensely deformed in the west making mapping very difficult (c) Simplified well log correlation across the line with gamma ray logs. Note the conical deformed feature in the eastern part. It lies directly above Mesozoic faults.

Fig. 3.4 (a&b) SW-SE seismic and geoseismic profiles with wells across the southern part of the area. CSS0 thins across structurally high areas. Overlying surfaces merge with the BCU above the Horda platform. The CSS4 is subdivided into upper and lower units by the Opal A/CT diagenetic horizon (H5) (c) Simplified well log correlation across the line with gamma ray logs.
3.4.2 CSS0 – Cretaceous (~145–66 Ma)

This unit corresponds to the Cretaceous succession and is bounded by the H0 and H1 surfaces (Figs. 3.2, 3.4 & Tab. 3.2). H1 represents the top of the Shetland Group, base Tertiary or base Cenozoic surface. The TWT structure map of the H1 surface reveals the Norwegian margin represents the major structural high at ~1000 ms TWT (1150 m) below subsurface with a western high of ~1700 ms TWT towards the Shetland margin. The basin centre deepens between these two highs to about 2200 ms TWT (Fig. 3.5c). The unit is characterised by variable seismic amplitudes from generally transparent to moderate with localised high-amplitudes. The reflections are often continuous across the basin. Internally, reflections within the CSS0 package onlap the BCU reflection at the basin margins and close to structural highs (Fig. 3.4). The main depocentre is located within the basin centre and is elongated along a NE-SW axis (Fig. 3.6a). The thickness of the CSS0 unit ranges from 0 to 4000 ms TWT (5680 m) with maximum thickness within the Sogn graben in the northeastern part of the area (Fig. 3.6a). Sediment thickness is relatively even along margins of the grabens and other parts of the basin with notable thinning above structurally high areas, horst and graben structures hosting the Jurassic-age giant gas and oil fields in the North Sea (such as Snorre, Huldra, Visund, Gullfaks fields) and completely absent above the Troll fault blocks (Figs. 3.4 & 3.6a). The thinner areas (Fig. 6a) correspond to relative highs on the time structure map of the BCU (Fig. 3.5a). Variation in thickness is associated with underlying fault-related topography, passive infilling of the syn-rift topography, differential compaction/subsidence and slope gradient (Martinsen et al., 2005; Zachariah et al., 2009). Geometries of the Sogn Graben and North Viking Graben are well represented from time structure and thickness maps of the BCU and CSS0 unit respectively (Figs. 3.5a & 3.6a).

The CSS0 is intensely deformed by small normal faults with minor offsets well imaged in cross sections (Fig. 3.7a). Time slices and horizon maps on conventional seismic and attribute volumes such as ant-tracking and variance reveal the polygonal geometry of these faults (Fig. 3.7). These non-tectonic faults were first identified in the Eocene succession of the North Sea and are associated with layer-bound contraction and de-watering of fine-grained lithology during shallow burial (Lonergan et al., 1998; Cartwright & Lonergan 1996; Cartwright 2007). They have similar dip angles and throw offsets to those measured elsewhere in the Central North Sea and in the Faro-Shetland basins (Olobayo et al., 2015b).

Deep-marine conditions prevailed during the Cretaceous with deposition of fine-grained, hemipelagic mudstones into the basin. The majority of wells used in the study penetrated the CSS0 unit and confirm the presence of thick mudstone successions of the Asgard, Sola, Rodby and Kyree Fm (Figs. 3.2 & 3.8). The predominant occurrence of this mudstone succession is responsible for the generally transparent reflections observed in seismic data. Isolated, coarse-grained siliciclastic sediments were deposited episodically during periods of sea-level fall (Bugge et al., 2001; Zachariah et al., 2009). No trace of chalk is observed compared to the Cretaceous sequence of the southern or central North Sea. Prograding wedges are not observed within the unit
but large slope canyons mapped from seismic data were interpreted as carrier medium for coarse-grained sediments from western Norway into the basin (Jackson et al., 2008). High-amplitude, bedding concordant and discordant anomalies were observed within the upper part of the CSS0 and restricted to the northeastern part of the area (Olobayo et al., 2015b).
Fig. 3.5. TWT (ms) structure maps of horizons in the area; from H0 – H11. (a) H0-Base Cretaceous Unconformity (b) variance on BCU (c) H1-Base Tertiary (d) variance on H1 to show Paleocene graben (e) H2-Top balder (f) H3&H4-Eocene-Oligocene Unconformity (g) H5-Opal A/CT diagenetic surface, W-E lines represents low confidence mapping of the surface (h) H6-Near base Miocene surface (i) H7-Mid-Miocene Unconformity (j) H8-Near base Pliocene surface (k) H9&10-Pliocene-Pleistocene Unconformity & Pleistocene Unconformity (l) Present day seabed
3.4.3  **CSS1 - Paleocene – Early Eocene (~ 66 – 53 Ma)**

This interval corresponds to MU1 of Rundberg (1991), CSS1 of Jordt *et al.*, (2000) and Pal 1 of Anell *et al.*, (2011) (Fig. 3.2). The CSS1 package encompasses sediments of Paleocene and Early Eocene age; and bounded by the Base Tertiary (H1) and the Top Balder (H2) surfaces (Figs. 3.4, 3.8 & Tab. 3.2). The seismic characteristics of the H2 surface vary considerably across the study area and variation is attributed to difference in acoustic response between overlying lithologies and lithology with the unit. Towards the northeast basin segment, where overlying coarser sands are present, the seismic characteristics of the H2 surface changes from a high-amplitude, continuous reflection to a relatively weak, semi-continuous reflection. TWT structure map of the surface is located at ~ 800 ms TWT along Norwegian margin and ~1500 ms TWT along the Shetland; deepening towards the basin centre to 2000 ms TWT (Fig. 3.5e). Seismic character of the CSS1 unit consists of variable seismic facies from low-to-moderate amplitude with occasionally high-amplitude, discordant and concordant reflections (Tab. 3.2 & Fig. 3.8).

The CSS1 has a relatively uniform thickness of ~ 200 ms TWT (230m) in the basin centre but thickness increases gradually towards the margins, where it reaches up to 600 ms TWT (690 m) and 900 ms TWT (1035 m) in the depocentres along the Shetland platform and Norwegian mainlands respectively as these form the major sediment sources during the Early Tertiary (Ahmadi *et al.*, 2003; Anell *et al.*, 2011) (Figs. 3.6b & 3.8). The two depocentres are N-S elongated with west and eastward prograding clinoforms. Above the Horda platform, the unit unconformably overlies the Early-Cretaceous and older Jurassic sediments where Cretaceous sediments were not preserved (Fig. 3.4).

Towards the Norwegian margin, the CSS1 unit is characterized by prograding reflections which down-lap onto the Base Tertiary surface and truncated up-dip by a major unconformity forming distinct wedge-shape package (Figs. 3.9d & e). At this location, the unit is directly overlain by sediments of Quaternary age due the unconformity (Figs. 3.9a - c). The wedge-like package correlates to the depocentre along the eastern basin margin (Fig. 3.6c). There is an on-going debate about the significance of the Norwegian mainland during sediment deposition in the Early Tertiary; little sedimentation was sourced from this area compared to the Shetland source area (Anell *et al.*, 2011). The seismic volume was flattened on the Top Shetland surface to visualize the geometry of the clinoforms prior to the uplift along the eastern margin (Fig. 3.9b). The prograding wedge package is still very pronounced and extends about 80 Km. Progradation along the western basin margin was associated with the Dornorch delta sourced from the East Shetland Platform (Underhill, 2001) (Fig. 3.4).

The unit is also pervasively deformed by small, normal faults and horizon map of the base and the top surfaces of the unit reveal polygonal geometry of the faults in plan view similar to those observed in the underlying unit (Figs. 3.7a, d & e).
The CSS1 unit is mudstone-dominated belonging to the Vale, Lista and Sele Formations with tuffaceous mudstones constituting the Balder Formation (Isaken & Tonstad 1989; Jordt et al., 1995, 2000). Wells penetrated sandstone units belonging to the Edga, Sotra, Hemod, Heimdal and Ty sandstone members the within the mudstone succession (Isaken & Tonstad 1989; Brunstadt et al., 2009) (Figs. 3.2 & 3.4). Wells in the Fram and Troll Field areas penetrated thick sandstones units belonging to the Sotra and Egga members (Brunstadt et al., 2009) (Fig. 3.10). Sandstone thickness ranges between 5 m to as thick as 100 metres in well 31/2-19S and 35/11-3S (Olobayo et al., 2015).

High-amplitude anomalies with discordant margins are observed in the seismic data and restricted to the eastern part of the basin (Fig. 3.10). Some of these amplitude anomalies are penetrated by wells and correlate to tens of metres of sandstone (Fig. 3.10b, Olobayo et al., 2015). Along the western margin, sandstone units are also encountered in wells 29/6-1 and 30/4-1 (Fig. 3.8). Sandstone units within CSS1 are best identified from well logs as some of the sandstones are either thinly bedded and below seismic resolution or do not have significant acoustic impedance contrast with surrounding mudstones thereby creating similar amplitude response. Lithologically, the prograding wedge is mudstone-dominated with 20 m and 15 m of sandstone units encountered in wells 35/8-3 and 35/8-5S respectively as shown by low gamma ray readings on wireline logs (Fig. 3.9c). Well 36/7-3, which is closest to the margin records very thins sandstone units.

A linear depression is observed consistently on the time structure surface of H1 and H2 (Figs. 3.5c - e). The feature cuts across the study area from the Horda platform to the Tampen Spur area and well imaged on variance maps of the surfaces (Fig. 3.5d). In cross section, displacement is observed on these surfaces forming a graben-like structure referred in the study as Paleocene Graben. It consists of two normal faults with fault throw of ~ 50 ms TWT (58 m) (Fig. 3.8). A third fault with smaller throw (35 ms) is also observed between the two main faults but does not continue towards the Tampen Spur area. All three faults are planar. The Paleocene Graben is best developed in the south eastern part near the Troll field and has a WNW-ESE trend in contrast to the dominant NNE - SSW trend of the Mesozoic faults (Fig. 3.5d). A marked thickening is observed in the upper part of the graben suggesting sedimentation during fault evolution.
Fig. 3.6. TWT-thickness maps of individually mapped sequences in the study area. Division adapted from Jordt et al. 1999; 2000. (a) CSS0 - Cretaceous (b) CSS1 - Paleocene-Early Eocene representing the Rogaland group (c) CSS2 - Eocene (d) outline of CSS3 unit is shown in the lower right corner of the map. CCS4 - Oligocene (e) CSS5 - Lower Miocene (f) CSS6 - Upper Miocene-Lowermost Pliocene (g) CSS7- Pliocene, thickness of CSS8 not shown but outline is represented in the upper left corner of the map (g) CSS9 - Pleistocene. Arrows indicate main outbuilding directions of sediments based on clinofoms (where available) and the location of the depocentre. Note change in depocentre through time. White dotted lines show simplified migration of prograding clinofoms. The Norwegian and Shetland landmasses were the main sediment sources for the North Sea during this time.
Fig. 3.7 (a) Seismic cross section through polygonal faults with interpreted horizons (b-h) horizon maps from variance volume and ant tracking; b-e: tier 1 or lower tier and f-h: tier 2 or upper tier (i) fault traces for all the faults. Rose diagrams show fault strike. Location of seismic line shown on individual maps.
Fig. 3.8. (a & b) SW-NE seismic and geoseismic lines with wells across the area to illustrate basin architecture and major depositional sequences. High-amplitude, discordant anomalies are observed in Eocene and Oligocene successions. Note presence of thick Paleocene wedge adjacent to Norway and large depositional sand systems from both western and eastern margins into the basin centre (c) simplified well log correlation across the line with gr logs.
Fig. 3.9. Paleocene clinoformal geometry (a) Seismic section (inset from Fig. 3.8a) across the eastern part of the area through wells 35/8-3, 35/8-3S and 36/7-3 showing a wedge shape geometry. (b) seismic section (a) flattened on the Top Shetland surface (c) log correlation between the wells showing the lithology of the wedge and surrounding stratigraphy (d&e) non-interpreted and interpreted W-E seismic profile across the Paleocene interval. Note downlaps onto underlying stratigraphy. The upper part of the prograding clinoforms has been eroded by the Pleistocene unconformity preserving only the bottom sets of the package.

3.4.4 CSS2 – Eocene (~ 53 – 33.9 Ma)

CSS2 corresponds to MU2 of Rundberg 1991, CSS2 of Jordt et al., 1995, 2000 and Pal 2 of Anell et al., 2011 (Fig. 3.2). It is bounded by the H2, Top Balder formation and H3, Eocene-Oligocene unconformity (Figs. 3.4, 3.8, 3.10 & Tab. 3.2). H3 marks significant changes in mineralogical and lithological properties between the CSS2 and overlying succession and also corresponds to period of global climatic transition from green house to ice house conditions (Fig. 3.2) (Rundberg 1991;
Rundberg & Eidvin 2005). H3 is encountered at ~ 700 ms TWT in the shallowest part of the basin along Norwegian margin and deepens towards the basin centre to up to 1800 ms TWT in the northern part (Fig. 3.5f). Seismic character of the unit is mainly transparent and chaotic especially in the western part of the study area but reflections are often parallel and fairly continuous in the basin centre (Fig. 3.8a). Maximum sediment thicknesses within the CSS2 unit reach 500 ms (530 m) and occur along the basin margins close to the Shetland and Norwegian margins. Other depocentres observed from thickness map of the unit are located in the NNW part in the Maruk basin and on the western side of the Horda Platform (Fig. 3.6c). Thickness is fairly uniform in the southern part of the North Viking Graben (300 ms/320 m) and separated from other depocentres by areas fairly thin areas (< 200 ms/220 m).

The CSS2 unit is truncated along the Norwegian margin by the unconformity with overlying Quaternary-aged sediments (Figs. 3.4, 3.8 & 3.10). The unit is pervasively deformed by polygonal faults as observed from cross sections and horizon map of the H3 (Figs. 3.7a & f). Fault cells are denser than underlying units and have a dominant orientation WNW (Fig. 3.7f). Polygonal faults are not easily observed in the western part within the unit and could be related to chaotic nature of the interval. High-amplitude, discordant anomalies are also observed within the unit and concentrated along the crest of underlying structural highs (Olobayo et al., 2015b).

Predominant transparent amplitude facies observed with CSS2 corresponds to fine-grained mudstones that are characterised from well cuttings by non-calcareous greenish-olive grey claystones with a high concentration of smectite in comparison to other CSS units (Rundberg 1991; Thyberg et al., 2000; Marcussen et al., 2009; NPD.NO). Although CSS2 is mudstone-dominated, thick-bedded sandstone packages are identified from the wireline logs (Figs. 3.8, 3.10 & 3.11).

Three major sandstone packages are described here within the CSS2 (Fig. 3.11). The first package (A) consists of sandstone of ~ 200 m gross thickness encountered towards the northeastern part of the study area within block 35/8 and underlain by a second sandstone unit (B) of similar thickness ~ 200 metres as shown from time thickness maps and well logs (Fig. 3.11b, c, e & f). Seismically, package A is distinguishable from underlying package B by its relatively high-amplitude, semi-continuous reflections compared to the much lower amplitude reflections of B (Fig. 3.11g). Internal reflections of package B downlap onto the Top Balder surface (Fig. 3.11e). Wells 35/8-1 and 35/8-2 show both sandstone packages are interbedded with thin mudstone units, which increases upwards from base of package B as well as towards the basin centre (Fig. 3.11f). The lower sandstone package B appears to have a ‘blockier’ gamma ray expression with relatively sharp top and basal contacts on the log in well 35/8-1 and have less mudstone intervals than package A, suggesting a more homogeneous unit with higher net-to-gross than the overlying package.
Fig. 3.10. (a) NW-SE trending seismic section showing mapped sequences, surfaces and internal characteristics of the units. Note westward progradation of Pliocene clinoforms and downlaps onto underlying surface. Line also shows the dip representation of the Eocene fans and abundant sandstone within the Paleocene interval. The white horizon (H5) represents the Opal A/CT diagenetic surface cutting across the Oligocene succession. High amplitude discordant features correlating to sandstone facies are observed within individual units. Multiple-tiers of polygonal faulting is well represented (Cretaceous to Miocene). Note the mounded morphology of the mid-Miocene unconformity e.g above the Snorre field. Isolated high amplitude anomalies, possible bright spots due to gas presence are observed in the Pleistocene unit.
Chapter 3

The underlying sand package (B) has not been previously documented in the literature within this block. Time structure maps of both sandstone packages reveal lobate to fan-shaped geometry that pinch out into deeper marine hemipelagic mudstones (Figs. 3.11b & c). Package A consists of fine-coarse grained sandstones with moderate sorting while the underlying package consists of medium to coarse-grained, medium-poorly sorted sandstones (NPD.NO). The two sandstone packages are overlain by Oligocene mudstones with no core data available from the wells (Figs. 3.11e & f).

A third Eocene sandstone package has been penetrated by well 29/6-1 in the western part close to the UK/Norwegian median line (Fig. 3.11a). The time thickness map of the package reveals a similar lobe or fan-shaped geometry as observed along the eastern margin (Fig. 3.11h). Well 29/6-1 penetrated the package and encountered sandstone unit with gross thickness of ~240 m (Fig. 3.11i). The package is thickens towards the south and into the middle of the lobe (Fig. 3.11h). The sandstone package has similar amplitude response as package B and separated from overlying unit by a high-amplitude, continuous reflection.

Other isolated sand-rich units are commonly observed within the CSS2 unit in the western part of the study area. They do not show any organised depositional architecture such channel systems or lobes, making it difficult to classify them under the Isaksen & Tonstad (1989) nomenclature within the Hordaland Group. Some of them are located along the fringe of the Eocene fan (Fig. 3.10). In cross section, they resemble incised valleys but time-slices reveal circular to oval-shaped and often isolated geometry (Olobayo et al., 2015b).

3.4.5 CSS3 - Oligocene Wedge (~33.9 – 32? Ma)

The CSS3 corresponds to the MU3 of Rundberg (1991), UH-1 of Rundberg & Eidvin (2005) but not differentiated in the Jordt et al., (1995, 2000) (Fig. 3.2). It is bounded by the intra-Oligocene unconformity (H4) and Eocene-Oligocene unconformity (H3) surfaces (Tab.3.2 & Fig. 3.4). The intra-Oligocene unconformity was identified based on seismic characteristics of overlying and underlying sediments. It was previously mapped as a continuous stratigraphic surface that extends from the eastern part to the basin centre (Martinsen et al., 1999, Jackson 2007); however, based on our regional 3D seismic mapping and well log observations, we observe the unconformity is more localized and restricted only to the basin margin. Seismically, the unit consists of uniform, low-to-transparent, semi-continuous reflections intensely offset by polygonal faults (Tab. 3.2). The top bounding surface, H4 of the unit represents an onlap surface for overlying reflections of CSS4 unit towards the eastern part of the study area (Fig. 3.4).

The CSS3 unit reaches a maximum thickness of ~300 ms TWT (261 m) along the Norwegian coastline and wedges out westwardly towards the basin centre (Fig. 3.4). The depocentre has an elongate geometry, which runs parallel to the coastline extending approximately 50 km along an N-S axis with an average width of 10 km. In the eastern part of the study area the surface is unconformably overlain by younger Quaternary-aged sediments (Fig. 3.4).
Fig. 3.11 (a) Map showing locations of the Eocene depositional systems (EDS) (b-c) (TWT of fan A & B (d) TWT (ms) from top of Fan A to Top Balder Fm (e) seismic profile across EDS. Note the difference in amplitudes. Location of line shown on maps (f) well correlation panel of e across the upper and lower Eocene fans showing change from massive sands into thinly-bedded sands with shale baffles and finally into basinal muds both chronologically and spatially (g) zoom on well 35/8-1 from 1b (h) TWT (ms) of Fan C (i) seismic section across Fan C
Lithologically, the unit comprises dominantly of non-calcareous carbonaceous mudstones with occasionally yellowish-grey clay stones as observed in wells 31/2-1&2, 31/3-1. Sandstones are not encountered in the CSS3 unit and no evidence of high-amplitude, discordant features are observed within the unit.

3.4.6 **CSS4 – Oligocene (~ 33.9 – 23.03 Ma)**

The Oligocene unit was previously classified as two separate units; CSS3 & CSS4 - Jordt et al., (1995), (2000), MU4 & MU5 - Rundberg (1989), UH-2 & UH-3 - Rundberg & Eidvin (2005) and part of PAL 3 - Anell et al., (2011). CSS4 is bounded at the top by the base Miocene surface (H6) in the centre and southwest of the basin and by the mid-Miocene unconformity in other parts of the study area and at the base by the Eocene-Oligocene unconformity (H3) (Figs. 3.4 & 3.10). The base Miocene surface is represented by a continuous, high-amplitude soft-kick reflection often parallel to underlying and overlying reflections (Tab. 3.2). The mid-Miocene unconformity is represented by a high-amplitude, hard-kick reflection mapable across the area (Fig. 3.5i). The CSS4 unit has varying amplitude and reflection character in seismic, which is a range of low to high amplitudes, and semi-continuous to continuous reflections (all seismic sections).

Previous classifications as two units are separated by a high-amplitude; continuous reflection described as intra-Oligocene unconformity (Jordt et al., 2005; Martinsen et al. 1999; Jackson 2007). However in this study, we identify this reflection as opal A to opal CT diagenetic boundary - H5 (Tab. 3.2, Figs. 3.4, 3.10 & 3.12). We propose that H5 is classified as a non-stratigraphic, diagenetic surface rather than a sequence boundary as often thought; formed as a result of transformation of diatomaceous silica from an opal A to opal CT state (Rundberg & Smalley 1988; Rundberg 1991; Thyberg et al., 1999; Davies et al., 2006; Rundberg & Eidvin 2005; Ireland et al., 2011). Our justification for this is that the seismic characteristic of H5 is represented by a hard-kick reflection event that crosscuts background stratal reflections corresponding to an increase in acoustic impedance produced from a downward increase in density and sonic at the reflection interface (Fig. 3.12) (Rundberg 1991; Davies & Cartwright, 2002).

Sediment thickness in CSS4 is greatest within the North Viking Graben, towards the southwest of the study area close to the Shetland mainland with thicknesses reaching up to 750 ms TWT (770 m) (Fig. 3.6d). No prograding clinoforms were observed from our seismic data from the west in CSS4, however sediments are likely to have been sourced from the Shetlands. Unit thickness reduces away from the graben and towards the north.
Internally, the CSS4 unit is characterized by varying amplitude and reflections. For the purpose of description and discussion, we sub-divide the CSS4 unit into an upper, opal A and lower, opal CT sub-unit (Fig. 3.12). Division is based on location of the diagenetic boundary and seismic facies change between them. The lower sub-unit has a distinct wedge-shaped geometry that pinches out towards the basin centre from the west (Fig. 3.4). Seismically, the unit primarily consist of low-moderate, amplitude reflections. The upper sub-unit is considerably thicker with an irregular top surface geometry (Fig. 3.10). Close to the Norwegian margin, the internal reflections within the upper sub-unit onlap directly onto the intra-Neogene unconformity (Fig. 3.4). Both sub-units are better defined in the eastern part of the study where reflections are continuous and parallel; unlike in the western part where reduced data quality results in chaotic reflections which hampered interpretation (Fig. 3.4a).

Transformation across the boundary is associated with porosity reduction estimated to be ~30%, based on values calculated from the Faroe-Shetlands (Meadows & Davies 2009). Morphology of the boundary varies across the area from flat and parallel to irregular and mounded. Detailed mapping of H5 was achievable only in the basin centre due to chaotic nature of seismic data (Fig. 3.5g). Well log correlation from the Brage field area to Tampen Spur shows increase in density and sonic logs at the boundary (Fig. 3.12a). At about 100 metres below the boundary, a similar but more subtle density and sonic log response is also observed. This second boundary is less consistent across the area based on the wireline logs and seismic data (Fig. 3.12a).

Lithologically, the two sub-units are mudstone-dominated and well log data shows increase in silica content from the underlying smectite-rich, Eocene mudstones (Rundberg 1991; Thyberg et al., 1999) (Fig. 3.12). Well log data also confirmed presence of coarser lithologies such as siltstones and sandstones within the CSS4 unit. Wells penetrated thick sandstone packages observed from low gamma ray reading around the Gullfaks field and in the southwest of the area, which is indicative of increased input of coarse-grained sediments in the system (Fig. 3.13). The individual sandstone units display a 'blocky' profile on the gamma ray logs with sharp top and base contacts. Some of these packages have gross thickness of up to 300 m and no distinctive erosive bases have been observed. The upper sub-unit is more sand-rich and comprises of numerous isolated, high-amplitude, discordant reflections (Fig. 3.13). Well penetrations through these unusual amplitude anomalies in the Snorre and Vega field areas reveal sandstone lithologies (Fig. 3.8, 3.10 & 3.13). The sediments of the CSS4 unit are coarser than the underlying finer-grained Eocene unit and sand content reduces gradually towards the basin centre (Martinsen et al., 1999). The sandstone units have not been formally named however Isaksen & Tonstad (1989) included them in their classification as belonging to the Skade member, equivalent to the Benton sandstones in the UK sector of the North Sea. Thick-bedded sandstones are also penetrated by the Agat wells (35/3-1, 35/3-4 and 36/1-2) in the northeast of the study area (Fig. 3.14). Sediments of different ages and lithology overlie the CSS4 Oligocene unit. Such that in the NE, the sediments of the CSS4 unit are overlain by upper Miocene-Pliocene aged, sandstone-rich sediments (Fig. 3.14) but in the basin centre, the unit is overlain by a mudstone succession of lower Miocene age (Fig. 3.10).
Seismic sections, horizon maps and time slices through the area also reveal the presence of randomly oriented small-scale, intra-formational faults with polygonal geometry within the CSS4 unit (Fig. 3.7a & g). Most often these faults co-exist with the high-amplitude, discordant anomalies and crosscut each other (Fig. 310) (Olobayo et al., 2015). Fault density decreases away from the basin centre until they almost disappear along the western margin. This could be due to the chaotic nature of the seismic or intense deformation in that part of the study area (Fig. 3.4a).

**Fig. 3.12.** (a) Well log correlation between five (5) wells from the Brage field area; 31/4-3 to the Snorre field area; 34/4-7 (Tamnspur) to show the log characteristics of Opal A – CT diagenetic boundary. Note abrupt increase in density and sonic log. No major response on the gamma ray log (b) seismic profile across the wells in a. H5 corresponds to abrupt changes in the logs.

### 3.4.7 Middle Miocene Unconformity (MMU)

The mid-Miocene unconformity (H7) is a high-amplitude, hard-kick reflection, which forms a regional unconformity in the North Sea and forms the base of the sandstone-rich Utsira Formation which is found in most of the basin (Gregersen 1998; Martinsen et al., 1999; Faleide et al., 2002; Rundberg & Eidvin 2005; Eidvin & Rundberg 2001, 2007) (Tab. 3.2 & all regional seismic sections). H7 is encountered at ~ 500 ms TWT in the shallowest part along the Shetland mainland and
deepens towards the basin centre to up to 1750 ms TWT in the north (Fig. 3.5i). H7 has variable seismic character across the study area; including mounded, incised or parallel with surrounding reflections (Fig. 3.14). In most of the study area, the unconformity is significantly deformed by series of mounds (both isolated and mound complexes) (Olobayo et al., 2015b). In locations where the unconformity is mounded, the underlying unit is severally affected by deformation from high-amplitude, discordant anomalies (Løseth et al., 2003; 2012; 2013; Huuse & Mickelson 2004; Jackson & Stoddart 2005). Detailed mapping of the H7 reveals the complex morphology of the surface as well as its mounded nature (Fig. 3.15). Along the western margin, the geometry of the mid-Miocene unconformity is characterised by alternating depressions and ridges, which are often symmetrical (Fig. 3.15b). Less than 1 km wide incisions are revealed from variance attribute on the mid-Miocene unconformity.

The mid-Miocene unconformity (H7) is also characterized by significant erosion, which formed deeply incised-channel systems that cuts into underlying Oligocene deposits (Figs. 3.14 & 3.15) (Huuse & Clausen 2001; Rundberg & Eidvin 2005; Goledowski et al., 2012). Incisions created into underlying Oligocene sediments were subsequently filled with younger sediments of upper Miocene age (Fig. 3.14). The main incision has been previously recognised in the area and has a flow direction of east to northeast (Martinsen et al., 1999; Ahmadi et al., 2003). Use of spectral decomposition techniques on the unconformity revealed smaller incisions with similar flow direction that have not been previously described in literature. This could be due to the limitations of 2D seismic data, which most of the previous studies were based on (Fig. 3.3a). Incisions can be traced for more than 20 km from the eastern margin to the north of the study area (Fig. 3.15a inset). The age and origin of these channels has been subject to debate over the years (Martinsen et al., 1999; Ahmadi et al., 2003; Eidvin & Rundberg 2007).

### 3.4.8 CSS5 - Lower Miocene (~ 23.03 – 15? Ma)

The CSS5 corresponds to the UH-4 of Rundberg & Eidvin (2005) and CSS5 of Jordt et al., (1995), (2000). The unit is bounded by H7 (mid-Miocene unconformity) and H6 (base Miocene surface) (Tab. 3.2, Figs. 3.4 & 3.10). Both surfaces are conformable to one another in most part of the basin. The CSS5 unit is persevered in two locations within the study area. Firstly in the basin centre where the unit has an N-S elongate geometry and secondly in the SW segment along the UK-Norway median line (Fig. 3.6e). At these locations, the unit forms the top of the Hordaland Group (Fig. 3.2). Internally, it is characterised by low to moderate strength amplitudes, and often parallel and continuous reflections with underlying and overlying reflections (Fig. 3.10).
Fig. 3.13. (a) NW-SE well correlation panel across the western part of the study area showing thick sandstone units within CSS4 (b) seismic section through 3 of the wells in a. Note presence of high-amplitude, discordant features within the interval. Intense deformation occur within the sandstone-rich interval.
CSS 5 unit is fairly uniform in the basin centre and reaches thickness of ~ 100 m in well 34/8-3A (Fig. 3.10). In the south-west, the unit is much thicker where it reaches thickness up to 200 m in wells 29/6-1, 30/3-3, 30/3-9 (Figs. 3.4 & 3.8). However, it pinches off towards the west and east; and is completely absent along the basin margins as confirmed by wells from the Snorre and Vega Fields (Fig. 3.10). Previous interpretations of the Lower Miocene unit restrict its extent to the basin centre in the Northern North Sea (Rundberg & Eidvin 2005). We suggest that the Lower Miocene sediments are also present in the south-west of the study area (Figs. 3.6e & 3.8). TWT (ms) thickness maps of the CSS5 reveal the thickness and distribution of the sediments in both locations (Fig. 3.6e).

Gamma ray logs from wells 30/3-3 and 30/3-9 from the basin centre shows the unit is dominated by mudstone (Fig. 3.4), while wells that penetrated the unit along the south-west margin reveal thick sandstone units (Fig. 3.8). The Lower Miocene unit is also affected by numerous, small-scaled faults characterised by polygonal geometries, similar to the underlying units. No high-amplitude, discordant features have been identified with this unit.

### 3.4.9 CSS6 - Upper Miocene - Lower Pliocene – (Ma?)

The CSS 6 unit corresponds to CSS6&7 of Jordt et al., (1995), (2000) and forms part of MU6 and NEO2 of Rundberg (1991) and Anell et al., (2011) classifications respectively (Fig. 3.2). It represents the youngest sediments of the Nordland Group. The unit is bounded at the top by the H7 (MMU) surface and the H8 (near base Pliocene surface) surfaces at the base (Tab. 3.2 & Fig. 3.14). H8 is represented by a high-amplitude, soft-kick reflection and forms a major down lap surface for the Upper Pliocene prograding clinoforms (Fig. 3.14 & Tab. 3.2). H8 is encountered at ~ 300 ms TWT in the south west close to the Shetland landmass and deepens towards the basin centre to up to 1700 ms TWT in the north (Fig. 3.5h).

The unit has varying amplitude and reflection character in seismic, which ranges from moderate to high amplitudes, and parallel to gently mounded, continuous reflections (Fig. 3.14). The CSS6 unit has variable thickness across the study area (Fig. 3.6f). Unit thickness ranges from 0 - 100 m along the SE-NW margins and reaches up to 600 m in the north-east and south-west, where they form prograding clinoforms (Figs. 3.8 & 3.14). Along the north-eastern margin, a clastic wedge-shaped sedimentary package with thickness reaching up to 600 m progrades westwards towards the basin centre (Fig. 3.14). Sediments within this package downlap onto the underlying H7 surface and are truncated at the top by the regional unconformity. This package was also identified in previous studies (Martinsen et al., 1999; Anell et al., 2011). In the south-west, clinoforms prograde eastwards into the basin centre; and the top sets are often well-preserved (Fig. 3.14). Progradation of sediments from both the west and east suggests sediments were sourced from the Norwegian mainland and Shetland platform, respectively (Gregersen et al., 1997).
Well penetrations (29/6-1 and 30/4-1) through the eastward prograding package indicate massive sandstone units within the wedge (Fig. 3.8). The westward prograding clinoforms in CSS6 were also penetrated by the Agat wells (35/3-1 & 2, 35/3-4) along the eastern margin. Wells confirm the presence of thick, amalgamated sandstone units interbedded with mudstone intervals in all the Agat wells except well 36/1-2 where sand is totally absent and Pleistocene-aged sediments are deposited unconformably directly on top of much younger sediments (Oligocene) due to the erosion from the regional unconformity (Fig. 3.14).

Regionally, the CSS6 unit encompasses the sandstone-rich Utsira Formation with sand thickness up to 200 ms TWT (210 m) (all seismic lines) (Jordt et al., 1995; 2000; Martinsen et al., 1999; Eidvin & Rundberg 2001, 2007; Faleide et al., 2002; Galloway 2002). Lithological characteristics of the sediments that fill the incised channels described in the section 3.4.7 are poorly constrained due to a lack of well penetration within the channel fill. However the channels' location within the Utsira sandstone interval; the domal morphology of overlying sediments potentially due to differential compaction and the similar seismic amplitudes and reflection characteristics with the surrounding Utsira sandstones, all suggest that they are sandstone-filled (Eidvin & Rundberg 2001).

### 3.4.10 **CSS7 - Upper Prograding Pliocene (~ 5 – 2.588 Ma)**

This unit is equivalent to MU8 of Rundberg (1991) and CSS8 of Jordt et al., (1995), (2000) (Fig. 3.2). CSS7 is underlain by the fairly continuous, high-amplitude, down-lap surface (H8) across most of the study area and H6 locally. The surface is overlain by the regional unconformity (H10) (Tab. 3.2 & Fig. 3.10) except in the NW where the unit is overlain by an intermediate unconformity (H9); identified as the mid-Pleistocene unconformity (Anell et al., 2011). H9 is locally present and forms a composite surface where it merges with the H10 surface (outline shown in Fig. 3.5i). It is characterized as a high-amplitude, soft-kick continuous reflection and represents a downlap surface for the overlying prograding clinoforms (Figs. 3.10 & 3.14). Although the exact age of H9 is unknown, we suggest a late Pliocene-Early Pleistocene based on its stratigraphic location within the Pliocene and Pleistocene succession as observed from seismic and well log data; and thus correlates with the base of the CSS9 unit defined by Jordt et al., (1995, 2000).

Internally, the unit is characterised by clinoforms as high as 900 m, which prograde towards the west from the Norwegian margin to the northern part of the basin (Fig. 3.10). Reflections within the unit downlap onto the underlying H8 surface that was formed during a time of starved sedimentation caused by a relative rise in sea-level (Faleide et al., 2002). The progradation direction suggests that the Norwegian margin was a significant sediment source during this period. The CSS7 has varying amplitude and reflection character in seismic, which ranges from moderate to high amplitudes at the margins to fairly transparent in the basin centre (Tab. 3.2).
Fig. 3.14. (a) NW-NE trending seismic section along the northern part of the study area. Note the incision on the mid-Miocene Unconformity. It represents ~40 km single channel system with surrounding smaller channels and suggested to be sand filled due to differential compaction above. Thick sandstone bodies separated by individual mudstone units are interpreted along the eastern margin from the Eocene to the Miocene. Norwegian landmass is a likely source of these clastic deposits. Prograding clinoforms along the margin supports sediment source (b) geoseismic section of a highlighting sandstone interval. Sandstone units belonging to the Agat Formation are also observed in the early Cretaceous (deeper than seismic line shown)
The main depocentre is located in the north-west of the study area with maximum thickness reaching up to 900 ms TWT (900 m) (Fig. 3.6g). The clinoform height reduces both towards the east and the south-west (along the UK-Norway median line) where they eventually become conformable with underlying and overlying Miocene-Pliocene and Pleistocene successions respectively (Fig. 3.8). The prograding wedge of CSS7 forms the thickest unit of the Nordaland Group and consists of poorly-sorted clastic materials with immature mineralogy (Martinsen et al., 1999; Jordt et al., 2000; Anell et al., 2011). The CSS7 unit is primarily mudstone dominated but wells in the north-west penetrate sandstone units. Wells 34/7-9 and 34/7-1 encountered 25 m and 15 m thick sandstone units respectively within CSS7 (Fig. 3.10) (Olobayo et al., 2015). The time structure map of the top of the sandstone unit reveal a mound complex ( Leseth et al., 2012, 2013). These sandstones are informally named as the Tampen Spur sandstone member as authors do not believe the Utsira sandstones go beyond the Lower Pliocene unit, CSS 6 (Eidvin & Rundberg 2007).

High-amplitude anomalous reflections are observed on the clinoforms across the area (Fig. 3.10). Time slices through them show channelized geometries, which migrate further, into the basin through time (Figs. 3.10 & 3.16a).

### 3.4.11 CSS8 - Uppermost Pliocene to Lower Pleistocene?

The CSS8 unit corresponds to the NEO3 of Anell et al., (2011) and CSS9 of Jordt et al., (1995), (2000) (Fig. 3.2). It is underlain by the top of the prograding unit (H9) and overlain by the regional unconformity, H10 (Tab. 3.2, Figs. 3.10 & 3.14). The unit post-dates the Lower Pliocene interval but pre-dates the Upper Pleistocene succession so we suggest it is likely to be between Upper Pliocene to Lower Pleistocene in age. It is constrained to the north-west of the study area (outline shown in Figs. 3.6g & h). Internally, it is characterised by prograding pattern similar to the underlying CSS7 (Tab. 3.2).

### 3.4.12 CSS9 – Pleistocene (~ 2.588 – recent)

The base of CSS9, H10, is an angular unconformity, which truncates underlying sequences from Paleocene (CSS1) to Pliocene (CSS7) (Tab. 3.2). The unconformity is represented by a high-amplitude, continuous reflection and regionally mapped across the entire area (Figs. 3.4, 3.8, 3.10 & 3.14). H10 was formed as a result of large-scale glaciation from grounded ice-sheets, which resulted in the angular unconformity (Sejrup et al., 1995, 1996; Martinsen et al., 1999; Gregersen & Johannessen 2007).
Fig. 3.15 (a) 3D image displaying variance attribute extracted on the mid-Miocene Unconformity (H7) to show the morphology of the surface. In the NE are channels flowing in E-N direction (from west of Norway). Details of channels shown in the inset figure (b) seismic section across the finger-like features (c) zoom in on the sw part showing the channels flowing towards to the basin centre.
CSS9 unit comprises of primarily parallel reflections above progradational reflections in the underlying CSS8 & 9 units. Sediments are mainly Pleistocene in age and overlain by the present day seabed (H11) which is relatively flat across the area (Fig. 3.10). Linear features are observed on horizon slices generated within the unit (Fig. 3.16b). They are often orientated NW-SE but occasionally show NE-SW trend.

The unit is characterised by large sediment accumulations along the basin margins to the NW and NE where it reaches maximum thicknesses of ~300 and ~400 ms TWT (300m/400 m) respectively (Fig. 3.6h). Otherwise, it is relatively thin in the basin centre and thickens gradually towards the margins. At discrete locations, isolated high-amplitude “soft” anomalies are observed within the CSS9 (Fig. 3.10).

Lithologically, the unit consists dominantly of mudstones with high concentration of siltstones and sandstones. No formal name is given to the sandstones encountered in CSS9 unit but classified as Peon sandstone member in the work of Eidvin & Rundberg (2007). Presence of glacial till and glaciomarine sediments was also recorded in some of the wells (Sejrup et al., 1996). Presence of till is indicative of erosion and grounded ice on the Norwegian shelf (Martinsen et al. 1999). Mineralogical analyses on the sediments of the Pleistocene and underlying Pliocene show they were derived from metamorphic basement rocks west of Norway (Thyberg et al., 2000).
Fig. 3.16 (a) Time slice @ 768 ms TWT showing channels on Pliocene clinoforms with CSS7 unit (b) Horizon within CSS9 showing abundant occurrence of iceberg scours in the Quaternary
3.5 DISCUSSION

We present our interpretation based on observations made from integration of 3D seismic Mega Survey with well log data. A complete record of the Cenozoic succession is preserved in the study area but the entire succession is truncated by the Pleistocene unconformity along the eastern margin (all regional seismic lines).

TWT thickness of the entire studied interval (from base Cretaceous unconformity to present day seabed) shows the major depocentres within in the Sogn and North Viking grabens with thickness reaching up to ~5000 ms TWT (5550 m) in the Sogn Graben (Fig. 17a). Figure 18 shows depocentres from each CSS unit mapped in the study based on two-way time thickness maps. TWT thickness map of the Cretaceous follows the same distribution pattern as the overall interval with depocentres in the Sogn and North Viking grabens (Fig. 17b) and sediment thickness reducing across major structural highs. The basin geometry changed during the Cenozoic with greater sediment thickness up to 2000 ms TWT (2120 m) within the North Viking graben (Fig. 17c). This shift in depocentre is related to thermal subsidence that occurred at the onset of the Cenozoic within the Viking graben (Huuse & Mickelson 2004). TWT thickness maps for the Paleogene and Neogene shows shift in depocentres from basin margins to basin centre (Fig. 17d & e). During the Quaternary, depocentre had shifted back to the basin margins (Fig. 17f).

3.5.1 Cretaceous unit

During the Cretaceous, the main depocentres of the Sogn and North Viking grabens formed an elongated NE-SW trend (Figs. 3.17b & 3.18). Large canyons transported clastic sediments into the basin close to the Maloy slope (Jackson et al., 2010). Deep marine conditions prevailed in the Cretaceous during which deposition was dominantly fine-grained, mudstones but was interrupted by localised deposition of sandstones in the Early and Late Cretaceous (Figs. 3.14 & 3.19a). Absence of regional depositional sand systems during the Cretaceous time in the Northern North Sea is in contrast with underlying Jurassic unit; a period when shallow marine conditions prevailed depositing huge sandstones from the Sognefjord delta that hosts most of the Jurassic fields in this part of the North Sea basin (Ahmadi et al., 2003). The sandstone beds in the Cretaceous are typically only 10 – 25 m thick and are interbedded with mudstones and restricted to the northeast of the study area (Fig. 3.19a). The sandstone packages, dated to the Early Cretaceous (Ahmadi et al., 2003; Martinsen et al., 2005; Zachariah et al., 2009) belong to the Asgard, Sola and Agat sandstone members and penetrated by wells in block 35/3 while those dated Late Cretaceous, Turonian in age belong to the Kyrre Formation and penetrated by wells much further down in block 35/9 (Jackson 2007; Jackson et al., 2010; chapter 4).

Previous studies based on seismic interpretation and well calibration (35/6-2S) have suggested that the sandstones of the Kyrre Formation were initially deposited as slope channels and terminal
fan complexes; which subsequently underwent post-depositional remobilization along their margins resulting in their present geometries (Jackson et al., 2008, 2010; Jackson & Somme 2011). These isolated sandstone bodies display high-amplitude seismic characteristics with discordant, high-amplitude anomalous reflections attached to their margins (chapter 4).

The Troll Field area is more tectonically active than other parts of the study area with faults relay zones, which could serve as pathway for deep seated migrating fluids (Fig. 3.5b & d) (Fossen et al., 2010). Small, extensional faults with polygonal geometries observed within the Early Cretaceous to Early Miocene intervals are interpreted as polygonal faults based on their geometries in planview and similarities with previously interpreted faults in other parts of the North Sea, Norwegian Sea and Faroe-Shetland Basin (Cartwright & Lonergan 1996; Lonergan et al., 1998; Shoulders et al., 2007).

### 3.5.2 Paleocene unit

During the Paleocene the major depocentres occur close to the margins of the Norwegian and Shetland landmasses (Fig. 6b & 18). TWT thickness map of the CSS1 shows a markedly shift in depocentres from the basin centre during the Cretaceous to the basin margins in the Paleocene (Figs. 3.6a & c). Basin ward progradation of clinoform packages from the western and eastern margins record slope to basin floor systems and suggest a low-stand system at this time (Martinsen et al., 1999). The Paleocene is considered the most sand prone unit in the Palaeogene North Sea with large, sandstone-rich, low-stand fans and channel systems deposited during uplift of the Shetland platform and Norwegian mainland (Fig. 3.19b) (Ahmadi et al., 2003). However, in the Northern North Sea, wells closest to the Norwegian margin penetrated less sandstone than expected (1 to 10’s of metres of sandstones) (Fig. 3.9b). Possible reasons could be simply the positioning of the wells so they do not penetrate thicker sandstone units or that most of the sandstones were deposited further down into the basin (in the Fram area) due to uplift along the basin margin thereby creating a by-pass region along the slope. The latter is supported by the presence of much thicker sandstone units observed in the basin centre than along the margin. The TWT thickness map of CSS1 reveals greater sediment thickness created by the Paleocene prograding wedge along the Norwegian margin compared to that close to the Shetlands (Figs. 3.6b & 9). The actual heights and limits of the prograding clinoforms is impossible to ascertain accurately as the top sets of the clinoforms have been eroded away by the regional Pleistocene unconformity leaving only the bottom sets preserved (Fig. 3.9). Based on presence of high-angled clinoforms and greater thickness along the Norwegian margin, we suggest Norwegian landmass was a more significant sediment source with more sediments been deposited into the basin in the Early Tertiary than previously thought (Den Hartog Jager et al., 1993; Fyfe et al., 2003; Goledowski et al., 2012).
Fig. 3.17. Composite TWT ms thickness maps (a) Total thickness of the entire studied interval; 145 - 0 Ma (base Cretaceous to present day seabed) (b) CSS0- Cretaceous sediments; 145 - 66 Ma (base Cretaceous to base Tertiary) (c) entire Cenozoic succession; 66 - 0 Ma (base Tertiary to present day seabed) (d) Paleogene (Paleocene-Oligocene); 66 - 23.03 Ma (base Tertiary to base Miocene) (e) Neogene (Miocene-Pliocene); 23.03 - 2.588 Ma (base Miocene to base Pleistocene) (f) Quaternary; 2.588 - 0 Ma (Pleistocene)
High-amplitude, discordant and concordant anomalies within the unit are calibrated to sandstone lithology in the Fram Field area and believed to have been formed as a result of subsequent remobilization and injection of originally deposited, deep-water gravity deposits (Fig. 3.10; Dmitrieva et al., 2011; chapter 4).

The evolution of the Paleocene Graben is unclear however marked thickening in the upper part of the faulted units within Late Paleocene to Early Eocene sediments helped to constraint timing of fault evolution. We suggest two possible models of graben formation: (i) linkage of smaller fault segments similar to development of underlying Mesozoic fault system around Gullfaks Field (Zanella & Coward 2003) (ii) formation during volcanism in the Late Paleocene – Early Eocene time.

Polygonal faults within the CSS1 unit behave slightly differently close to the graben. Time slices and horizon mapping through the unit reveal those polygonal faults around the graben have a dominant orientation in WNW-ESE direction similar to the Paleocene graben. This slight change in the pattern of polygonal faults close to the graben could be related to response of these nontectonic faults to local stress change due to propagation of the Paleocene graben (Cartwright 2011). Volcanism associated with deposition of Balder Formation prevailed during the Late Paleocene to Early Eocene, which correlates with the timing of formation of the Paleocene graben and thus could have had some influence on the formation (Ahmadi et al., 2003).

### 3.5.3 Eocene unit

The distribution of depocentres during the Eocene was more complex than the underlying units (Figs. 3.6c & 3.18). The Shetland and Norwegian landmasses were the main clastic sediment sources during the Eocene as in underlying Paleocene unit however the presence of depocentre in the NNW part of the study area also suggests a likely source from the Faroe-Shetlands. This depocentre could have been created by subsidence within the Maruk basin during Eocene times (Fig. 3.6c).

Over most areas, the depositional sequence is dominated by hemipelagic, smectite-rich mudstone of the Horda Formation (Rundberg 1991) (Fig. 3.2). Sandstone-rich depositional systems described in previous section have lobate, fan-shaped geometry and interpreted as large, slope to deep-water fans deposited by gravity processes into the basin centre (Figs. 3.8 & 3.10). The upper and lower fans are deposited on top of each other and named fan A and B respectively (Fig. 3.11). The source area for these sandstones was probably the Norwegian mainland during the Eocene (Figs. 3.8 & 3.19c). There are no channels imaged from seismic or attribute data within the fan; however such channels may have existed up-dip of the depositional fan system and have subsequently been eroded by the Pleistocene unconformity (Fig. 3.8). Biostratigraphic data from well 35/8-1 suggests the sandstones are Eocene in age (NPD.NO). These Eocene sandstones have not been formally named in literature, but we suggest they belong to the Frigg sandstone member, which
formed the reservoir for the Frigg Field in the southwest of the study area, based on their similar stratigraphic location, (Isaksen & Tonstad 1989; Ahmadi et al., 2003).

On the western side of the basin, a similar sandstone package is observed and interpreted as a depositional fan system (Fan C) (Fig. 3.11h). Information from biostratigraphic data in well 29/6-1 dates sandstones in fan C as Late Paleocene to Early Eocene in age and likely to have been deposited from the Shetland platform during uplift along the margin. Paleo-geographical location, extent and geometry of the three depositional fan systems in the Eocene suggest significant sediment deposition related to fall in sea-level or uplifts along the margin (Jordt et al., 2000). A smaller Eocene depositional sandstone system was observed in block 35/3 (Martinsen et al., 2005) (Figs. 3.14 & 3.19c). Depositional environment during the Eocene was probably slope to basin-floor setting (Martinsen et al., 1999). Traces of tuffaceous material were found within the unit in some of the wells suggesting reworking of the underlying Balder Formation.

The high-amplitude, discordant anomalies show many typical characteristics in seismic cross section, plan view and 3D geometry of the sandstone injectites commonly interpreted in the Eocene succession of the North Sea (Molyneux et al., 2002; Cartwright et al., 2008; Huuse et al., 2010; Hurst et al., 2011). Based on these characteristics and calibration to sandstone lithology in
wells where available, we interpret these high-amplitude, discordant anomalies within CSS2 unit as sandstone injectites; some of which occur at the fringe of the fans suggesting some form of modification to the original sandstone geometry (Figs. 3.10 & 3.19c) (chapter 4).

### 3.5.4 Oligocene unit and MMU

During the Oligocene, the main depocentre had shifted back to the basin centre and very thick sandstone packages were deposited into the basin from the Shetland platform (Figs. 3.6d, 3.18 & 3.19d). The Shetland platform became a very significant source during this time with very little contribution the Norwegian margin. The wedge (CSS3 unit), dated Early Oligocene by Rundberg & Eidvin (2005) is the only indication of sediment supply from the Norwegian margin. A time structure map of the base of the Oligocene unit (H3) reveals a markedly shallowing of the basin at the onset of Oligocene (Fig. 3.5f). Change in the basin architecture correlates to the significant changes at the Eocene-Oligocene boundary such as global change from greenhouse to ice house conditions; increase in deposition of biogenic silica from underlying smectite; significant fauna change; lithological and mineralogical change in composition of sediments (Rundberg 1991; Zachos 2001; Huuse 2002; Miller et al., 2005; Rundberg & Eidvin 2005).

A remarkable change in sediment composition between underlying fine-grained, smectite-rich mudstone to siliceous-rich mudstones were interpreted from several wells in the study area during the Oligocene (Rundberg & Thyberg et al., 1999). The Oligocene unit is made up of coarser-grained sediments such as siltstones and sandstones compared to the underlying Eocene unit (Fig. 3.13a). Oligocene sandstone systems along the western margin were deposited during sea-level fall (Fyfe et al., 2003; Rundberg & Eidvin 2005) and these sandstones were interpreted to be entirely depositional in origin (Rundberg & Eidvin 2005). However, some of the high-amplitude, discordant anomalies calibrate to sandstone lithology within the upper Oligocene unit (Figs. 3.8 & 3.10). During this period, we proposed that these sandstones have been subjected to intense remobilization and injection, which have resulted in their present starta-discordant geometries (chapter 4).

Mounded geometry and deformation on the mid-Miocene unconformity corresponds to the locations of high-amplitude, discordant anomalies within the underlying Oligocene unit (Figs. 3.10 & 3.13). Based on this, we suggest that the deformation on the unconformity is a result of jack-up created by these anomalies, which are interpreted as sandstone injectites (Rodrigues et al. 2009; Olobayo et al., 2015b). Previous interpretations of similar mounded geometries elsewhere include shale diapirs, mobilized mud masses, mud diapirs, differential compaction & subsidence, density inversion (Gregersen et al., 1998; Rundberg 1991; Clause et al., 1999; Loseth et al., 2003; Davies 2005; Jackson & Stoddard 2007).
The channels on the unconformity are highly sinuous with evidence of an abandoned, chute cut-off loop along the main channel axis (Fig. 3.15a). Variability in width and depth increases towards the north of the study suggesting flow direction was from east to north. No well penetrated into any of the channels, but presence of Utsira sandstone above the unconformity and at similar stratigraphic level in the area, mounding above the channel-cut as well as high-amplitude reflections within these channels suggests sandstone lithology. Several workers have assigned different ages to the formation of the main channel such as: Late Oligocene to Earliest Miocene (Gregersen 1998); Middle Miocene during the formation of the unconformity (Rundberg et al., 1995; Martinsen et al., 1999); and Late Pliocene (Eidvin & Rundberg 2001). Some of the workers also proposed the channel formed in response to marginal uplift in the northern part of the North Sea basin suggesting a fluvial origin (Rundberg et al., 1995; Martinsen et al., 1999; Rundberg & Eidvin 2001), while the others favoured a more marine origin (Gregersen 1998).
We propose a Late Oligocene to Late Miocene age for the main channel. Our interpretation is based on age of sediment, which the channel is eroded into, and sediments within the channel body (Fig. 3.14). The channel cuts into Oligocene succession suggesting erosion post-dates the Oligocene time and channel is filled with Miocene-aged sandstones from the Utsira Formation, which is Late Miocene in age in this part of the basin as no Lower Miocene or mid-Miocene sediments are preserved. Similar age is applied to the smaller channels in the area.

### 3.5.5 Miocene unit

The Lower Miocene unit has only been previously interpreted in the centre part of the basin (Fig. 3.6e) (Rundberg & Eidvin 2005). However biostratigraphic information from wells 29/6-1 and 30/6-1 confirm the presence of sandstones of Lower Miocene age in the southwest of the study area (NPD.NO) (Fig. 3.8). Based on this, we propose presence of Lower Miocene-aged sediments in the southwest of the study area deposited from the Shetland Platform during the Early Miocene. We support our interpretation based on other studies south of our study area where Lower Miocene sandstones were preserved and assigned to the Skade Formation (Jordt et al., 1995, 2000, Eidvin & Rundberg 2001; Rundberg & Eidvin 2005). Polygonal faults do not extend beyond the Lower Miocene unit.

Presence of the sandstone-rich, prograding delta package observed in the southwest suggests sediments were transported into the basin centre from the Shetland mainland (Fig. 3.8). The clastic, wedge-shaped package towards the northeast could be an eroded paleo-delta similar to Paleocene wedge interpreted in CSS1 unit (Fig. 3.14). The Miocene is the most sandstone-rich unit in the entire Cenozoic (Fig. 3.19e).

### 3.5.6 Pliocene and Pleistocene units

High-angled, clinoforms that prograde north-west from the western margin of Norway constitute the thickest part of the Pliocene unit. The high-amplitude anomalous features observed along the clinoforms are interpreted as slope channels based on their sinuous geometries in planview (Figs. 3.10 & 3.16a). These channels are very abundant in the area and flow from east to northeast.

Sandstone units observed within wells 34/7-9 and 34/7-1 have been previously interpreted as bottom-set sands deposited by turbiditic processes (Gregersen & Johannessen 2007) based on the apparent onlap of the sands onto the toe-sets of the Pliocene prograding clinoforms (Fig. 3.10). Revised interpretation for these Pliocene-emplaced sands proposes a post-depositional process of remobilization and extrusion from underlying sandbodies (Huuse & Mickelson 2004; Løseth et al., 2012; 2013). According to Løseth et al., (2012), the sands were extruded into the background stratigraphy during the period of high sedimentation rate and subsidence typical of Pleistocene glaciations. We support also the extrusive model based on the morphology of the sandstones in the
unit. Mapping reveals mounded geometry and pinch-out into surrounding, background mudstones of Pleistocene age meaning the extrusions are likely to be younger than this (Olobayo et al., 2012; chapter 4).

Isolated, high-amplitude “soft” anomalies observed within CSS9 unit are interpreted as possible gas accumulations within thin layers of sands (Fig. 3.10). During the Pliocene to Pleistocene, sedimentation was influenced by glaciation in the North Sea. Linear features observed on horizon slices are interpreted as ice-berg scours, which are imprints formed during the Pleistocene when glacial conditions prevailed (Sejrup et al., 2003) (Fig. 3.16b).

### 3.5.7 Net accumulation rate

Net sediment accumulation rates were estimated from thickness maps and interval velocities within each unit throughout the studied interval (Tab. 3.3 & Graph 3.1). It should be noted that the thicknesses have not been compensated for compaction or erosion.

Sediment accumulation rate was lower during the Cretaceous than any period in the Cenozoic except during Eocene time (Graph 3.1). The drastic drop in sediment accumulation from a minimum of 23 m/Ma and maximum of 109.25 m/Ma in CSS1 to 4.82 m/Ma and 24.10 m/Ma in CSS2 respectively could have been controlled by depletion of available sediment following the earlier uplift and reduction in tectonic activities along the basin margins at this time (Jordt et al., 2000).

Highest sediment accumulation in the Paleogene occurred during the Paleocene to Early Eocene. The minimum and maximum net accumulation rates estimated for the CSS5 unit are 18.08 m/Ma and 108.50 m/Ma respectively and come close to accumulation rates in CSS1; but deposited over shorter period (Tab. 3.3). The subsequent erosion that formed the mid-Miocene unconformity could have interrupted deposition. The accumulation rate from CSS6 to CSS7 shows a very significant change from 76.56 m/Ma to 415.63 m/Ma for maximum rates respectively (Tab. 3.3 & Graph 3.1). This is attributed to increased accommodation space and sediment supply from the Norwegian margin during deposition of CSS7 unit. Such a significant change in sediment deposition could be attributed to sea-level drop or global climatic change or increased subsidence (Clausen et al., 1999; Huuse & Clausen 2001; Huuse 2002; Goledowski et al., 2012). The CSS7 sequence has the largest amount of sediment deposited within a very short period of time throughout the study area giving much greater sedimentation rates than any other period (Rundberg & Smalley 1989). Sedimentation rate was also relatively high during the Quaternary (CSS9).
Graph 3.1 a graphical representation of table 3.1 showing estimated sediment accumulation rate from the Cretaceous to the present day seabed from the study

3.6 CONCLUSIONS

We have presented in this paper results from mapping of a 3D Seismic MegaSurvey and well data integration of the Cretaceous to Cenozoic sediments in the Northern North Sea. Previous works were based on 2D seismic survey or localized 3D seismic volumes (Fig. 3a). Ten (10) major sequences bounded by time-significant surfaces were mapped across the entire area.

In summary we conclude that:

- Our study, as with many others confirms that both Norwegian mainland and Shetland platform were the main sediment provenances in the area throughout the Cenozoic. Evidence of this can be inferred from location of depocentres and presence of prograding clinoforms/wedge
- Thick sediment wedges along the eastern margin suggests the Norwegian hinterlands may have been a more significant source during the Paleocene to Early Eocene (CSS1) than
Fig. 3.20 Northern, central and southern profiles across the study area showing overall stratigraphy and underlying Mesozoic faults
previously thought, although it is difficult to ascertain the actual heights of the prograding clinoforms due to erosion by the Pleistocene unconformity.

- A linear depression termed the Paleocene graben was mapped across the area within the CSS1 unit and attributed to extension of smaller faults or volcanism in the Late Paleocene to Early Eocene times.
- A newly-studied slope to deep-water fan B interpreted within the CSS2 unit. We propose this fan, along with previously mapped fan A, are Eocene in age and belong to the Frigg sandstone member. These fans show evidence of sub-surface remobilization and injection. A third Eocene fan C was also interpreted. Fans were deposited during uplifts along the basin margins.
- The presence of a high-amplitude, continuous, hard-kick reflection (H5) that cross-cuts the CSS4 unit was formed during silica diagenetic transformation of opal A to opal CT. This reflection correlates to an increase in acoustic impedance produced from downward increase in the density and sonic logs. We propose that this diagenetic surface should not be used to divide the Oligocene unit (CSS4) as previously interpreted.
- Sandstone-rich, Lower Miocene sediments (CSS5) are preserved in the south west of the basin as well as in the centre of the basin as previously observed.
- Small channels were imaged on the Middle Miocene Unconformity by seismic data and spectral decomposition techniques in the north east of the study area; the geomorphology and flow direction of these additional channels are similar to a major channel previously described in literature and likely to be sandstone-filled.
- The Middle Miocene unconformity is intensely deformed into mounded geometry and related to presence of underlying, high-amplitude, discordant anomalies.
- The presence of high-amplitude, discordant and concordant anomalies are observed from Cretaceous to Pliocene and believed to be associated with sub-surface sandstone remobilization and injection.
- The Cretaceous to Miocene intervals are also pervasively deformed by small-scaled, intraformational, polygonal faults similar to those in the other parts of the North Sea, Norwegian Sea and Faroe-Shetland Basin.
- Overall, the Cenozoic sequence stratigraphic framework of the Northern North Sea was influenced by intense remobilization and injection of sandstones, polygonal faults and mudstone diagenesis (Fig. 3.20). These post-depositional processes contributed to the basin evolution and should be considered along with tectonics, eustatic and climatic factors.
ACKNOWLEDGEMENTS

We wish to thank Petroleum Technology Development Fund (PTDF) Nigeria for proving full scholarship that has made this research possible. We want to thank Richard Lamb of PGS and entire PGS for providing the 3D MegaSurvey seismic volume which most of this interpretation was based on and TGSNOPEC for proving regional 2D seismic lines for this project. We also want to thank Norwegian Petroleum Directorate (NPD.NO) website for information on the wells used. Appreciation also goes to the reviewers for their constructive comments in the process of reviewing this paper.

REFERENCES


Chapter 4

4  THE SAND INJECTITE STRATIGRAPHY OF THE NORTHERN NORTH SEA

ABSTRACT

The Northern North Sea is the archetype Giant Injected Sand Province (GISP). Previous studies have documented individual stratigraphically bound injectite complexes in the North Sea and other parts of the world. Despite two decades of continuous studies, based on core, wireline log, outcrop and seismic data, there are still some speculations in terms of parent sand identification, visible pathways, fluid source, overpressure generation mechanisms and triggers. This study is based on a 29,000 km² 3D seismic reflection volume calibrated to numerous boreholes, and documents for the first time, the stratigraphy of the Northern North Sea Basin GISP, spanning five (5) intrusion episodes over 80 m.y. Sizes range from 500 m to 8 km wide and from 50 to 250 m in height, for individual intrusions.

The intrusions are often manifested as high-amplitude, discordant, strata-concordant or steep-mounded anomalies. Well data, where available, confirms that these amplitude anomalies correspond to sandstones and can be classified as conical and saucer-shaped sandstone injectites, in-situ remobilized sandstones and extrudites, emplaced within fine-grained, polygonally-faulted mudstones. We present examples of these post-depositional sandstones from different stratigraphic units of the Northern North Sea. This includes details on their geometries, sizes, distribution, time of emplacement and likely parent sand bodies; and potential mechanism, responsible for their generation. Channel- and fan-shaped deep-water depositional bodies mapped in the vicinity of the intrusion complexes are considered as potential parent bodies and located at multiple intervals.

Seismic, well logs, SEM and XRD data provide evidence of a silica diagenetic transformation (opal A to opal CT) within Paleocene to Oligocene interval, with the present location of the boundary directly below Oligocene-hosted sandstone injectites. Fluid budget for such a large-scale remobilization and injection would have been combination of several sources, which includes hydrocarbons and diagenetically-released water from opal A to opal CT transformation, smectite to illite transformation and physical compaction of sediments. Hydrocarbon generation started during Late Cretaceous for oil and Late Neogene for gas.

Presence of these sandstone injectites and their counterparts through the entire interval, suggests breach in the sealing host rocks. We, therefore, propose a need to incorporate them into existing stratigraphic framework for accurate reservoir models, not only in the study area, but also in the other hydrocarbon basins in the world, where they have been encountered.
4.1 INTRODUCTION

Recently, high-resolution, 3D seismic data, integrated with well log and outcrop studies, have helped to improve identification, geometry, interpretation and implications of sandstone intrusions/extrusions in sedimentary basins (Dixon et al., 1995; Molyneux et al., 2002; Duranti et al., 2011; Monnier et al., 2014). Although sandstone injectites have been described as far back as the early 1900’s (Newsom 1903; Jenkins 1930), their petroleum significance was only realized in the last two decades, as they were completely overlooked. They are recognised at wide scale, ranging from cores (Dixon et al., 1995; Bergslien 2002; Duranti et al., 2002), to wireline (Duranti et al., 2002; De Boer et al., 2007) to outcrop (Thompson et al., 2007; Pringle et al., 2007; Vigorito et al., 2008; Hurst et al., 2011) and to seismic scale (Lonergan & Cartwright 1999; Lonergan et al., 2000; Bergslien 2002; Molyneux et al., 2002; Rensbergen et al., 2003; Hurst et al., 2003, 2004, 2005; Huuse & Mickelson 2004; Shoulders & Cartwright 2004; Jackson 2007; Lonergan et al., 2012; 2013). The North Sea basin, Faroe-Shetland basin and San Joaquin valley are classified as Large Scale Intrusion Provinces (LSIPs), where kilometre-scale intrusions, emplaced in thick, fine-grained mudstone units, have been mapped (Cartwright 2010).

The study area is located in the northern part of the North Sea basin encompassing mostly the North Viking and falls within the North Sea Sand Injectite Province (NSIP) (Fig. 4.1a). It is comprised of kilometre-scaled sandstone intrusions and extrusions, emplaced within sediments from upper Cretaceous to Pliocene in age. There have been detailed sub-studies that focused either on individual feature, or stratigraphic interval, but not a regional detailed study that ties everything together in time and space, putting into consideration possible parent bodies, fluid sources and multiple timing of emplacement.

The Paleocene and Eocene intervals of the North Sea record the best examples of sand injectites and extrudites (Fig.4.1a) (Dixon et al., 1995; Huuse & Mickelson 2004; Hurst & Cartwright 2007). Three models are proposed for occurrence of sandstones in the North Sea; they include: deposited, remobilized and injected/extruded models (Fig.4.1b) (Huuse et al., 2009, AAPG). They differ from conventional depositional sandstones, mainly, based on their geometries and mode of origin. Criteria for classification in seismic data includes: V, U or W-shaped geometry in cross section, discordant with host mudstones, high-amplitude reflection, circular to oval geometry in plan view, 3D conical geometries and jack-up or forced folding above intrusion. Moreover, intrusions often occur within polygonally faulted units (Huuse & Mickelson 2004). If penetrated by well bore, the amplitude anomaly should calibrate to sandstone lithology. For mound anomalies, they have steep dip angle, flat base, lack of underlying erosion, onlap onto the mound and circular to oval geometry in plan view (Fig. 4.1b) (Huuse et al., 2004; Andresen et al., 2009).

Previous studies in the North Sea show that they cause significant modifications to reservoir geometries, architecture, connectivity, properties and top surface geometry (Lonergan et al., 2000). Outcrop studies have also provided wealth of information that improved understanding of sandstone intrusions/extrusions (Vigorito et al., 2008; Hurst et al., 2011). This includes details on
varying geometries at which the sand bodies are emplaced, their connectivity and relationship with encasing mudstone and parent bodies. Outcrop exposures from Panoche-Tumey hills, California, remain the best site for detailed studies of sandstone injectites. This location is unique, as it gives insight on both small-scale injectites (few centimetres) and larger bodies that extend for hundreds of metres to kilometre, similar to those observed in seismic data. It also gives additional information on the regional, lateral and vertical extent of the sandstone injectites. Outcrop examples are sometimes limited by 2-dimensional representation, size, weathering, extent and continuity, hence the advantage of 3-dimensional seismic data, calibrated by boreholes, improves our overall understanding of GSIPs.

**Fig. 4.1 (a)** Structural map of the North Sea basin showing major structures, such as the triple arm, highs, sub-basins, terraces, platforms, faults and surrounding landmasses (modified from Fraser et al., 2003). Location of study area is shown in the red outline. Acronyms as in Figure 1.2. Also included on the map are locations of some hydrocarbon producing fields/discoveries. Yellow numbered squares represents fields associated with remobilised/injected sands (same as in fig.1.2). Yellow stars show locations of previous work done in the area, related to post-depositional products or soft-sediment deformation. Inset shows present day bathymetry of the North Sea.
Fig. 4.1(b) Three (3) models suggested for the occurrence of sandstone in the North Sea basin. These include: the conventional depositional model; remobilization of the sands after deposition and partially or completely injection of the sands. When sands reach the seabed, extrudites are formed (Adapted from Huuse et al., 2009, AAPG).

Additional features observed within the studied interval include polygonal fault networks and silica diagenetic transformation zones (Opal A - CT and CT - Quartz silica phases). Polygonal faults are layer-bound faults, formed as a result of contraction and de-watering of fine-grained lithology, usually mudstones during shallow burial (Cartwright 1994; Lonergan et al., 1998; Lonergan & Cartwright 1999; Goulty 2001). They were first recognised in the Eocene mudstones in the North Sea basin, but have subsequently been identified in other basins worldwide, using both seismic and outcrop data (Shoulders et al., 2007; Cartwright et al., 2008; Bureau et al., 2013; Tewksbury et al., 2014). Recognition from seismic data and outcrop is based mainly on their polygonal nature in plan view and could occur in single or multiple tiers. Seismic data revealed extensive polygonal fault system, affecting Lower Cretaceous to Lower Miocene mudstones in study area. Silica diagenesis is the conversion of sediments rich in biogenic silica (Opal – A) to crystalline silica (Opal – CT) and sometimes to quartz during early burial (Ireland et al., 2011). The implication of this process includes: sediment compaction, dramatic porosity reduction and release of significant...
volume of water; and can generate excessive overpressure within sediments (Davies & Cartwright 2002; Davies et al., 2006; Cartwright 2007). Evidence of silica diagenetic transformation within Paleocene to Oligocene sediments in the study area was first documented by Rundberg (1991).

Polygonal faults, silica diagenesis and clastic remobilization have previously been linked in some sedimentary basins, and the northern North Sea represents one of the best-documented examples where these relationships are observed (Fig. 4.1c). Large-scale sandstone intrusions are interpreted within polygonally faulted networks and above the present-day location of the Opal A-CT diagenetic boundary (Davies et al., 2006).

**Fig. 4.1(c) Global distribution map showing location of sandstone intrusions, polygonal faults and sites of silica diagenetic transformation.**

The main aim is to document the occurrence, geometry and distribution of sandstone intrusions/extrusions, understand the relationship between sandstone intrusions/extrusions and underlying Mesozoic faults, as well as investigate potential parent bodies of the sands in the study area. We also discuss their origin, timing of emplacement, possible priming and triggering mechanisms associated with their formation. We have benefitted from the integration of 3D seismic and well log calibration across the entire area, to answer outstanding questions in the current literature, such as vertical and lateral distribution of the intrusions, presence and location of parent bodies, fluid sources and very importantly, whether the basin underwent single or episodic emplacement. The study is unique because it is the first documentation of such repeated, basin-scale remobilization and injection in a single basin from Cretaceous to Pliocene, through, possibly, five discrete remobilisation and injection/extrusion events.
4.1.1 Mechanics of sandstone intrusions

Extensive literature on sandstone intrusion complexes from seismic, well and outcrop data reveals that they occur in a wide range of environments, which includes glacial, lacustrine, tidal, deltaic, fluvial, aeolian, offshore shallow marine and deep-water settings (Fig. 4.1c). However, they have been more documented in deep-water settings and this has been attributed to presence of the main pre-requisite required for their formation (Lonergan et al., 2000; Jolly & Lonergan 2002). They include: uncemented source sand or parent body, low-permeability host rock (mostly mudstones), overpressure generation mechanism, significant volume of fluid and a possible trigger.

Mechanics of sandstone intrusions and products are similar to those in igneous environment (Fig. 2.11) (Jolly & Lonergan 2002; Duranti & Hurst 2004; Cartwright et al., 2008; Polteau et al., 2008). Based on the similarities in their formation, a sandstone dyke is considered as a typical example of natural hydraulic fracture (Jolly & Lonergan 2002). The source sediment or parent body of an intrusion must be uncemented at the time of formation and sealed within the host rock, such that excessive pressure is generated; the seal then will have to be breached, to allow sand inject into the surrounding host rock (Fig. 4.2a X/X,1) (Lonergan et al., 2000; Hurst et al., 2011). For this to happen, a differential pressure must be created between the pore fluid and the surface (Graph 2.1) (Huuse et al., 2010). The actual sand movement is facilitated by fluid, such that the sand-fluid mixture flows through the openings, created during hydraulic fracturing, in a process called fluidization. The source rock or parent body can be located very close to the intrusions or some distances away and sand can be intruded upwards, downwards or laterally depending on the hydraulic gradient (Jolly & Lonergan 2002; Shoulders et al., 2007; Andresen & Clausen 2014).

Sandstone intrusions are commonly encountered in tectonically active, mud-dominated sedimentary basins that have high sedimentation rates. Tectonic stresses applied on the sediments generate differential pressure between the pore fluid in the sub-surface and the seabed or shallower aquifer (Jolly & Lonergan 2002; Huuse et al., 2010).

Jolly & Lonergan (2002) divided the sandstone intrusion formation, discussed above, into three phases: (1) overpressure development (2) seal failure and (3) fluidization of sand. Details of the processes have been discussed in chapter 2.

Overpressure, liquefaction and fluidization

Overpressure or excess fluid pressure is achieved when the pore fluid pressure with a sealed system is greater than hydrostatic pressure at a given depth (Graph 2.1) (Maltman 1994; Swarbrick & Osborne 1998). The weight of the overburden is partly supported by the excess pore pressure generated as a result of disequilibrium compaction between the sand body and the surrounding mudstones; and rest is partly supported by the effective stress, \( \sigma^I \) defined as overburden or lithostatic pressure - fluid pressure \( \sigma^I = \sigma_{Lith} - P_f \) (Jolly & Lonergan 2002). Overpressure can be generated by a variety of mechanisms and will be discussed in the next section. Obermeier (1996)
defined liquefaction as the state at which overpressure is and this involves the conversion of sediments from solid to liquid state, such that the grains are separated and no longer supported by them, but by the pore fluid (Fig. 4.2a X2) (Allen 1984)

Fluidization on the other hand is simply defined as suspension of sediment grains by drag forces, as a result of upward migration of fluid (Fig. 4.2a X3) (De Felice 1995; Hurst et al., 2011). It is the ability of fluid to lift cohesionless sediments, such that the unconsolidated sands are carried from their source or parent sand body into fracture networks (Fig. 4.2aX3) (Obermeier 1996; Duranti & Hurst 2004). Fluidization occurs when movement of pore fluid exceeds the minimum fluidization velocity (Obermeier 1996; Hurst et al., 2011). It requires significant volume of fluid (hydrocarbon or water) either produced from pore water within the sediments, or introduced from an external source (Lonergan et al., 2000; Van Rensbergen 2003; Huuse et al., 2010; Szarawarska et al., 2010). In large sandstone intrusion provinces, such as the North Sea, Faroe-Shetland and San Joaquin basins, additional fluid migrating from deeper part of the basin into the parent body may have contributed greatly to drive remobilization and injection of sands (Lonergan et al., 2000; Wild & Briedis 2010; Huuse et al., 2010). In the simplest of terms, in order for grains to move, a differential pressure gradient must be generated across the unit; as such the force carrying the grain (drag force) must be greater than the weight of the grains (Jolly & Lonergan 2002).

![Fig. 4.2a Schematic diagrams showing effect of liquefaction and fluidization of sand from depositional parent body during burial (Hurst et al., 2011)](image-url)
4.1.2 Petroleum systems and implication for hydrocarbon exploration and production

The North Sea is one of the most prolific basins in the world, with an active petroleum system since the Mesozoic, which continues to the Cenozoic in the North Viking Graben, with the Late Jurassic Kimmeridge Clay Formation, as the main source rock. This is age equivalent of the Draupne Formation in the Norwegian sector (Kubala et al., 2003). Other potential source rocks are the Heather Formation and Middle Jurassic coal-bearing rocks of the Brent Group, for mainly gas generation, with limited oil potential (Kubala et al., 2003). In the North Viking Graben, reservoirs are mostly mid to Late Jurassic shallow marine sandstones, sourced from either of the Draupne, or the Heather Formations, for oil and the Brent Group, for gas. Maturity for oil generation in the North Viking Graben was reached in the Late Cretaceous, with peak maturation since the mid-Paleogene (~54 Ma) and maturation for gas generation since the Late Neogene (~14 Ma); and active generation continues till present-day (Fig. 4.2b) (Kubala et al., 2003; Schlakker et al., 2012). Main traps include series of horst and graben and fault-related structures, formed during rifting; and they formed fields, such as Troll, Snorre, Stratfjord and Gullfaks (Ahmadi et al., 2003).

Exploration and production activity in the Northern North Sea was concentrated in the Mesozoic succession, within giant fields, such as Troll, Statfjord, Snorre and Gullfaks. However, in the last few years, there has been increasing interest in the overlying Cenozoic succession. Hundreds of wells, drilled to target Mesozoic accumulations that penetrated some of the Cenozoic sandstones, have been recorded only traces of hydrocarbon or water-wet. Deliberate drilling of Tertiary reservoirs has not yielded desired results with the exception of Statoil’s Peon and Gullfaks (34/10-8-A) discoveries, within the Pleistocene and Paleocene intervals, respectively. Most recently, an attempt made by Tullow Oil to test a Paleocene prospect (well 31/3-4) was unsuccessful, even though excellent reservoir was encountered (Tullow Oil press release – www.tullowoil.com).

Sand injectites constitute great reservoirs or enhanced reservoir connectivity in adjacent parts of the study area, such as the Outer Moray Firth and South Viking Graben, but not the case in the Northern North Sea (Fig. 4.1a). The presence of sandstone intrusions and extrusions that crosscut thick-mudstone intervals is evidence of seal failure; and possible interconnectedness between them may have compromised seal integrity of cap rocks, jeopardizing prospectivity in the Tertiary interval in the area. Therefore there is need for intrusions to be incorporated into the present stratigraphic framework of the basin and considered at the early stages of exploration and for reservoir models.
Fig. 4.2b Petroleum system chart for the North Viking Graben in the North Sea. Also shown are timing for sandstone injectite emplacement in the study area (Adapted from Kubala et al., 2003; Schlakker et al., 2012)

4.2 REGIONAL SETTING

The Cenozoic North Sea basin formed as a thermal sag basin above pre-existing, rift-related structures, associated with extensional events during the last two phases of the rifting in the Permo-Triassic, and the Late Jurassic-to-Early Cretaceous (Ziegler 1990; Fossen et al., 2010). Sediment thickness is greatest in the North Viking and Sogn Grabens reaching up to 5s two-way-time (TWT) (Ahmadi et al., 2003). The study area is located between 60-62° latitude and 1-5° longitude. It is bounded by the Norwegian coastline to the east, the Shetland Isles to the west, North Atlantic in the north and to the south by the South Viking Graben (Fig. 4.1a). The study interval encompasses the Cenozoic and Cretaceous interval, bounded above and below by present-day seabed and base Cretaceous unconformity, respectively (Figs. 4.3 & 4.5). Sediments are dominantly fine-grained mudstones with large, sand-rich fans and channel systems, which are deposited during uplifts along the basin margins (Martinsen et al., 1999, 2005; Jordt et al., 1995, 2000; Faleide et al., 2002; Ahmadi et al., 2003; Rundberg & Eidvin 2005). Sandstones were sourced from both the east (Norway) and the west (Shetlands) (Jordt et al., 1995, 2000; Ahmadi et al., 2003; Anell et al., 2011; Goledowski et al., 2012).

The stratigraphic evolution of the Cenozoic North Sea basin is believed to have been controlled by tectonics, eustatic and climatic processes; however, post-depositional processes, such as subsurface remobilization and injection of sands, polygonal faulting and diagenetic transformation have greatly contributed to the present-day configuration of the basin (Huuse & Mickelson 2004; Huuse 2008; Davies et al., 2006; Løseth et al., 2013).
Based on Isaksen & Tonstad (1989), the Cretaceous stratigraphy is divided into Cromer Knoll and Shetland groups, composed mainly of thick mudstones throughout the study area (Fig. 4.3), but very thin or almost absent over the Troll fault blocks. Large slope fan, channels and terminal fans, belonging to the Kyrre Formation in the Upper Cretaceous, were mapped along the Malay slope (Jackson et al., 2010). The overlying Cenozoic interval is divided into three main groups: Rogaland, Hordaland and Nordland Groups. Anomalies are located within the Shetland, Rogaland, Hordaland and lower part of the Nordland Group (Fig. 4.3). Uplifts along the basin margins, related to breakup of North Atlantic, resulted in deposition of clastic sediments from main areas, such as the Shetland platform and western Norway (Ahmadi et al., 2003). During the Late Paleocene to Early Eocene, separation of Norway and Greenland resulted in volcanic activity that deposited ash-rich, tuffaceous deposits, which formed the Balder Formation (Jordt et al., 1995, 2000; Ahmadi et al., 2003; Anell et al., 2011). This marks the top of the Rogaland group; a regional marker horizon across the North Sea. Uplifts along the basin margins resulted in deposition of channel-lobes and sand-rich fans into the basin (Huuse & Mickelson 2004; Brunstadt et al., 2009). The Hordaland Group comprises of siliciclastic sediments, bounded above and below by the mid-Miocene unconformity and the top Balder Formation, respectively. Deposition within the basin at this time was characterised by fine-grained, smectite-rich mudstones and coarser-grained, siliceous-rich mudstones in the Eocene and Oligocene intervals, respectively (Rundberg 1991, Thyberg et al., 1999). The Eocene-Oligocene transition records significant events globally; these include: changes from greenhouse to icehouse conditions, reduction in water bottom temperature, global mass extinction, faunal and mineralogical changes from smectite-rich to biogenic, and deposition of silica-rich sediments (Rundberg 1991; Zachos 2001; Miller et al., 2005; Rundberg & Eidvin 2005). The Eocene and Oligocene deep-marine Horda and Lark Formation, respectively are comprised of three sandstone members, namely, Frigg, Grid and Skade members (Isaksen & Tonstad 1989, Jordt et al., 1995, 2000).

The mid-Miocene unconformity (MMU) represents a period of significant erosion in the North Sea and separates the Hordaland from the Nordland Group with a time-gap of about 15 m.y (Isaksen & Tonstad 1989; Martinsen et al., 1999; Galloway 2002; Rundberg & Eidvin 2005; Løseth et al., 2013). It is occasionally mounded in the study area, due to effect of underlying units. All sediments deposited after the erosion were classified under the Nordland Group. The Utsira Formation (Late Miocene or Early Pliocene) is dominated by sandstone and bounded at the base by the MMU or base Miocene surface. The Utsira Formation is overlain by westwardly-prograding, Pliocene-age clastic wedge, sourced from the Norwegian mainland (Jordt et al., 2000). Clinoforms are truncated at their tops by the regional Pleistocene unconformity, formed from grounding ice sheets and mappable across the entire area. The Pleistocene unit is composed of mudstones interbedded with sandstones and glacial tills to glacial marine sediments (Gregersen & Johannessen 2007).
Fig. 4.3A simplified stratigraphic column of the studied interval, this includes chrono, seismic and litho stratigraphy. (Modified after Rundberg 1989; Jordt et al., 1995, 2000; Brundstadt et al., 2009; Anell et al., 2011; time scale adapted from International Chronostratigraphic Chart 2014). Horizon and units mapped in this study are also shown. Case studies used in this work are shown at different stratigraphic intervals, which are related to their timing of emplacement. Other post-depositional products are also shown. Note that these features occur at same intervals.

4.3 DATABASE AND METHODS

4.3.1 Database

Data available comprises a subset of the Northern North Sea 3D seismic MegaSurvey (courtesy of PGS), which is a survey created by merging a large number of legacy 3D surveys, which includes a coverage area of 29,000 km$^2$, 38,000 km long 2D seismic reflection profiles from TGSNOPEC, over
Fig. 4.4 (a) Seismic and well data, used for study. Red outline represents extent of 3D MegaSurvey (courtesy of PGS); with a time slice @ -2300ms. Green lines show 2D lines (TGSNOPEC), used to complement gaps in the 3D seismic volume. Black circles show well locations. Locations of used regional transects are represented as black lines. Irregular diagrams are hydrocarbon producing fields

50 wells with wireline logs (GR, DEN, SON, RES) and check shot data for most of the wells (Fig. 4.4a, Tab. 4.1). Completion logs, biostratigraphic data and well reports were available from the Norwegian Petroleum Directorate (NPD.NO) website. The study area covers the whole of exploration quadrant 34 and 35 and part of quadrants 29, 30, 31, 32, 33, and 36 in the northern North Sea. A time-to-depth relationship was established from the check shot data, which made it possible to estimate thicknesses in metres. Seismic data was processed in zero-phase with a reverse polarity, such that a downward increase in impedance represents negative amplitude (trough or red reflection) based on European polarity convention. Seismic data quality is good to moderate, but quality deteriorates towards the western part of the study area, due to chaotic nature of the seismic, which made mapping very challenging. Dominant frequency ($df$) was estimated for each interval and used with the interval velocities from wells to calculate horizontal ($\lambda /2$) and vertical resolutions ($\lambda /4$) (Tab. 4.1.). Frequencies and interval velocities vary across the study area. The 3D survey has a bin spacing of 50 metres and vertical sample interval is 4 ms.
Tab. 4.1 Frequencies, velocities and vertical resolution for each of the CSS units

<table>
<thead>
<tr>
<th>CSS UNITS</th>
<th>Frequency (hz)</th>
<th>Velocities (km/s)</th>
<th>Horizontal Resolution (m)</th>
<th>Vertical Resolution (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>CSS0</td>
<td>40</td>
<td>2.840</td>
<td>36</td>
<td>18</td>
</tr>
<tr>
<td>CSS1</td>
<td>30</td>
<td>2.300</td>
<td>38</td>
<td>19</td>
</tr>
<tr>
<td>CSS2</td>
<td>35</td>
<td>2.130</td>
<td>30</td>
<td>15</td>
</tr>
<tr>
<td>CSS4</td>
<td>40</td>
<td>2.05</td>
<td>26</td>
<td>13</td>
</tr>
<tr>
<td>CSS6</td>
<td>40</td>
<td>2.12</td>
<td>27</td>
<td>13</td>
</tr>
<tr>
<td>CSS7</td>
<td>55</td>
<td>2.10</td>
<td>27</td>
<td>13</td>
</tr>
</tbody>
</table>

4.3.2 Methods

A number of sequence stratigraphic and litho-stratigraphic frameworks have been established over the years for the Cenozoic succession of the North Sea (Galloway 1993; Rundberg 1991; Martinsen et al., 1999; Jordt et al., 1995, 2000; Rundberg & Eidvin 2005; Anell et al., 2011). We adopted the CSS classification of Jordt et al., 1995, 2000, to divide the Cenozoic succession in this study (Fig. 4.3). 12 major seismic horizons (Figs. 4.3 & 4.5) were mapped, spanning across the Base Cretaceous Unconformity to the present-day seabed. Time thickness maps were created to identify depocentres within each sequence (Chapter 3).

High-amplitude, discordant, concordant and mound anomalies, interpreted to be sandstone intrusions and extrusions, were mapped across the area using both conventional and attribute seismic volumes. Time slices through the intervals revealed plan view geometries of the intrusions. Recognition was based on specific criteria identified in cross section, 3D and in plan view (Fig. 4.4b) (Molyneux et al., 2002; Hurst et al., 2003; Rensbergen et al., 2003; Huuse et al., 2004; Huuse & Mickelson 2004; Jackson 2007; Cartwright et al., 2008; Andresen et al., 2009). In cross section, they are often manifested as high-amplitude anomalies, clearly distinguishable from the low-amplitude background strata. Conical and saucer-shaped injectites have discordant margins, commonly known as dykes (Huuse et al., 2004; Braccinni et al., 2007; Vigorio et al., 2008). The dykes usually thin upwards and terminate abruptly within the host stratigraphy. For saucer-shaped intrusions, examples of dykes turning into a bedding-concordant anomaly (sill) are also common. In plan view, individual intrusions have circular to oval-shaped geometries (Fig. 4.4b). Time slices through an injectite reveal a subtle decrease in diameter with depth, which is mostly observed for conical-shaped ones; saucer-shaped injectites have uniform diameter throughout their body. The conical or saucer-shape geometry of injectite is clearly imaged using 3D seismic data and this gives the best representation in the subsurface. Extrudites are characterized by a mound-shaped
Fig. 4.4b Recognition of sandstone injectites using different attributes in Opendtect. These are the main characteristics of sandstone injectites.
geometry in cross section with steep flank angles. Clear onlaps of overlying strata, identified above the upper surface of an extrudite, distinguishes them from depositional mounds, as the overlying sediments onlap onto the mound rather than draping across it, as in depositional mound. In plan view, they have circular to oval-shape geometry. Available well data was used for lithological interpretation and fluid-type delineation. Knowing the lithology was very crucial, as there are other types of sedimentary rocks, with similar characteristics to sandstone intrusions/extrusions.

Simple quantitative measurements of the intrusions, mapped in the area, were made, such as dip angle, upper/lower width and height of intrusions. Dip angle represents the angle between the discordant margin (wing) and the lowest part of the intrusion. Upper and lower width represents the distance from shoulder to shoulder of individual intrusion, while the height represents the difference between the base and tip of the intrusion in TWT and was converted to metres using the time-depth relationship (Fig. 4.4c). Time slices from variance cube and horizon mapping of key boundaries were useful to identify and characterize the polygonal fault networks in the area. Ant-tracking attribute in Petrel® was applied to a sub-cropped volume, to image the faults in details. Fault population statistics, such as dip angle, azimuth and length were measured and rose diagram was plotted to show orientation.

![Diagram showing parameters to measure conical sandstone intrusions](image)

**Fig. 4.4(c)** Parameters to measure conical sandstone intrusions (not drawn to scale)
Exact timing of intrusions is not easy to ascertain. Dating techniques, applied for intrusions, include: presence of extruded sand on the paleo-seafloor, dating of sediments that onlaps onto the mounds or jack-up and dating the stratigraphic horizon or event at which the oldest intrusions terminate (Shoulders & Cartwright 2004; Huuse & Mickelson 2004; Huuse et al., 2007; Cartwright 2010). Seismic attribute maps, such as root mean square (RMS) and maximum amplitude, generated on single surfaces and between two surfaces, were useful to identify the gross architecture of deep-water depositional systems, such as channel-systems and fans. These gravity-driven deposits are potential sources for the sandstone intrusions and extrusions in the area.
Fig. 4.5 NW-SE trending seismic and geo-seismic section showing mapped sequences, surfaces, internal characteristics of the units and underlying structural highs and faults. Pliocene clinoforms progrades westwardly and downlaps onto the top of Utsira Fm. Note the mounded morphology of the mid-Miocene unconformity. Both depositional and post-depositional sands are shown on the seismic. White horizon represents the Opal A/CT diagenetic surface cutting across the Oligocene succession. High-amplitude, discordant anomalies correlate to sandstone facies within individual units. The amplitude anomalies primarily occur above underlying structural highs. Paleocene sandstones deposited from Norway. Note polygonal faulting from Cretaceous to Miocene succession.
4.4 OBSERVATIONS AND RESULTS

4.4.1 Polygonal faults

Numerous normal faults are observed in the study area, from the Lower Cretaceous to Base Miocene intervals (Fig. 4.5). They are characterized as small, extensional faults with polygonal geometries in plan view. They are well imaged on the normal seismic, attribute volumes, horizon and time slices through the volume. An apparent characteristic of the fault is, although dominant trends are identified, they are randomly oriented. These faults extend over a very wide area and as a result of this, fault pattern, such as length, density, spacing, dip, height and shape can change considerably, both vertically and laterally. Fault population statistics measured here, are based on a sub-volume and key horizons, mapped within the volume. The faults form the main background fabric across the area. Similar faults are well documented in the North Sea and are interpreted as polygonal faults, based on their plan view geometries (Cartwright 1994; Cartwright & Lonergan 1996; Lonergan et al., 1998). These types of faults are often recognised in tiers. It is unclear, as to the number of tiers present in the study area, but we suggest, at least, two stratigraphic tiers (Fig. 4.6). The lower tier or tier 1 contains Paleocene to Lower Cretaceous sediments, bounded above and below by the top Paleocene (Fig. 4.6e) and lower Cretaceous horizons (Fig. 4.6a), respectively. The upper tier or tier 2 contains Lower Miocene to Eocene intervals, bounded above and below by the mid-Miocene (Fig. 4.6h) and top Paleocene horizons (Fig. 4.6e). We based our distinction on change, observed in dominant fault orientation between both levels. Lower or tier 1 is dominantly WNW (Figs.4.6 b-e) and upper or tier 2 is dominantly NNE and WNW (Fig. 4.6f-h). We also observe systematic increase in fault density with depth, for each identified tier, e.g. horizon maps of figures 4.6e-b for tier 1 show denser faults (smaller cell size) at the lower edge or lower tip of the tier (Fig. 4.6b). A second trend is also observed from figures 4.6h-f.

According to Cartwright (2011), the edges of polygonal faults or termination of a tier, occur, where it thins below seismic resolution or where a pronounced change in bulk facies is observed within the tier. Lonergan & Cartwright (1999) and a recent study by Jackson et al., (2014) also suggested that a change in fault density and pattern, could indicate presence of sandstone unit. We observe this pronounced change at the base of the upper tier, which is, likely due to presence of sandstone lithology, based on the high-amplitude, concordant anomaly within the Eocene unit (CSS2) or change from smectitic-rich, Eocene mudstones to less smectite-rich, hemipelagic, Paleocene mudstones (Fig. 4.6a) (Rundberg 1991; Thyberg et al., 2000; Marcussen et al., 2009).

Alternatively, variation of fault pattern and spacing on each mapped horizon could be indicative of multiple tiers (more than two) that are stratigraphically bounded by key horizons with individual tier, propagating and overlapping the adjacent tier (Cartwright & Lonergan 1996; Lonergan et al., 1999).
Fig. 4.6 (a) Seismic cross section through polygonal faults with interpreted horizons and (b-h) horizon maps from variance volume and ant tracking; b-e: tier 1 or lower tier and f-h: tier 2 or upper tier and i: fault traces for all the faults. Rose diagrams for fault strike and seismic line location are shown on individual map.
Ranges of the measured dip angles are 31° – 43° and 35° – 58°, with average values of 36° and 46° for tier 1 and 2, respectively. Fault dip reduces with depth from tier 2 to tier 1 (Graph 4.1). Values are comparable to published examples from other parts of the North Sea and Faroe-Shetland Basin (Tab. 4.2) (Chapter 5).

**Table 4.2** Comparison of polygonal fault dip angles in the Northern North Sea, Nigeria Transform Margin and other published examples. Based on true dips, no exaggerations

<table>
<thead>
<tr>
<th>BASIN EXAMPLE</th>
<th>FAULT</th>
<th>RANGE/AV FAULT</th>
<th>AUTHORS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Central North Sea</td>
<td>NA</td>
<td>30 – 70 (45)</td>
<td>Cartwright &amp; Lonergan 1996</td>
</tr>
<tr>
<td>Central North Sea</td>
<td>8 – 100</td>
<td>27 – 67 (45)</td>
<td>Lonergan et al., 1998</td>
</tr>
<tr>
<td>Faroe-Shetland Basin</td>
<td>NA</td>
<td>55 – 85 (58 +/ -2)</td>
<td>Shoulders et al., 2007</td>
</tr>
<tr>
<td>Faroe-Shetland Basin</td>
<td>NA</td>
<td>Type 2a – 63 Type 3 - 68</td>
<td>Bureau et al., 2013</td>
</tr>
<tr>
<td>More Basin</td>
<td>Few m – 80</td>
<td>25 – 40</td>
<td>Stuevold et al., 2003</td>
</tr>
<tr>
<td>Nigeria Transform Margin</td>
<td>3 - 11</td>
<td>41 – 50 (46)</td>
<td>Olobayo et al., 2015</td>
</tr>
<tr>
<td>Northern North Sea (This study)</td>
<td>8 – 35</td>
<td>Tier 2 - 35–58 (46)</td>
<td>Olobayo et al., 2015</td>
</tr>
</tbody>
</table>

### 4.4.2 Temporal and spatial distribution of clastic intrusion styles

Discordant reflections emanating from steep-sided mounds and other style of anomalies may be either high, or low amplitude, positive or negative reflection (Huuse et al., 2004; 2007). The seismic response is dependent on a number of factors, such as porosity, cementation, pore fluid, sandstone thickness, continuity, acoustic properties of both the sand and the encasing mudstones, geometrical complexity, seismic wave propagation and energy attenuation (Huuse et al., 2004; 2007).

The main spectrum of sand injectites identified in the study area are wings attached to in-situ depositional sand bodies, concordant intrusions, such as sills (Lonergan et al., 2000; Huuse et al., 2004; Jackson 2007; Jackson & Somme 2011) or conical or saucer-shaped intrusions,
which are believed to have been sourced from underlying, or near-by parent sand bodies (Huuse & Mickelson 2004; Shoulders & Cartwright 2004; Shoulders et al., 2007; Rodriguez et al., 2009; Szarawarska et al., 2010).

In this section, anomalies are discussed based on the CSS unit they are located in and not the actual time of emplacement or movement.

For each CSS unit, anomalies are discussed, based on their geometries, dimensions, spatial distribution, and relationship with background stratigraphy, timing of emplacement and potential parent bodies using individual case studies from the area. Anomalies have only been observed in CSS0 – CSS2, CSS4, CSS6 and CSS7, but not observed in CSS3, CSS5, and CSS8 – CSS9, therefore not included in the next section (the units are described in Chapter 3).

Table 4.3 Summary of geometric characteristics of intrusions, measured in the area. Cretaceous measurements from Jackson et al. (2010)

<table>
<thead>
<tr>
<th>CSS UNIT</th>
<th>UNIT AGE</th>
<th>DIP ANGLE (degrees)</th>
<th>HEIGHT (metres)</th>
<th>UPPER WIDTH (metres)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>MIN</td>
<td>MAX</td>
<td>MEAN</td>
</tr>
<tr>
<td>CSS0</td>
<td>Cretaceous</td>
<td>1</td>
<td>20</td>
<td>7</td>
</tr>
<tr>
<td>CSS1</td>
<td>Paleocene</td>
<td>17</td>
<td>32</td>
<td>25</td>
</tr>
<tr>
<td>CSS2</td>
<td>Eocene</td>
<td>14</td>
<td>38</td>
<td>25</td>
</tr>
<tr>
<td>CSS4</td>
<td>Oligocene</td>
<td>12</td>
<td>35</td>
<td>20</td>
</tr>
</tbody>
</table>

4.4.2.1 CSS0 (Cretaceous)

Distribution, geometries, and relationship with background strata

CSS0 is composed of Cretaceous sediments, bounded above and below by the Base Tertiary surface (H1) and Base Cretaceous unconformity (H0), respectively (Figs. 4.3a & 4.5). CSS0 is extensively deformed by small-offset faults, visible in cross section and characterized by polygonal geometry in plain view (Fig. 4.6). They are randomly oriented, and are sometimes associated with discordant anomalies, as described in other parts of the North Sea basin (Lonergan & Cartwright 1999; Lonergan et al., 2002).
Fig. 4.7 Mapped intrusions overlain with TWT thickness maps (ms) of individual sequences (a) CSS6 – Miocene-Pliocene (b) CSS4 - Oligocene (c) CSS2 - Eocene (d) CSS1 - Paleocene (e) CSS0 – Cretaceous (f) injectite distribution overlay for all sequences. Note regions, where two or more levels overlie, they are possible regions of interconnectivity between injectites. Injectites do not occur within the basin centre alone, but also along the margins.
A time-structure map of CSS0 highlights the NE-SW trend of the North Viking Graben. Sediment thickness in the unit reaches up to 4000 ms TWT (5200 m), within the Sogn Graben and reduces considerably above underlying structural highs (< 500 ms; 650 m). The unit is sometimes absent above fault blocks in the Troll area (Figs. 4.5 & 4.7e). Maximum amplitude extraction between the top Turonian and top Cenomanian horizons reveal distribution and planform geometry of depositional features within the CSS0 (Fig. 4.8a).

The attribute map images an oval-shaped body, extending ~ 15 km in length and represented as a region of maximum amplitude on the map (Fig. 4.8a). Jackson (2007) and Jackson et al., (2010) interpreted the oval-shaped body as a submarine slope fan, sourced from the Maløy Slope during the Late Cretaceous. On the western part of the slope fan are four small, channelized features, extending towards the basin centre (Fig. 4.8a). The slope fan and smaller channelized features are likely to belong to the same depositional system.

Random seismic profiles along the depositional features reveal high-amplitude, bedding concordant anomalies, labelled ‘c’, emplaced within low-amplitude background stratigraphy in Turonian interval of CSS0 (Figs. 4.8 d – h). Strata terminations, such as erosional truncations, are observed below them.

A series of high-amplitude, discordant anomalies, labelled ‘d’, inform of wings on the seismic profiles, are identified coming upwards from the sides of ‘c’ (Figs. 4.8d – h). The discordant parts crosscut some 7 - 90 ms TWT of the host stratigraphy and average measured dip angle is 7º. Although jack-ups are rarely preserved above anomalies, thinning of overburden was observed in the northern anomaly (Fig. 4.8f). These anomalies are restricted to the north-eastern part of the area, the Maløy slope (Figs. 4.7e, 4.9e & 4.10a).

**Well Calibration**

The CSS0 unit is mudstone dominated. Gamma ray log recorded presence of sandstone lithology from wells 35/7-3 and 35/9-3/4T2. The wells penetrated the downslope edge of the fan (Jackson et al., 2008). Core analysis of well 35/7-3 revealed characteristics of a turbidite deposit within the sandstone unit. Only one well, 35/6-2S penetrated the wing of one of the anomalies in CSS0 and corresponds to thick sandstone unit. This sandstone unit is manifested on seismic as high-amplitude, strata concordant sill (Fig. 4.8f) (Jackson & Somme 2011).
Fig. 4.8 (a) Maximum amplitude between Top Turonian and Top Cenomanian horizons to image channels and upper Cretaceous fan (b & c) TWT structure and maximum amplitude map of zoomed area in (a), showing polygonal nature of the faults; (d) uninterpreted and interpreted section to show the 3D geometry of one of the anomalies (e) uninterpreted and interpreted strike line through the remobilized channels above paleo canyons. Note discordant wings of the channels (f-h) dip lines, along remobilized channels. Annotations c and d in all figures represent the concordant and discordant parts of the intrusions.
Origin of anomalies

Based on observations, such as presence of erosional incision and truncations, continuous and channel-like geometry, sandstone lithology, turbiditic characteristics, lack of circular-shaped geometry in plan view, we interpret these anomalies as depositional channel systems that were subsequently modified by post-depositional processes, resulting in their present geometries (Jackson & Somme 2011). Figure 4.8f shows a very subtle folding and thinning of the overburden above remobilized channel bodies. This could be associated with jack-up, created during the remobilization or generated by differential compaction above the depositional channel system (Dmitrieva et al., 2012). Folding is not always observed and no onlaps have been identified above it. This could either be they have not been preserved, due to erosion, or interference from polygonal faults do not occur (Fig. 4.8).

Potential sand source

Intrusion usually have its parent body either physically attached to it at the same stratigraphic level, or completely separated from it and located at a much greater depth. In the CSS0, the concordant parts (c) represent the base and main part of the depositional channel system. The discordant margins (d), attached to, it represent the wings created by the remobilization process (Figs. 8f – h, 4.9a, d). Based on this, we interpret anomalies within CSS0 as remobilized channels which constitute an insitu depositional parent body and remobilized wings. Hence they are not completely injected, as in other examples from the North Sea or Faroe-Shetland Basin (Shoulders et al., 2007; Szarawarska et al., 2010). This distinction has been discussed by previous workers (Huuse et al., 2009; Szarawarska et al., 2010; Jackson et al., 2011; Andresen & Clausen 2014). A large slope fan was also mapped.

Timing of emplacement

Timing of emplacement for these Late Cretaceous-emplaced intrusions was inferred by dating the age of the common stratigraphic horizon, which the upper tips of the intrusions terminate against (Molyneux et al., 2002; Huuse & Mickelson 2004; Cartwright et al., 2008). This approach has been used by the above-mentioned workers, to date time of emplacement of sandstone intrusions in the North Sea and Faroe-Shetland basin. Based on this and with the absence of any more evidence, we infer remobilization took place before the end of the Turonian time, as upper tips of intrusions terminate close to the Top Turonian horizon, which could have represented the seabed during remobilization (Fig. 4.8e).
Fig. 4.9 Outline of intrusions in the study area above a variance map of the base Cretaceous unconformity, to show the relationship between the intrusions and underlying structural elements. Each phase is represented by a colour, as shown in the legend. Note that intrusions occur above structural highs, along crest of highs, above fault planes, as well as with the lows. Red lines represent underlying fields and discoveries. Distribution of intrusions appears to follow dominant NNE-SSW orientation of the underlying Mesozoic faults. Paleocene graben has a different WNW-ESE trend. Also note the stratigraphic overlap between intrusion complexes.
4.4.2.2 **CSS 1**

*Distribution, geometries, and relationship with background strata*

CSS1 is bound above and below by the Top Balder (H2) and Base Tertiary surfaces (H1), respectively (Figs. 4.3 & 4.5). It encompasses Paleocene and earliest Eocene strata. The unit is also deformed by series of polygonal faults (Fig. 4.6). The faults also have a dominant WNW orientation. Although similar in orientation to underlying polygonal faults in CSS0, the faults have a preferential strike to the west (Figs. 4.6 e & f). This variation in pattern is clearly imaged on time slice and horizon maps. Locally, the polygonal faults exhibit a more linear and elongate geometry. This bias in fault geometry reflects the WNW-ESE orientation of the Paleocene graben (Chapter 3).

Main depocentres within CSS1 are located along the basin margins. The depocentres are adjacent to the Norwegian landmass on the eastern part and the Shetland landmass on the western side with thicknesses, reaching up to 900 and 500 ms (990/550 metres), respectively (Fig. 4.7d).

High-amplitude anomalies are observed within CSS1 (Figs. 4.4, 4.10 & 4.11). They are restricted to the northeastern part of the study area and form a NE-SW trend, similar to orientation of the underlying structural highs and faults (Figs. 4.5 & 4.9). Spatial relationship suggests that these faults may have influenced distribution of the anomalies. The distribution of the anomalies does not closely match the eastern depocentre, rather they extend away from the depocentre towards the basin centre (Fig. 4.7d).

Two main styles of anomalies, observed within the CSS1 unit, include: high-amplitude, V or U-shaped, discordant anomalies and mound-shaped anomalies (Figs. 4.11 – 4.12). The first style of anomalies, identified in this interval, is characterized by highly discordant reflections, with individual flank dips, ranging between 17° and 32° (Tab. 4.2). They are typically V or U-shaped in seismic cross-sections and crosscut about 90 to 210 metres of background strata. Upper width measurements of these anomalies range between 440 and 1290 m. In 3D, they exhibit conical and saucer-shape geometry and make up ~ 99% of the total anomalies within the unit. The anomalies are found within Paleocene mudstones, belonging to the Lista Formation. The reflections that make up the mudstones are offset by polygonal faults and thickness increases towards the eastern part of the basin (Fig. 4.5). The majority of the amplitude anomalies have a common datum, which is often folded or jacked up locally, where anomalies are observed (Fig. 4.11a-d). TWT structure map of the common datum (top host horizon) reveal the distribution of the anomalies and their plan view geometry, which is mostly circular or isolated in nature (Fig. 4.12e). Onlap of overlying reflections are observed, where the horizon is folded or jacked up above anomalies.
Fig. 4.10 a-e Simplified sand distribution maps re-drawn from previous and present study, showing depositional (yellow outlines) and post-depositional sandstone (red outlines) facies. Main sediment sources are the Shetlands and western Norway.
Fig. 4.10f Overlay of depositional sandstone units (based on units they were mapped) with post-depositional sandstones (based on proposed timing of emplacement). Intrusions are likely to be sourced from sand bodies below them or at the same stratigraphic level. Depositional outline for CSS6/7 units not included on map.
The second style of anomaly observed within CSS1 has mound-shape geometry in cross section and is located above a high-amplitude, concordant, hard reflection, followed by a soft event (Fig. 4.12). The reflection is extensive across the area, but is only characterized as a high-amplitude event locally, around the Troll field. Only one mound is observed within the unit and has it has a diameter of up to 2 km. Two-way-time thickness between the top and base of the mound reveals the thickness ~ 50 ms TWT (Fig. 4.12d).

A single onlap was identified directly above the mound and overlying lying reflections are parallel and continuous (Fig. 4.12a). Polygonal faults are pervasive with the CSS1 and observed around the mound, but terminate right above it (Fig. 4.11a). Series of high-amplitude, discordant anomalies are mapped below the mound (Fig. 4.11c). The anomalies are characterized by V-shape reflections, with tapering apexes about 100 ms above the Base Tertiary surface. Below these high-amplitude, discordant anomalies is a high-amplitude, concordant reflection directly above the base Tertiary surface.

**Well Calibration**

The CSS1 unit is dominated by mudstone lithology, often represented by uniform and low-amplitude reflections in seismic. The mudstones belong to the Lista Formation and form the host unit for the anomalies. Tens of metres of sandstones were penetrated by wells in blocks 35/11 and 35/12, in the Fram Field area (Fig. 4.11d, 4.13 & Appendix 4.1). Sandstone thickness changes rapidly across the area. Previous studies have interpreted these sandstones as channels, formed from gravity processes along the margin and subjected to subsequent remodification by post-depositional processes (Dmitrieva et al., 2011).

Short cores were available from wells 35/11-3S and 31/2-19S (Fig. 4.13b & d). In well 35/11-3S, a 9m core shows massive, structureless and clean sandstone, belonging to the Sotra sandstone member. Presence of host fragments of the Lista mudstone, inform of round/angular clasts, are observed within the massive unit. No visible sedimentary features were identified. The core was taken from the base of a 95 m thick sandstone unit and calibrates to a thick sandstone unit, represented by low gamma ray on the wireline log (Fig. 4.13a). Thin or ratty sandstone units (< 5 m) are observed above the massive sandstone body. The massive unit is suggested to be part of the depositional parent sand body that was subsequently modified by the process of sandstone remobilization, which resulted into its clean, structureless nature, devoid of primary sedimentary structures (Hurst et al., 2011). A second core from well 31/2-19S shows discordant sandstones within host mudstone unit (Fig. 4.13b). The discordant sandstone in the core calibrates to thin or ratty sands above massive sandstone unit in wireline logs (Fig. 4.13c). No core is available from the underlying
Fig. 4.11 (a-e) interpreted and uninterpreted seismic sections showing high amplitude, discordant anomalies within CSS1. Note presence of jack up of the top host horizon above anomalies and onlap of overlying reflections onto jack up. Anomalies correspond to thick sandstone units in log. (e) TWT map of top host horizon showing plan view geometry of anomalies (f) TWT thickness between top host horizon and base Tertiary surface.
Fig. 4.11g Schematic diagram illustrating sandstone deposition from Norway and subsequent remobilization, injection and extrusion of the sands
massive unit in well 31/2-19S. Presence of thin or ratty sands with discordant contacts above massive sand body was diagnostic for interpreting injected sands in the well 16/26-15, from the Alba field in the North Sea (Duranti et al., 2002). All sandstone units are water-wet.

The high-amplitude, hard/soft event beneath the mound was a secondary target by well 31/3-4 (Kuro prospect, Tullow Oil). Post drilling confirmed presence of ~50 metres of reservoir quality sandstone within fine-grained Lista Fm mudstones. The hard/soft event represents the cemented part of the sandstone unit (In-house discussion) (Fig. 4.12c). Due to lack of well penetration through the mound, the lithology cannot be directly constrained. The ‘dim’ reflection in seismic cross section and its location above the cemented sandstone unit suggests similar lithology (Fig. 4.12a).

**Origin of anomalies**

Interpretation of the origin of high-amplitude, discordant and concordant anomalies in the CSS1 of the Northern North Sea is based on the amplitude response, conical and saucer-shaped geometries in cross section and 3D, emplacement within low-permeable mudstone succession, isolated occurrence, sandstone lithology, change in sand thickness between closely-spaced wells, presence of forced folding and onlaps (Fig. 4.11). Based on the above-mentioned observations, they are interpreted as remobilized and injected sandstone intrusions. Although in cross sections, they may resemble channels, the lack of continuity of individual sand body does not support a completely channelized origin (Fig. 4.11e & f).

For the second style of anomaly, observed within CSS2 (Fig. 4.12), we considered several geological processes may form mound-shaped features in sedimentary basins. Some of these include: (i) mud volcanoes or diapirs (Deville et al., 2010; Huuse et al., 2010), but the likelihood of a sandstone lithology rules out a mud volcano origin, (ii) carbonate reef/bryozoan mound (Heggeland 1998; Sharples et al., 2014), we have no evidence of carbonates in the area, as the Tertiary North Sea was dominated by siliciclastic sediments and formation of a carbonate mound or reef is unlikely, (iii) volcanogenic mound (Magee et al., 2013), no record of volcanic eruption or activity in the area at this time (iv) depositional or erosional feature. We discard a depositional or erosional origin based on the following: (1) presence of external onlap on the mound (2) no evidence of erosion below the mound as observed below the Sele mound (Fig. 4.14e), base is flat instead (3) presence of underlying discordant amplitude anomalies similar to conical intrusions. Based on these observations, we suggest the mound is a possible extrudite emplaced on a paleo-seabed represented as the high-amplitude, fairly continuous event (cemented Kuro reservoir interval).
Fig. 4.12. Mound (a) uninterpreted and interpreted seismic sections of mound (b) seismic sections to show underlying possible feeders (c) sand extrudite from the Norwegian-Danish basin (d) TWT (ms) of mound (e) Sele mound

(a) Possible extrudite (study area)
- Onlap onto mound
- Lacks erosive base
- Base of mound is flat
- Presence of underlying feeders

(e) Depositional/Erosional origin
- No onlap
- Erosive at the base
- No underlying injectites
Fig. 4.13 Wireline logs and core photos from CSS1 (a) 35/11/3S shows thick sandstone with thin sands above it (b) Core photo from thick unit (c) Well 31/2-19S shows presence of thin or ratty sands above a massive sandstone (d) Core photos from thin sand interval reveals discordance nature of the sands within the mudstone host rock. Both logs show that the sands are water wet.
A similar mound in size and shape have been described on the mid-Miocene unconformity above the Siri Canyon, in the Norwegian-Danish basin (Fig. 4.12c) and interpreted as sand extrudite above the Siri play fairway (Fig. 4.12c) (Andresen et al., 2009).

**Potential sand source**

Constraining the actual parent body or sand source for intrusions is very challenging without petrophysical and/or geochemical analysis, such as heavy mineral analysis on the intrusions and the potential parent bodies (Morton et al., 2014). Therefore, determing the potential source sand for intrusions within this level and other levels in the study area was based on proximity to depositional sandstone units.

A series of large, sand-rich, deep-water channels and fans were deposited from the Norwegian mainland in the basin in the Early Tertiary during uplifts along the basin margins (Figs. 4.5 & 4.11g) (Ahmadi et al., 2003; Brunstadt et al., 2009; Dmitrieva et al., 2012). Well data confirms the presence of 10 to up to 100 m thick units of sandstones within the interval (Appendix 4.1). Parts of these sandstones are likely to have undergone intense remobilization and injection, leading to modification to their original depositional geometries. In most cases, the V-shaped or conical intrusions are likely to represent injected bodies and the U-shaped or saucer-shaped intrusions are the in situ remobilized sandstones, such that the basal concordant part/sill represents the original depositional sand body (Andresen & Clausen 2014). Majority of the intrusions within this interval are U-shape in geometry, suggesting an in-situ remobilization of an originally depositional sand body (Lonergan et al., 2000). TWT thickness of the interval, affected by remobilization, reveals the geometry and distribution of sandstone within the unit. Thickness increases towards the source area on eastern part (Norwegian mainland), (Fig. 4.11f)

Presence of an extrudite above the cemented sandstone horizon (cemented Kuro sandstone interval) suggests that fluid and/or sand was transported through the sandstone horizon. Such a scenario can be observed in the sandstone intrusion complex in Panoche - Tumey hills, where depositional sands, with well-preserved and pristine primary depositional features, show evidence of partial or local remobilization, when intersected by a dyke. Core or well logs through the non-affected area will not show any evidence of remobilization. Directly on the Base Tertiary horizon, a high-amplitude, concordant anomaly is imaged on the seismic data (Fig. 4.12a). This feature is located below potential feeders for the possible extrudite. Lack of well penetration through the interval makes it impossible to determine lithology of this reflection. This could be an isolated sand body within the Lista Formation mudstones and possible parent body for the extrudite. However, this cannot be confirmed without well penetration through the unit.

An alternative source in the underlying Cretaceous for the Paleocene-emplaced remobilized and injected sandstones was also considered. Wild & Briedis (2010) proposed the Balder mounds were sourced by a much deeper parent body (pre-Cretaceous) above the Utsira high, through upward migration of fluid. Andresen et al. (2009) also suggested a deeper source from the Siri play fairway.
(Paleocene in age), as the parent body for the sand extrudite, interpreted on the mid-Miocene unconformity (Fig. 4.12c). However, Cretaceous sandstone is not very extensive and restricted to the northern part of the area and none of the wells in this area encountered Cretaceous sandstone (Fig. 4.10f).

**Timing of emplacement**

One of the methods for dating timing of intrusion is presence of an extrudite as the surface which the extrudite is emplaced on would have been the paleo-seabed at the timing of intrusion and extrusion (Huuse *et al.*, 2004; Hurst *et al.*, 2006; Andresen *et al.*, 2009). The mound, now interpreted as a possible sand extrudite in CSS1 provides clue to timing of emplacement of the intrusions within this unit. The underlying hard/soft reflections that form the cemented Kuro sandstone interval would have represented the paleo-seabed at the time of emplacement. The cemented interval is within the Top Balder and Top Lista Formations (Fig. 4.12). The Top Balder Formation is Early Eocene in age and the Lista Formation is mid to Late Paleocene in age, in this part of the basin, based on well data (Ahmadi *et al.*, 2003; Brunstadt *et al.*, 2009). We do not know the actual age of the sediment that forms the onlap onto the mound in CSS1; but its location below the Top Lista Formation suggests a mid-Paleocene age. Similar feature was mapped on the mid-Miocene unconformity above the Siri play fairway and interpreted as a sand extrudite emplaced during the mid to Late Miocene (Andresen *et al.*, 2009). Presence of sand volcano (extrudite) above a sandstone horizon was also observed in outcrop at the Bridge of Ross (Pringles *et al.*, 2007).

A strong relationship is observed between discordant anomalies and forced folding or jack up of the overburden (Figs 4.11a-d). Majority of the anomalies terminate at the top host horizon and the horizon is onlapped by younger sediments. It is likely that this horizon represented the seabed at the time of emplacement (Shoulders *et al.*, 2007). Well data confirms that the top host horizon is located within the Lista Formation, which is mid-Late Paleocene in age. Shoulders *et al.*, (2007) suggested that by dating the sediments that onlap onto the horizon, it is possible to constraint the timing of intrusion. Using similar approach, it is likely the intrusions were formed in between the mid and Late Paleocene. This corresponds to the timing interpreted based on the extrudite. Therefore we propose a mid-Paleocene time for intrusions and extrusion emplacements at this interval in the Northern North Sea (Huuse *et al.*, 2007; Andresen *et al.*, 2009; Cartwright 2010).
4.4.2.3  **CSS2 (Eocene)**

*Distribution, geometries and relationship with background strata*

The CSS2 is bounded above and below by the Eocene - Oligocene unconformity (H3) and Top Balder surface (H2) (Figs. 4.3a & 4.5). Seismic cross section and horizon map on the top bounding surface reveals presence of polygonal fault networks (Figs. 4.6). Fault pattern has polygonal shape in plan view, unlike those in CSS1 (Figs. 4.6d). This suggests that whatever influenced the stress change during Paleocene had stopped or became inactive during the Eocene (Paleogene graben). Main depocentres in the CSS2 occur along the margins, with thickness reaching up to 450 ms (490 m) (Figs. 4.7c).

The most striking features, observed in seismic data within this unit, are high-amplitude, crosscutting anomalies. They are usually V, U, W-shaped in cross section with well-defined 3D geometries and oval-shaped in plan view (Figs. 4.14). Although, they can also form very complex geometries outside the common ones, mentioned above, thus making detailed mapping difficult. They crosscut ~ 120 – 215 m of the Eocene strata with their apexes either directly above the Top Balder surface, or about 100 m above it (Figs. 4.14a & b; Fig. 4.15).

Average measured dip angle is about 25°, similar to those described in Eocene section in other parts of the North Sea (Tab. 4.2). Amplitude extraction above the Top Balder reveals patches of high-amplitudes representing the distribution of anomalies (Fig. 14g). They are concentrated in the western part of the study area within quadrants 30 and 34 (Fig. 4.7c). 3D image of the conical anomalies above the Top Balder surface shows relationship with underlying structural highs associated with Mesozoic hydrocarbon fields, such as the Gullfaks, Snorre and Visund Fields (Figs. 4.14e & f). This observation is consistent with previous work, done in the Tampen Spur area (Huuse & Mickelson 2004). Upward bending of the Top Balder surface and slight distortion of the seismic data is observed below individual intrusions (Fig. 4.15a & b). Upward bending of reflections is usually formed from presence of a formation with much higher velocity than surrounding lithology, thereby creating pull-up in the stratigraphy below the higher velocity lithology. In some cases, distortion extends as far as the reflections within the Cretaceous interval and could suggest evidence of upward migration of fluid or sand (which would have to be unconsolidated) (Fig. 4.14b) (Løseth *et al.*, 2003; Hurst *et al.*, 2004; Andresen *et al.*, 2009; Monnier *et al.*, 2014.

In some cases, forced fold or jack up (20 – 30 m high) of the Eocene-Oligocene unconformity is observed directly above individual intrusions (Fig. 4.15).
Fig. 4.14 Eocene anomalies (a & b) strike and dip sections and well log calibration through high-amplitude, discordant anomalies around the Gullfaks area. Anomalies are interpreted as sand injectites with extreme brightness, due to cementation (c) well calibration of anomalies (d) Image of a single injectite with location of time-slices. Slices reveal its oval shape and how it decreases in diameter with depth (d) time-slice @ 1772 ms showing the near-circular to oval-shape anomalies.
Fig. 4.14 (continued) (e) RMS amplitude at 150 ms above the Top Balder surface. Anomalies are imaged as patches, (f) 3D image showing spatial distribution of Eocene injectites along the crest of the structural highs, (g) schematic diagram of possible parent bodies for Eocene injectites
**Well calibration**

Sandstones in the Eocene (CSS2) have not been deliberately targeted by exploration wells in the area; however few wells intersected the high-amplitude anomalies and confirmed presence of sandstone lithology. Wells 34/10-30 encountered 40 m and 50 m of sandstone units at ~ 1400 metres and 1600 m, respectively, within the Horda Formation mudstones. Well 34/10-2 encountered 4 sandstone packages with thickness ranging from 15 m to 30 m. The lowest sandstone packages encountered by these wells are calibrated to the discordant margins of the amplitude anomalies within CSS2 (Fig. 4.1c). Tops or bases of some of these sandstones are partially cemented causing a drastic increase on the resistivity log. Above the Snorre field in block 34/7, well calibrations to discordant anomalies also confirm presence of tens of metres of sands (Huuse & Mickelson 2004).

All sandstone units encountered are water wet, unlike Eocene interval in the Outer Moray Firth and South Viking Graben, where high-amplitude, conical or saucer-shaped anomalies calibrated to tens of metres of sandstones, are filled with hydrocarbons, such as the Alba, Chestnut, Volund Fields (Dixon *et al.*, 1995; Lonergan *et al.*, 2002; Hurst *et al.*, 2003, 2005; Huuse 2008; De Boer *et al.*, 2007). Wells 35/8-2 and 35/8-1 encountered thick sandstone packages within the Eocene interval, which created the depocentre along the eastern margin (Figs. 7c & 4.16). Individual gross thickness of each package is ~ 200 m and reduces towards the basin centre. Time structure map of each of the packages reveals two fan-shaped bodies on top of each other, which are interpreted as Eocene fans (fan A and fan B), deposited into the basin from the Norwegian mainland (Chapter 3). Figure 4.15c shows the thickness map between the top of the upper fan A and the base of the lower fan B. High-amplitude, discordant anomalies are also observed at the fringe of the fans, though not penetrated by any well (Figs. 4.7c & 4.16a). No core data is available for the CSS2 unit.

**Origin of anomalies**

Based on observations presented, such as V and U-shaped in cross section, conical 3D geometries, oval to circular shape in planform, discordant crosscutting nature, jack up of overburden, calibration to sandstone lithology encased within low-permeable mudstone successions and similarities with previously interpreted features in the North Sea; we interpret these anomalies as conical sandstone intrusions or sandstone injectites (Lonergan *et al.*, 2000; Huuse *et al.*, 2004; Monnier *et al.*, 2014).

In cross section, they sometimes resemble incised channels, but in plan view, they are characterized by distinct isolated and circular geometries making a channelized origin unlikely (Figs. 4.14 d & e). Similar features have been interpreted as seismic artefacts, created from effect of migration of point diffractions (Łøseth *et al.*, 2003). This origin is unlikely, as anomalies have similar size, terminate at similar stratigraphic level and are distributed in an organized fashion, along the crest of structural highs. An igneous origin was also considered, based on the high
amplitude response and similar geometries with igneous environment, both form dykes and sills; however, well penetration, where possible, confirms sandstone lithology.

**Potential source sand**

Large, sand-rich systems belonging to the Frigg Sandstone Member were also deposited into the basin during Eocene (Fig. 4.10c) (Jones et al., 2003). Presence of high-amplitude, discordant anomalies within the CSS2 unit, suggest that part of these sandstones may have undergone remobilization and injection into surrounding Horda Formation mudstones (Fig. 4.14).

The distribution of anomalies now interpreted as sandstone intrusions does not perfectly match that of the depositional sandstone distribution, some sandstone intrusions appear at distances up to 5 km laterally away from edges of the depositional systems (Fig. 4.10c). These isolated intrusions could have been sourced either from a deeper Paleocene parent body or through from the Eocene sandstone units by lateral transport of sand and fluid. Similar suggestions were made in the Faroe-Shetland Basin; the distribution of sandstone intrusions mapped did not closely match the distribution of the nearest depositional sand body (Shoulders et al., 2007; Bureau et al., 2013). The distribution maps in our study area shows presence of underlying Paleocene depositional sandstones that could have been remobilized or injected into the unit. This is feasible where intrusions are underlain by Paleocene depositional sandstones; however, in the basin centre, there are no mapped Paleocene sandstones below some of the intrusions (Figs. 4.10b, c & g). A deeper alternative from the Cretaceous was also investigated, but wells do not encounter sandstone units within the Cretaceous interval in this area, making a deeper Cretaceous source very unlikely. Presence of thin or isolated sand bodies not well imaged by seismic data may also be present within the interval or the whole volume of source sand was intruded in this part of the area; however it is unclear why part of the parent sand will be completely intruded and the others not. Heavy mineral analysis on the intrusions and potential parent bodies might provide additional clue on the source sand within the unit (Morton et al., 2014).

**Timing of emplacement**

Majority of sand injectites, studied in CSS2, occur at two levels; those that have apexes directly above Top Balder surface and those that have apexes ~ 100 m above the surface occur in two levels and terminate upwards at a common stratigraphic level (Fig. 4.14 & 4.15). It is however difficult to map the common datum, at which the injectites terminate, due to the chaos nature of the seismic in this area. Further north, above the Tampur Spur, Huuse & Mickelson (2004) suggested the Eocene-emplaced injectites terminated at the Middle Eocene unconformity suggesting formation of injectites was synchronous throughout the Northern North Sea. A major Eocene-Oligocene unconformity is mapable across and this surface is often mounded locally above...
injectites (Fig. 4.15). The unconformity represents transition from the Eocene to Oligocene period. The common datum, at which majority of the injectites terminate, occur about 100ms below the unconformity and the injectites terminate downwardly in the Lower Eocene (directly above or close to the Top Balder surface).

The common datum, at which the intrusions terminate, may have represented a paleo-seabed at the time of emplacement (Huuse et al., 2004). Recent experimental analysis revealed that the upper tips of sand injectites represent the free surface at the time of emplacement (Bureau et al., in press).

Based on these observations, injectites within CSS2 occurred during the mid-Late Eocene. No extrudites are observed within CSS2, as preservation could have been impossible, due to erosion or the sand never reached the paleo-seabed, to form them (Jolly & Lonergan 2002). Identification may have been hindered by seismic resolution.

4.4.2.4 CSS4 (Oligocene)

Distribution, geometries and relationship with background strata

The CSS4 unit is bounded below by Eocene-Oligocene unconformity (H3) and above by base Miocene surface (H6) in the basin centre and western part, but by MMU (details discussed in CSS6) in the northern and eastern part of the basin (Fig. 4.3 & 4.5). Main depocentre is along the western margin close to the Shetlands, where thickness reaches up to 1100 m (Fig. 4.7b). The unit encompasses the entire Oligocene succession and pervasively deformed by polygonal faults (Fig. 4.6). The upper interval of CSS4 onlaps onto the intra-Oligocene unconformity towards the eastern part (Fig. 4.5) (Martinsen et al., 1999; Jackson 2007). The intra-Oligocene unconformity is only present in the eastern part of the area and represents the top-bounding surface of CSS3, not discussed here (Chapter 3).

The most conspicuous features, observed within the CSS4 unit, are a series of high-amplitude, discordant anomalies that crosscut polygonally faulted mudstone succession (Figs. 4.16 -4.18). They form wide range of geometries from simple isolated conical and saucer-shape to very complex clusters of V or W shape (Fig. 4.18). The simple geometries have a paired parallel reflection, similar to anomalies in previous units. Average dip angle is 20° and height range is from 60 to 215 m (Tab. 4.2). The more complex geometries are often thicker, with well-defined top and base, separated by very transparent amplitude reflections (Fig. 4.18e - g). A pair of double reflection forms the top and base of the anomalies. The complex anomalies also tend to be wider, some of them extending up to 8 km and this could be attributed to amalgamation of individual conical-shaped ones, crosscutting one another (Fig. 4.18f).
Fig. 4.15 Discordant amplitude anomalies within CSS2 and relationship with background stratigraphy within CSS2. Forced folding or jack up is observed above anomalies. TBS-Top Balder surface, EOU-Eocene Oligocene unconformity, OACB-Opal A-CT boundary, BTS-Base Tertiary surface
Fig. 4.16 (a) Uninterpreted and interpreted seismic section and well calibration through Eocene fans. Note presence of amplitude anomalies at the fringe and above the fans. Well 35/8-2 penetrated an anomaly above Opal A-CT boundary (b), zoom to show well calibration. (c) TWT thickness map (ms) of the Eocene fans
Discordant margins of these anomalies sometimes follow polygonally fractured networks, when preferentially oriented, but also crosscut the faults (Fig. 4.16b & 4.18a). Spatial relationship exists between forced folding/jack up of the overlying MMU and location of discordant amplitude anomalies with the unit (Figs. 4.18b-h). Fold or jack is more pronounced above the complex anomalies than the simple conical-shaped ones (Figs. 4.18). Jack up height can be estimated by measuring the height of the fold above the anomalies from the regional location of the unconformity, which represents the top host horizon. Values range from < 5 ms to 100 ms.

Forced folds or jack ups, created above anomalies within CSS4, are more pronounced than those in CSS2 (Fig. 4.15). The MMU is onlapped and downlapped by overlaying sediments (Fig. 4.18). Depressions (PM) are also observed on the unconformity. In plan view they exhibit circular geometries and commonly occur above the margins of the amplitude anomalies (Fig. 4.18a & d). Discordant anomalies within the CSS4 are distributed within the basin centre (above the North Viking graben) and along the margins (Fig. 4.7b, 4.9 & 4.10d).

Some of the saucer-shaped anomalies encountered with CSS4 show a prominent uplift or jack up of the basal or concordant part ‘s’ (sill) (Fig. 4.19a). Jack up height, which is the thickness between the present location of the concordant part and the location before the jack up, is within the range of 30 to 90 m. Reflections are primarily low and chaotic locally below the jack up part (Fig. 4.19a). Figure 4.19b shows a 2 km long basal sill, flanked on both sides by discordant margins ‘w’, known as wings or dykes. In cross section, the margins crosscut some 100–150 ms (120-160 m) of the Oligocene unit and transforms into a bedding concordant unit/sill at the top of the wing, which extends ~ 50 m away from the margins. The sill corresponds to a boundary that separates underlying medium-amplitude, parallel and continuous reflections from an upper unit, characterized by low-amplitude, parallel and continuous reflections (green dotted horizon; Fig. 4.19b). The configuration is very similar to the Volund structure, with the conformable event coinciding with Early Eocene horizon (Top Frigg) and interpreted as an unconformity or a paleo-seabed (Fig. 4.19f) (Huuse et al., 2004).

A mound-shaped feature is observed ~ 50 ms above the saucer-shaped anomaly in seismic cross section. It is located directly on top of the MMU and ~ 2.5 km in diameter (Fig. 4.19). In plan view, it has a sub-circular to oval shape geometry and steep flank angle of >10° (Figs. 4.19c). Isochron map between the top and base of the mound shows thickness of about 80 ms TWT (Fig. 4.19d). The upper surface of the mound is defined by a high-amplitude, strong trough reflection, representing a downward increase in acoustic impedance between overlying sediments and reflections within the mound (Fig. 4.19a). It is bounded at the base by the mid-Miocene unconformity and onlapped by surrounding sediments. A small depression labelled ‘p’, characterized by a negative topography, is observed at the base of the mound on unconformity (Fig. 4.19b). Although embedded within upper CSS6 unit, mound emplacement is considered to be related to underlying saucer-shaped anomaly in CSS4 unit (Fig. 4.19).
Discordant anomalies, described in CSS4, primarily lie above a high-amplitude, crosscutting positive reflection. The reflection, which is characterized as a strong trough, is indicative of an increase in acoustic impedance on seismic data, created by a downward increase in density and sonic log, and is interpreted as Opal A – CT silica diagenetic boundary (Fig. 4.16 - 4.18) (Rundberg 1991; Thyberg et al., 1998; Olobayo et al., 2012; Wrona et al., in press). The boundary formed from conversion of sediment rich in amorphous, biogenic silica (Opal – A) to a more stable, crystalline silica Opal – CT through the process of dissolution and precipitation (Rundberg 1991). This conversion has been documented globally in siliceous mudstones within sedimentary basins (Fig.4.1) (Davies & Cartwright 2002; Ireland et al., 2011). Relationship between discordant anomalies and silica diagenetic boundary was first observed in the Faroe-Shetland basin, North Sakhalin, Santa Cruz (Davies et al., 2006, Thompson et al., 2007) (Fig. 4.1c).

Well calibration

Few amplitude anomalies within CSS4 were penetrated by exploration wells. Well 35/8-2 intersected the discordant wing of saucer-shaped anomaly and encountered 24 m thick sandstone encased in Horda Fm mudstones (Figs. 4.16b & 4.17b). Also in block 34/10, wells that penetrated high amplitude anomalies confirmed presence of thick sandstone units (Davies et al., 2006). Petrophysical log analysis revealed excellent reservoir properties in the sandstone with porosity as high as 32% and a net-to-gross of 80%. The sandstone is, however, brine filled (Fig. 4.17b). Saucer-shaped anomaly in figure 4.19 is not intersected by any well, making lithology of anomalies in the unit difficult to constrain, but based on similar seismic amplitude responses with underlying Eocene fan A and lithological calibration from similar features in the area, we infer that these anomalies are conical and saucer-shaped sandstone intrusions sandstone (Figs. 4.18 & 19).

It is not possible to determine the lithology of the mound, due to lack of well penetration. However, lithology is assumed to be sandstone based on the following observations: (i) top surface represented by an increase in acoustic impedance, (ii) location above the saucer-shaped anomaly interpreted as sandstone intrusion, (iii) gentle draping of overlying prograding sediments suggesting differential compaction, (iv) lack of any evidence of salt, carbonate or igneous materials in the area and (v) strong similarity in size and shape to the giant sand mound/sand extradite, described in the Norwegian-Danish Basin (Andresen et al., 2009).

Origin of anomalies

Based on observations discussed above, such as presence of conical, saucer-shaped and complex high-amplitude discordant anomalies, forced folding/jack up of the MMU above anomalies, onlap of overlying sediments, jack up of basal sills and calibration to sandstone lithology; we suggest these anomalies represent sandstone dykes and sills, formed as a result of remobilization and injection of the sands into low-amplitude, background mudstones (Huuse et al., 2004).
Fig. 4.17a 3D image showing a tripartite association, which includes parent body, injectites and extrudite from the study area. Image reveals the mounded morphology of the mid-Miocene unconformity. The MMU is intensely deformed, due to jack up, created by the underlying Oligocene-emplaced anomalies. Note relationship between Eocene fan and overlying intrusions with intrusions. Injectites are also present at the fringe of the fan. Injectites, emplaced within Oligocene interval above the fan, are likely to have been sourced from the fan.
Fig. 4.17b. Petrophysical analysis of well 35/8-2. Sandstone interval corresponds to discordant anomaly in figure 4.16. Analysis revealed excellent reservoir properties in the sandstone, with porosity as high as 32% and a net-to-gross of up to 80% (carried out in Tullow Oil, Oslo).
Several geological processes that could facilitate mound formation (as discussed under CSS1) were investigated. Depression below the mound and other depressions on the MMU, observed above other discordant anomalies in the CSS4 unit, exhibit circular geometry in plan view and are interpreted as pockmarks, formed from expulsion of fluids onto paleo seabed or present-day seabed (Fig. 4.18a, d & 4.19a, b) (Judd & Hovland 2007). We infer a possible genetic relationship between the saucer-shaped anomaly (now interpreted as sandstone intrusion), mound (sandstone extrudite) and depression (paleo-pockmark) (Fig. 4.19). Saucer-shaped intrusions are also well exposed in outcrops of Panoche Hills in San Joaquin Basin at similar scales with the ones observed in seismic (wings are up to 100 metres in height) (Fig. 4.19g)

**Potential source sand**

Very thick sandy units, belonging to Grid and Skade sandstone members, were deposited into the basin centre from uplifts, along the basin margins during the Oligocene (Fig. 4.10d & f) (Rundberg & Eidvin 2005). These sandstone units are difficult to map from seismic data alone, due to the chaotic nature of the seismic within the Oligocene interval (Fig. 3.4 & 3.8). Their presence is confirmed by thick sandstone units in well logs (Fig. 3.13) (Chapter 3). The unit is also presumed to have been greatly affected by process of remobilization and injection of sand, resulting in modification to original sandstone geometry (Lonergan et al., 2000).

Distribution of sand injectites and remobilized sands, mapped within CSS4 unit, partly coincide with extent of depositional sandstone systems in the area (Ahmadi et al., 2003; Rundberg & Eidvin 2005). It is reasonable to suggest that these depositional sandstone systems sourced the injectites and remobilized sands were emplaced within the unit. An additional parent body for these injectites would be younger sand bodies either from the Eocene, or Paleocene located below (Fig. 4.10f). Large volumes of underlying depositional sandstone systems are present and could have been injected into the Horda Formation mudstones. It is not possible, without heavy mineral analysis, to determine if it was a single source from Oligocene depositional systems or multiple sources including Paleocene and Eocene depositional systems.

**Timing of emplacement**

Extrudites are formed, when fluidized sand reaches to the seabed and forms a mound (Jolly & Lonergan 2002; Hurst et al., 2006; Pringle et al., 2007; Loseth et al., 2012). They are usually associated with underlying injectites, which are considered as feeder systems, as observed in the example presented (Figs. 4.12 & 4.19). Therefore location of the possible sand extrudite on the MMU suggests that the unconformity represented the seabed during formation (Figs. 4.18h & 9h). Presence of extrudite is very useful in constraining the time of emplacement of the underlying
Fig. 4.18 **a-g** Simple and complex geometries of anomalies, within polygonally faulted CSS4 unit, are interpreted as sand injectites. Note relationship between forced fold/jack up on MMU (top host horizon) and injectites. Onlap of overlying sediments onto the top host horizon. Injectites occur above the opal A to opal CT boundary (OACB). Note depressions on the MMU. PM-pockmark, Abbreviations as fig.15. Note presence of onlaps above MMU and (h) diagram to illustrate timing of emplacement.
sandstone injectites and overlying extrudite, as they are considered to belong to the same intrusion complex, hence the same episodic event (Hurst et al., 2006).

Dating the sediments that onlaps onto forced fold or jack up, created by underlying injectites, also provides estimate for time of emplacement (Shoulders & Cartwright 2004; Shoulders et al., 2007). The top host horizon (MMU) for the CSS4 injectites shows strong evidence of positive relief (forced fold/jack up), created by underlying injectites (Fig. 4.18). Overlying sediments onlap directly onto these forced folds. The top host horizon represents the mid-Miocene unconformity, during which significant erosion occurred across the whole of area and resulted in non-preservation of mid-Miocene sediments in the area (Chapter 3) (Ahmadi et al., 2003; Rundberg & Eidvin 2005). The unconformity, in the study area, is overlain by sediments of Late Miocene to Early Pliocene in age (Fig. 4.5). Based on this, sediments that onlap onto the top host horizon/MMU and extrudite are Late Miocene in age. We therefore propose mid to Late Miocene time for intrusions within the CSS4, based on similar approach used in the Faroe-Shetland basin (Figs. 4.18 & 4.19).
Fig. 4.19. Saucer-shaped intrusion and sand extrudite (a), seismic section through anomalies showing pronounced jack up of the basal sill above the Eocene fan. Note presence of mound on the MMU and sediment onlap on to it (b), zoom on the anomaly in 4.19a and representative diagram(c) 3D representation of the intrusion and overlying extrudite
4.4.2.5 CSS6 (Miocene)

**Distribution, geometries and relationship with background strata**

The CSS6 is bounded above and below by the base Pliocene unconformity (H8) and mid-Miocene unconformity (H7), respectively (Fig. 4.3 & 4.5). CSS5 unit is not discussed in this study. The main depocentres in the CSS4 are located in the north-eastern and south-western parts of the basin (Fig. 4.7a). Thickness and character of this unit is variable across the basin and very dependent on the morphology of the mid-Miocene unconformity (Fig. 4.5). The MMU, which is the top of the Hordaland group, represents a high-amplitude trough reflection, mapable across the North Sea. There has been debate about the formation of the unconformity; while some workers believed it was formed as a result of sub-aerial exposure and erosion (Martinsen et al., 1999), others proposed a sub-marine erosional formation (Rundberg & Eidvin 2005). Irrespective of the formation model, the unconformity represents a ~15 my time gap (Rundberg & Eidvin 2005; Eidvin & Rundberg 2007; Chapter 3). The morphology of the surface is either parallel to surrounding erosional reflections, or irregularly mounded, due to jack-up created by underlying high-amplitude, discordant anomalies (Fig 4.17 & 4.20). The upper tips of polygonal faults sometimes propagate into the CSS6 unit, but most often they terminate at MMU (Fig. 4.6a). No polygonal faults are observed from this unit and younger units in the study area.

Two different types of mounds are recognised within CSS6 in the study area: (i) those formed from forced folds above underlying high-amplitude, discordant anomalies – Class A and (ii) those formed due to present of sediments within the unit – Class B (Fig. 4.20). The example presented here is irregularly shaped, elongate mound complex, located in the eastern part of the area, within quadrant 35. This example shows distinctively the two classes of mounds in the CSS6. The mound complex presented here and similar ones have been previously studied in the area (Løseth et al., 2003; Jackson & Stoddart 2005; Løseth et al., 2013).

Class A mounds represent the forced folding or jack up created due to presence of high-amplitude, discordant anomalies within CSS4 (Fig. 4.20a-c). They have been mentioned previously in the previous section and create significant deformation on the MMU. The mound complex is ~ 5 km wide, 12 km long and up to 150 m high (Fig. 4.20).

Class B mounds represent those formed from thickness of the CSS4 unit, between the base Pliocene unconformity (H8) and MMU (Fig. 4.20 a,b & d). The CSS6, named as unit 3 in previous work (Olobayo et al., 2012) is variable across the area and severely affected by morphology of the MMU. The unit thins considerably across class A mounds and represented in cool colours from the TWT thickness map of the interval (Fig. 4.20c). In plan view, the thin units have circular to oval-shape geometry and are located in between the much thicker units (Fig. 4.12d). Class B mounds are usually thickest within depressions on the mid-Miocene unconformity.
Seismic and well log calibration showing mounded morphology of the MMU and its relationship with underlying high-amplitude discordant anomalies. Pronounced positive topography is observed (c & d) on TWT thickness map of the Utsira Formation (CSS6) and Opal A (CSS4) unit, respectively. Note how the CSS6 gets thinner, where there are anomalies in underlying unit and vice versa. Part of Utsira sand could have been extruded. (e) Variance attribute extracted on Opal A-CT surface.
At discrete locations where the mounds are thinnest, they coincide with thicker underlying CSS4 units and vice versa (Fig. 4.20). The entire CSS6 is often thick along the flanks of class A mounds and thins away from them, before eventually pinching out into surrounding strata (Fig. 4.20a). In areas that have no underlying anomalies, reflections within CSS6 are usually conformable with underlying CSS4 (Fig. 4.20a). Distribution map showing mounds occur both in the basin centre and along the basin margins (Figs. 4.10e & f).

**Well calibration**

Generally, the CSS6 unit in the study area encompasses the Utsira Formation, which is mainly dominated by thick sandstone units of the Utsira member (Figs. 4.3, 4.5 & 4.20a, b). Sandstone thickness varies considerably within the unit across the entire study area (Fig. 4.5) (Isaksen & Tonstad 1989). For example well 35/11-12 penetrated up to 100 metres of sandstones, but well 35/8-4 encountered only very thin sandstone beds (Fig. 4.20a).

No cores are available from these wells, but gamma ray logs reveal blocky log patterns. Well penetrations through the mound complex confirm the presence of thick sandstone, directly above the MMU and thickness varies across the mound. We estimated the volume of sandstone, within the mound complex presented here, as ~ 240 km² (Fig. 4.20).

### 4.4.2.6 CSS7 (Pliocene)

**Distribution, geometries and relationship with background strata**

CSS7 unit is bounded above and below by the base Pleistocene and base Pliocene surfaces, respectively (Figs. 4.3 & 4.5). The interval encompasses the Pliocene-aged, westwardly prograding clinoforms which downlaps onto underlying sediments of Early Pliocene or Late Miocene age (Fig. 4.5). Depocentre is greatest in the north-western part of the study area, where thickness reaches up to 1000 ms TWT (Chapter 3).

At approximately 50–80 ms above the mid-Miocene unconformity, a mound-shaped, amplitude anomaly is observed with the CSS7 unit (Fig. 4.21) (Huuse & Mickelson 2004; Løseth et al., 2012; 2013). The surface, bounding the top of the mound complex, is characterised by a high-amplitude, trough reflection, which locally is slightly mounded, while the lower bounding surface is relatively flat and conformable with surrounding reflections (Fig. 4.21a). Thickness between the two reflections represents the thickness of the mound complex. This thickness is variable across the mound complex and significantly controlled by underlying forced folding (class A mounds). We observe a relationship between the thin part of the mound and underlying high-amplitude, discordant anomalies. Mound complex thins considerably or completely absent above forced folds (class A mounds). Along the flanks of the forced fold (class A mound), created by underlying
anomalies, mound complex is thicker and gradually pinches out into surrounding mudstones (Fig 4.21a). Only one mound complex is recognised within CSS7 unit and restricted to quadrant 34 above the Snorre field.

Well calibration

Wells in block 34/7 and 34/4 penetrated thick sandstone units within the mounded unit. Sand thickness decreases gradually away from the centre. Well 34/7-4 encountered ~ 80 metres of sandstones and well 34/4-7, which is less than 2 kilometres away, penetrated only ~ 33 metres (Fig. 4.20a). Gamma ray logs show sands, which have blocky patterns and often two sand packages are separated by a thin mudstone bed.

Sidewall cores examined from the upper package in well 34/4-7 reveal fine-grained, rounded to sub-rounded sands (Fig.4. 21b) (Løseth et al., 2012). Sandstone units are very thin or completely absent above forced folds (Figs. 4.21a & b). Anomalies in Oligocene and deeper Eocene successions are also calibrated to thick sandstone units. They are interpreted as sand injectites encased within polygonally faulted mudstone successions (Huuse & Mickelson 2004).

Origin of anomalies

Similar origin is proposed for anomalies in CSS6 and 7. For the former, sands overlay the mid-Miocene unconformity and pinches out away from a centre (Fig. 4.20a & 4.21). Based on results from laboratory experiments, increase in pore pressure caused fluidized sands to be forcefully injected into the host rock. When sand and fluid mixture reached a free surface or seabed, pressure is reduced and fluidized sands flowed laterally away from the source point by gravity currents (Rodrigues et al., 2009; Ross et al., 2011).

On the other hand, the CSS7 example above Snorre field, sandstone units do not overlie the MMU directly, but are present within lower Pliocene sediments, before gradually pinching out into the mudstone dominated host strata (Fig. 4.21). Map of top sand revealed irregular mound topography in the Snorre area and were interpreted as sand extrudites (Huuse & Mickelson 2004; Løseth et al., 2012; 2013).

Potential source sand

The sand that form the extrudite complexes, in both examples discussed above, are likely to have been soured from deeper intervals. Previous workers in the Snorre area, revealed presence of injectites in the underlying Oligocene interval and we present similar interpretation for both examples in both case studies. We speculate that the injectites are connected to the overlying
extrudites supplying sands onto the paleo seabed. Large, sand-rich depositional systems, deposited from the Shetlands, were penetrated by wells within the Oligocene interval in the western part of the area (Fig. 10e & f) (Rundberg & Eidvin 2005). The sands could have undergone extensive remobilization and injection into surrounding and overlying intervals. We therefore propose that these Oligocene sands, as possible parent bodies of the sands, extruded onto the paleo-seafloor. Source from deeper part of the basin cannot be discarded.

**Timing of emplacement**

As discussed in previous sections, presence of an extrudite is useful in determining the timing of an intrusion complex, as the surface underlying the extrudite would have represented a paleo-seabed during emplacement. According to Løseth *et al.*, (2012), the extrudite complex above the Snorre field (example from CSS7) was extruded during the Pleistocene glacial period and stratigraphically emplaced within Pleistocene interval. We propose an earlier event (Pliocene), as the extrudite complex occurs within Pliocene interval and onlapped by Pliocene age sediments, rather than Pleistocene, as suggested (Fig. 4.21a).
Fig. 4.21a. Seismic section with well log calibrations above the Snorre field, showing sand distribution in the area. Sands within Pliocene mudstones are interpreted as extrudites (b), seismic section through the same wells above showing intrusive and extrusive sands by Løseth et al., 2013.
4.5 DISCUSSION

4.5.1 Possible interpretations of amplitude anomalies in the Northern North Sea

We presented in the previous section evidences of high-amplitude, discordant/concordant and mounded anomalies encased within low-amplitude background extending from Cretaceous to Pliocene intervals similar to those observed in adjacent parts of the North Sea and Faroe-Shetland Basins (Molyneux et al., 2002; Duranti et al., 2002; Hurst et al., 2003; Huuse et al., 2004; Shoulder et al., 2007; Murphy & Wood et al., 2011; Løseth et al., 2012, 2013). According to Huuse & Mickelson 2004, an interpretation of the origin of discordant anomalies must account for V, W or U-shaped in cross section, circular to oval geometry in plan view, conical geometry in 3D, emplaced within low-permeability host unit (usually mudstones), often high amplitude refection, create forced folding in the overburden and calibrate to sandstone in well bore (Figs. 4.1b & 4.4c).

Several geological processes in the subsurface can cause formation of conical or saucer-shaped high-amplitude, discordant anomalies, similar to those observed in the study area. Some of them include: igneous intrusions, incised valleys, fault planes, pockmarks, seismic artefacts and sand injectites. The origin of these anomalies is investigated based on the criteria presented in figure 4.1b and a summary of characteristics of the anomalies observed in the area is shown in table 4.4.

Channels or incised valleys - The conical V, U or W-shaped geometry in cross section is typical expression of channels or incised valleys; however, when observed in plan view, they are often circular to oval in shape and not representative of channels or incised valley systems (Fig. 4.14).

Igneous intrusions – Igneous intrusions often have high-amplitude reflection in seismic and form similar cross section, plan view and 3D geometry, as anomalies interpreted in the study area (Hansen et al; 2005; Shoulders & Cartwright 2004; Polteau et al., 2008). Very close relationship in mechanics and geometries between igneous intrusions and discordant anomalies have been invoked by these workers. However, there are no records of igneous rocks in the area and calibrations of anomalies to sandstones make an igneous origin unlikely (Figs. 4.14c & 4.16b).

Polygonal fault planes – This unique class of fault often occurs with discordant anomalies observed in the area (Huuse & Mickelson). They are characterized by polygonal-shape in plan view and sometimes crosscut stratigraphy in cross section. However, we reject a polygonal fault origin, as anomalies described in the area form conical or saucer-shaped geometries in cross section, which is unlikely for polygonal faults and also anomalies do not form polygonal geometries in plan view, instead they are characterized by circular or oval-shape (Fig. 4.14d).

Pockmarks – Pockmarks are fluid escape features and are generally formed within fine-grained sediments, like anomalies observed in the study area. Pockmarks form depressions in cross
sections and majority of them are characterised by circular to oval geometry in plan view (Judd & Hovland 2007). Similar features were interpreted as pockmarks in the Outer Moray Firth (Cole et al. 2000); however in this study, the thickness of anomalies, which corresponds to the sand thickness, is almost uniform throughout its entire body, unlike pockmarks, which increases towards the centre (Huuse & Mickelson 2004). Also uplift or jack up of overburden, which is usually observed above anomalies in the study area is not common to pockmarks, making a pockmark origin unlikely (Figs. 4.15 & 4.18) (Monnier et al., 2014).

**Seismic artefacts** – Similar V-shaped anomalies in seismic cross sections were originally interpreted as artefacts from diffraction (Løseth et al., 2003). However, seismic artefacts are unlikely to terminate at nearly same stratigraphic level as we observe here and anomalies in the Northern North Sea are too organised to be artefacts (Fig. 4.14) (Huuse & Mickelson 2004). Also calibration to sandstone lithology suggests anomalies, as related to sedimentary bodies, rather than artefacts. Pull-up effects are typically observed beneath the conical-shaped anomalies; this relationship often exists when velocity within the feature of interest is higher than surrounding sediments, suggesting a geological feature, rather than an artefact (Løseth et al., 2003; Andresen et al., 2009). Lithologies that create such features include salt, carbonate, sand and magmatic materials. We have no knowledge of salt or thick carbonates around the area that could have remobilized into the intervals in question. Though anomalies show evidence of carbonate cementation in boreholes, but not often is the entire lithologies composed of carbonate (Hurst et al., 2003; Huuse et al. 2004; Jonk et al., 2003. 2004).

**Lithology of amplitude anomalies and interpretation as remobilized and injected sand**

Wells do not penetrate all the amplitude anomalies interpreted from the area, therefore lithological interpretation will be based on anomalies intersected by boreholes. Lithologies of those anomalies not penetrated by wells were determined indirectly from seismic observations, similar seismic expressions and geometries with those penetrated by wells and other parts of the North Sea. However, this should be properly investigated, as several other geologic features have similar seismic expression and geometries.

Lithologies often associated with injections or give rise to high-amplitude anomaly in seismic include: salt, carbonate, tuff, chalk igneous rocks and sand (Løseth et al., 2003; Hudec & Jackson 2004; Hansen et al., 2005; Wild & Briedis 2010; Andresen & Clausen 2014). We have no knowledge of salt, carbonate, chalk and igneous materials in the area that could have created the anomalies observed. Tuffaceous mudstones exist within the Balder Formation, in the Late Paleocene to Early Eocene, however; we have no previous knowledge, where conical, discordant anomalies have been calibrated to tuff and this location of the tuffaceous mudstones does not explain the deeper anomalies (Huuse & Mickelson 2004). Salt and carbonate often create much higher acoustic impedance contrast with surrounding mudstones (Andresen & Clausen 2014).
### Tab. 4.4 Summary of geometrical characteristics of sandstone injectites observed in the Cenozoic Northern North Sea basin

<table>
<thead>
<tr>
<th>Interval</th>
<th>Acoustic Impedance</th>
<th>Dip Angle</th>
<th>Dimensions (m)</th>
<th>Cross section/3D Geometry</th>
<th>Plan View Geometry</th>
<th>Overburden</th>
<th>Lithology</th>
<th>Timing</th>
<th>Injected/Remobilized</th>
</tr>
</thead>
<tbody>
<tr>
<td>CSS0 (Upper Cretaceous)</td>
<td>High-amplitude</td>
<td>1-20 (7^\circ)</td>
<td>W: 150 - 1740 m; H: 7-90 m</td>
<td>Bedding concordant base and discordant margins</td>
<td>Channelized</td>
<td>Jack up, differential compaction</td>
<td>Sandstone confirmed from well</td>
<td>Upper cretaceous channels, extruded</td>
<td></td>
</tr>
<tr>
<td>CSS1 (Paleocene to Early Eocene)</td>
<td>High-amplitude, low-amplitude</td>
<td>17-32 (25^\circ)</td>
<td>W: 440-1290 m; H: 90-210 m</td>
<td>Same as CSS0, V-shaped geometries, mound</td>
<td>Isolated, oval-circular</td>
<td>Jack up, sediment onlaps</td>
<td>Sandstone confirmed from well</td>
<td>Middle Paleocene Channels, extruded</td>
<td></td>
</tr>
<tr>
<td>CSS2 (Early Eocene to Oligocene)</td>
<td>High-amplitude</td>
<td>14-37 (24^\circ)</td>
<td>W: 490-1830 m; H: 120-215m</td>
<td>V, U, W and W U and saucer-shaped geometries</td>
<td>Isolated, circular</td>
<td>Jack up, sediment onlaps</td>
<td>Sandstone confirmed from well</td>
<td>Mid-Late Eocene Injected, remobilized</td>
<td></td>
</tr>
<tr>
<td>CSS3</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>No intrusions observed</td>
<td></td>
<td></td>
</tr>
<tr>
<td>CSS4 (Oligocene to Miocene)</td>
<td>High-amplitude, low-amplitude</td>
<td>12-35 (20^\circ)</td>
<td>W: 500 - 1940 m; H: 90-215m</td>
<td>V, U, W, saucers, ziz-zag, complex geometries</td>
<td>Isolated, oval, circular, complex</td>
<td>Jack up, sediment onlaps</td>
<td>Sandstone confirmed from well</td>
<td>Mid-Late Miocene Injected, remobilized</td>
<td></td>
</tr>
<tr>
<td>CSS5</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>No intrusions observed</td>
<td></td>
<td></td>
</tr>
<tr>
<td>CSS6</td>
<td>High-amplitude, low-amplitude</td>
<td>NA</td>
<td>Extensive</td>
<td>Mounded geometries</td>
<td>Circular, culmination</td>
<td>Sediment onlaps</td>
<td>Sandstone confirmed from well</td>
<td>Mid-Miocene to EarPliocene Extruded</td>
<td></td>
</tr>
<tr>
<td>CSS7</td>
<td>High-amplitude, low-amplitude</td>
<td>NA</td>
<td>Extensive</td>
<td>Mounded geometries</td>
<td>Circular-elongated mounds</td>
<td>Sediment onlaps</td>
<td>Sandstone confirmed from well</td>
<td>Early Pliocene Extruded</td>
<td></td>
</tr>
<tr>
<td>CSS8-9</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>No intrusions observed</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Direct well calibration confirms that amplitude anomalies observed in the northern North Sea coincide with sandstone units in boreholes (Figs. 4.14c & 4.16b). For anomalies not intersected by wells, lithology determination was based on seismic expression and similar geometries, as those intersected by wells and those observed in other parts of the North Sea (Lonergan et al., 2002; Huuse et al. 2004; 2007; Jackson & Somme 2011).

Anomalies observed in the study area are similar to conical and saucer-shaped sandstone intrusions, sand injectites and remobilized sandstones in the North Sea and other sedimentary basins (Molyneux et al., 2002; Huuse & Mickelson 2004; Huuse et al. 2004; Shoulders et al., 2007; Cartwright et al., 2007; Sapronova et al., 2012; Monnier et al., 2014). Therefore based on the mounting evidences provided above and similarities with known examples from other basins, we interpret these discordant, conical and saucer-shaped anomalies as sandstone intrusions and remobilized sandstones.

### 4.5.2 Parent sand body and feeder systems

Potential source sand or parent body for each intrusion level have been presented in the previous section. Identifying the actual source or parent sand body for sandstone intrusions complexes is one of the key uncertainties and challenges in the study of sand injectites (Cartwright 2010; Morton et al., 2014). The presence of remobilized sand, sand injectites or sand extrudite indicates the existence of a parent sand body, either directly attached to, or detached away from it (Hurst et al., 2003; Shoulder et al., 2007). A parent body for an injectites can be located either very close to the injected part, or at some distance away from the injectites. Therefore, sand can be injected upwards, downwards or laterally (Jolly & Lonergan 2002; Vigorito et al., 2008; Svendsen et al., 2010; Kazerouni et al., 2011; Andresen & Clausen 2014).

The source sediment or parent body must be uncemented and sealed within the host rock such that when excessive pressure is generated, fracture gradient is exceeded and seal fails, so that the sands can inject into surrounding host rocks (Lonergan et al., 2000; Hurst et al., 2011). Substantial fluid must also be present in the system (hydrocarbon or water or both) and fluid migration in the subsurface must be strong enough to entrain the sands, when the fluid velocity is exceeded (Hause et al., 2010). The effective stress, which is the difference between overburden stress/load and fluid pressure within the parent sandstone body, must be zero (Lonergan et al., 2000; Jolly & Lonergan 2002; Hurst et al., 2011).

Sandstones were deposited into the basin in form of channels and low-stand fan bodies during the Late Cretaceous and Cenozoic periods, providing direct evidence of depositional source sandstone bodies in the area (Figs. 4.5 & 4.10). Identifying the exact source of parent sand for a sandstone intrusion complex is difficult without heavy mineral analysis on both the injected sand and the potential parent body. Recent studies in the Eocene succession of the North Sea on two potential parent bodies and Maule Field sand injectite were carried out by Morton et al., (2014). The two
parent bodies initially proposed were the Brimmond channel system and underlying Forties Sandstone Member; ages of the depositional systems are Eocene and Paleocene, respectively. Heavy mineral and garnet geochemical analysis of the Maule injectite, however, revealed similar characteristics with the Eocene-aged depositional Brimmond sandstones (Morton et al., 2014). Heavy minerals analyses have also helped to distinguish between in-situ depositional or remobilized bodies and injected bodies, based on different sorting patterns (Kazerouni et al., 2011). In the absence of such information and detailed analysis in our study area, our interpretation of parent body for injectites was based on closeness to depositional sandstone bodies.

Figure 4.10f shows that the distribution maps for depositional sandstones do not always match the distribution of intrusions in the area; however, there is evidence of potential source sand, either at the same stratigraphic level, where intrusions have been mapped, or below the intrusions. suggesting either of these depositional sandstone bodies may have sourced injectites in the area (Jolly & Lonergan 2002; Shoulders et al., 2007). As mentioned earlier, majority of the saucer-shaped intrusions, interpreted from the study area, are likely to have been part of originally deposited sand bodies related to sediment gravity flows that were later remobilized and injected creating complex geometries (Figs. 4.8 & 4.11) (Jackson et al., 2008; Dmitrieva et al., 2012; Huuse et al., 2012). In such a case, the remobilized or injected parts i.e. the wings are attached to the basal concordant part which represents the parent body and considered to be in situ remobilization, not whole injection (Fig. 4.2b) (Szarawarska et al., 2010). Majority of those interpreted within the CSS0 (Late Cretaceous) and CSS1 (Middle Paleocene) belong to this category (Figs. 4.8 & 4.11).

Alternative sand sources from deeper part of the basin were also suggested in the area based on interpretations made by Wild & Briedis (2010) for the Balder mounds on Utsira high. They suggested sands were entrained by underlying fluid from pre-Cretaceous and injected into the Paleocene unit. In the Northern North Sea, however, Cretaceous sandstones are only restricted to the north-eastern part and not very extensive.

As mentioned earlier, constraining the parent body of an intrusion complex is very challenging and this study area has been proven more challenging, due to the multiple locations of intrusions at different intervals. However, presence of potential multiple sources will suggest; individual source would have been buried deeply enough to facilitate generation of overpressure close to lithostatic, such that the seal failed and sands were injected into surrounding mudstone at each time, without need for repressuring the parent body (Cartwright 2010).

4.5.3 Sandstone Intrusions and polygonal faults

Small extensional faults observed from Cretaceous to Miocene are interpreted as polygonal faults, based on their distinct polygonal nature in plan view (Cartwright 1994). The faults are pervasive throughout the study area in, at least, two distinct tiers (Chapters 3-5). Tier 1 or lower tier is bounded above and below by the top Paleocene and lower Cretaceous horizons, respectively,
while tier 2 or upper tier is bounded above and below by the Middle Miocene and top Paleocene horizons, respectively (Figs. 4.6 & graph 4.1). Fault dip angles are similar to those measured in other sedimentary basins (Chapter 5).

Extensive studies of sandstone intrusions show that often occur within polygonally faulted mudstones area. Their occurrences with sand injectites extend beyond the study area and they are observed in several other basins (Fig. 4.1c). Previous studies have inferred that the faults exert major control on the geometry of sand injectites, based on their close physical relationship (Lonergan & Cartwright 1999; Lonergan et al., 2000; Gras & Cartwright 2002; Molyneux et al., 2002). In the Central North Sea, the Middle Eocene Alba reservoir shows evidence of modification from subsurface remobilization and injection and was attributed to polygonal faults, which had major control on their formation (Lonergan & Cartwright 1999; Lonergan et al., 2000; Gras & Cartwright 2002; Molyneux et al., 2002). However, more recent studies have shown that the faults do not exert control on the geometry or formation of the sandstone intrusions, as previously thought (Huuse et al., 2004; Huuse & Mickelson 2004; Shoulders et al., 2007; Cartwright et al., 2007). This is supported by the difference in dip angles between them and the fact that sandstone intrusions still form in the absence of polygonal faults.

Dip angle population between intrusions and polygonal faults is presented below (Graph 7.1). Dip measurements taken for both intrusions and polygonal faults from our study area show that the dip angles of the discordant wings of the intrusions are much lower than the polygonal fault dips inline with previous observations (Shoulders et al., 2007; Cartwright et al., 2007). This lack of relationship suggests that they are not directly related and the geometry of intrusions is not directly controlled by polygonal faults. The genesis of polygonal faults is beyond the scope of this study and has been documented extensively in literature (Cartwright, 2011).

4.5.4 Sandstone Intrusions and underlying structures

Sandstone intrusions and normal faults in the south-western Barent Sea reveal similar NNE-SSW orientation. This suggested the faults had control on their distribution and likely served as pathways for deeper fluids into parent sand bodies in the Eocene (Safronova et al., 2012). Similar relationship was observed in Faroe-Shetland Basin, such that sandstone intrusions and underlying basement faults have same NE-SW trend (Shoulders et al., 2007). The North Sea basin was tectonically active in the Mesozoic time, with series of normal faults and grabens, which formed during the rifting (Fig. 4.5) (Ahmadi et al., 2003). Major Jurassic Fields in the Northern North Sea are associated with horst, grabens and structural highs, created as a result of the rifting (Fig. 4.9) (Ahmadi et al., 2004).

Map of the base Cretaceous unconformity reveals the structural elements by highlighting structurally high areas from low areas (Fig. 4.9). The map also reveals relay fault zones, fault linkage systems and graben step overs linked to underlying faulting and rifting (Fossen et al.,
The faults and structural highs have NNE-SSW orientation across the basin, which locally coincides with distribution of some of the injectites in the area (Fig. 4.9). For example, the mid-Late Eocene injectites occur along the crest and above underlying structural high (Fig. 4.14). This relationship was also observed from the mid-Paleocene intrusions.

This spatial relationship suggests the Mesozoic faults may have influenced distribution of sandstone intrusions locally in the Northern North Sea, similar to the SW Barents Sea and Faroe-Shetland Basin. Faults are likely to act as pathways for fluids from these underlying reservoirs, as fluid may preferentially flow along fault planes (Ligtenberg 2005; Cartwright et al., 2007).

**Graph 4.1** Polygonal faults and sandstone intrusions dip angles. Note faults have higher dip angles than sandstone intrusions
4.5.5 **Timing - Single or Multiple episodic events**

What makes the study area unique is the multiple occurrences of the sandstone intrusions and extrusions through ~ 4000 m interval within the duration 95 Ma and identification of events used in dating suggests at least five episodes of emplacement within the basin. The extensive literature documenting sand injectites or sandstone intrusions have recorded only single episode (Shoulders *et al.*, 2007; Monnier *et al.*, 2014) or two distinct episodes in Outer Moray Firth and South Viking Graben (Huuse *et al.*, 2004; 2005).

The actual timing of emplacement for sandstone intrusions is not easy to constrain. In addition to calibration of age, quality and resolution of seismic data; constraining the timing depends on the nature of the injectite complex, i.e. whether it comprises well developed extrudites and whether these were preserved in the stratigraphic record, acoustic impedance contrasts (between sands and shales), the nature of subsequent sedimentation (pelagic or turbidites) and finally, assumptions based on current understanding of the injection process (whether wing tips reach seafloor or not). The extensive literature on sandstone intrusions have estimated timing, based on three (3) main criteria, each with their own assumptions and uncertainties (Cartwright 2010). They are:

1. **Presence of an extrudite vented on the paleo-seafloor** – Identifying an extrudite above sand injectites is very crucial, as it defines the position of seabed at the time of intrusion and extrusion (Fig. 4.22a) (Huuse *et al.*, 2004; Hurst *et al.*, 2006; Vigorito *et al.*, 2008; Cartwright 2008). The surface, which an extrudite is emplaced on, or the seabed at the time of formation, pre-dates the extrudite and sediments that onlap onto an extrudite clearly post-dates it; suggesting emplacement is between the age of the seabed and the onlapping sediments. However, identifying extrudites in the sub-surface is difficult, due to low level of preservation mainly because of erosion or strong bottom currents (Andresen & Clausen 2004).

![Fig. 4.22a Estimating timing of emplacement of an intrusion based on extrudite](image)

---

**Chapter 4**
(2) **Termination of wings at a common datum** – A stratigraphic datum, at which intrusions terminate, may have represented a paleo-seabed at the time of emplacement (Fig. 4.22b) (Huuse *et al.*, 2004). Ability to map and date the datum can provide estimation into timing of emplacement of intrusions. This is prone to misinterpretation where quality of seismic data is very poor and the datum is not mapped or dated correctly. Also the true upper tips of injectites might not have been clearly imaged due to seismic resolution limit (Cartwright 2010), interferences from polygonal faults and erosion.

![Fig. 4.22b Estimating timing of emplacement of an intrusion based upper tip termination](image)

(3) **Dating of onlapped sediments** – Forced folds or jack up, created above injectites, are onlapped by latter sediments. Dating the sediments that onlap on to the forced folds indirectly helps to estimate the timing of injectites (Shoulders & Cartwright 2004; Shoulders *et al.*, 2007; Cartwright 2010) (Fig. 4.21c). The main challenge with this method of dating is if onlaps are not preserved on folds, due to erosion.

![Fig. 4.22c Estimating timing of emplacement of an intrusion based onlap onto jack up](image)
In chapter 4, we presented evidences from each unit, where injectites have been emplaced and using similar approach from those illustrated in figures 4.23. Based on this, we propose at least five (5) major episodes of emplacement: Late Cretaceous, Middle Paleocene, Middle to Late Eocene, Middle Miocene and Mid-Late Miocene to Early Pliocene.

Some of the events are synchronous with other parts of the North Sea. For example, in the South Viking Graben, two episodic events are interpreted in the earliest Eocene and Middle Eocene based on presence of extrusion and termination of conical intrusions at the unconformity respectively (Huuse et al., 2004). Middle-to-Late Eocene timing was also proposed for conical intrusions in the Tampen Spur area, west of our Eocene-emplaced case study (Huuse & Mickelson 2004). Rodriguez et al., (2009) also identified onlaps on forced folds above underlying sandstone intrusions during the mid–Miocene in the Tampen Spur area. Above the Siri Canyon in the Norwegian - Danish basin, an extrudite was interpreted on the mid - Miocene unconformity (Andresen et al., 2009). Examples mentioned above with our independent observations suggest the Middle - Eocene and Middle-Miocene times were periods of regional sandstone intrusion and extrusion, and related fluid flow in the North Sea.

4.5.6 Mechanism of Formation

Pre-requisite elements for formation of sandstone intrusions and extrusions include presence of unconsolidated sands emplaced within low-permeable mudstones, sufficient fluid to entrain the sands, excessive pore pressure and a triggering mechanism (Lonergan et al., 2000). Several authors have investigated different processes for formation of sandstone intrusions and extrusions but exact mechanisms that initiate actual remobilization and injection are still very speculative. Driving mechanisms for sandstone intrusions are often classified under primers and triggers, with the former being the processes that facilitate overpressure generation and the latter includes the mechanisms that triggers the actual injection (Huuse et al., 2010).

Some of the priming mechanism, invoked by previous workers to drive sandstone remobilization and injection, include: disequilibrium compaction resulting in rapid burial of sand bodies and inability of pore fluids to escape normally (Osborne & Swarbrick 1997; Jackson et al., 2010; Leeseth et al., 2013), hydrocarbon generation, lateral pressure transfer and fluid buoyancy (Yardley & Swarbrick 2000; Reilly & Flemings 2010; Andresen et al., 2009; Monnier et al., 2014), migration of basinal fluids (Jolly & Lonergan 2002; Molyneux et al., 2002; Safronova et al., 2012), silica diagenesis (Davies et al., 2006; Huuse et al., 2010) and tectonic stresses (Cartwright 2010), whereas triggering mechanisms include: (Jolly & Lonergan 2002; Cartwright 2010), seismic waves from large magnitude earthquakes (Molyneux et al., 2002; Huuse & Mickelson 2004), bolide impact (Cartwright 2010), propagation of polygonal faults into overpressured sandstone bodies (Molyneux et al., 2002) and buoyancy effects of hydrocarbons (Jonk 2010; Monnier et al., 2014).
We investigated some of these mechanisms in the study area and detailed discussion is presented in chapter 7.

**Disequilibrium compaction** resulting in rapid burial of sand bodies and inability of pore fluids to escape normally is a very common overpressure generation mechanism (Osborne & Swarbrick 1997; Jackson *et al.*, 2008). This mechanism is efficient when the seal integrity is very good and sedimentation rates are as high as or greater than 600 m /Ma (Durant & Hurst 2004; Osborne & Swarbrick 1997). Sedimentation rates, estimated in the study area from CSS0 to CSS9, are within the range of 24.10 and 415.63 m/Ma, for maximum rates observed in the CSS2 (Eocene) and CSS7 (Pliocene) units, respectively (Tab. 3.3 & Graph 3.1) (compaction not taken into account). If units are decompacted, only the rate during Pliocene (CSS7) would be close to or greater than the 600 m/Ma. Based on these low values, with the exception of the Pliocene, we do not think disequilibrium compaction sedimentation rate in the area was high enough to generate enough overpressure in the area. However, the rates in the Pliocene may have contributed at that time.

Another process that generates excess pressure is **high tectonic stresses**. Areas with applied tectonic stresses, such as strike-slip basins, fold and thrust belts have very high differential and applied stresses that can create excess pressure (Lonergan *et al.*, 2000). The North Sea is characterized by series of rift structures with the last phase of rifting between Late Jurassic to Early Cretaceous time (Ziegler 1990). By Late Cretaceous times, the North Sea was no longer actively rifting and the post-rift phase was characterized by thermal subsidence (Lonergan *et al.*, 2000). The oldest intrusions in the Northern North Sea are observed in the Late Cretaceous interval, by then the area was no longer tectonically active (Lonergan *et al.*, 2000); making tectonic stresses an unlikely mechanism for overpressure generation.

**Addition of fluid**, such as hydrocarbon, is another common mechanism, often sited in literature to generate overpressure in parent bodies of injectites (Lonergan *et al.*, 2000; Molyneux *et al.*, 2002; Jolly & Lonergan 2002; Duranti & Hurst 2004; Andresen *et al.*, 2009; Wild & Briedis 2010; Monnier *et al.*, 2014; Andresen & Clausen 2014). This process is also thought to be very effective in remobilizing large volumes of unconsolidated sand and facilitate injection. Introduction of hydrocarbon, especially gas can generate high pore-fluid pressure in sealed sands, due to buoyancy (Jolly & Lonergan 2002; Duranti & Hurst 2004; Hurst *et al.*, 2011). This is a very attractive mechanism for overpressure build up in the study area; first, because of the presence of underlying Late Jurassic Kimmeridge Clay Source rock (age equivalent of Draupne Formation in the Norwegian Margin) and basin modelling studies shows hydrocarbon generation in the North Sea, started since the Late Cretaceous (Fig. 4.2b) (Kubala *et al.*, 2003; Schlakker *et al.*, 2002). This is coeval with the timing of emplacement for the Late Cretaceous intrusions in the study area (Fig. 4.8). Second, the location of some of the intrusions above structural highs and Mesozoic faults, which houses most of the underlying reservoirs, suggests some kind of relationship between them (Figs. 4.9, & 4.14). However, not all intrusions are present on structural highs and faults, as they are also observed within the structurally low areas, absent above some structural highs, such
as the Troll fault blocks and located above areas, not underlain by hydrocarbon fields (Fig. 4.9). Therefore, it is possible that this generation and migration of hydrocarbon constituted an important role in both generation of overpressure and subsequently formation of intrusions; this mechanism alone, however, might not be sufficient enough in the study area, due to partial correlation between underlying structures and mapped injectites.

Recently, the process of opal A to opal CT silica diagenetic transformation was invoked as a potential primer and trigger for sandstone intrusions (Davies et al., 2006). The conversion, which often occurs at shallow burial (first 0.5 - 1 km), causes collapse of the pore framework, drastic porosity loss and rapid pore fluid expulsion, which facilitates generation of overpressure within the unit. This study favours this mechanism based on the following:

1. Evidence of multiple emplacements of sandstone intrusions in the Northern North Sea - Late Cretaceous, Mid-Paleocene, Mid-Late Eocene, Mid-Late Miocene and Early Pliocene
2. Evidence of transformation of opal A to opal CT within Paleocene, Eocene and Oligocene intervals (Fig. 5.13) from seismic, well data and petrophysical analysis (Rundberg 1991)
3. Presence of sandstone intrusions within siliceous-rich intervals, where transformation has taken place
4. Location of present day boundary of diagenetic boundary below Oligocene-emplaced intrusions (observations from seismic and well logs) (Figs. 4.16 & 4.18)
5. Presence of potential parent sand body within opal rich interval. Potential parent bodies for intrusions are located within silica bearing intervals in the area
6. Average depths at time of injection are between 300 – 600 m in the area (for intrusion of about 200 m to 400 metres in height) and if diagenesis usually occurs within the first 0.5 - 1 km (Davies et al., 2006); this suggests that both processes occurred at similar depths
7. Nature of the host rock – presence of extensive polygonal fault system developed in Cretaceous to Miocene aged sediments is evidence of early dewatering (Fig. 4.6). Mudstones are also smectitic-rich and have undergone transformation to illite (Rundberg 1991; chapter 5). Providing more fluid into the system
8. Diagenetic processes result in shear fracturing in fine-grained sediments
9. Finally, the co-existence of opal-rich rock and sandstone intrusions is very compelling in the North Sea, Faroe-Shetland Basin, Sakhalin Island, More Basin and San Joaquin Basin (Fig. 4.1c) (Davies et al., 2006; Thompson et al., 2007).
Prior to the Cretaceous, series of horsts and grabens and other structural elements were formed, as a result of the rifting (Fig. 7.6a, time0). This interval houses the Late Jurassic Kimmeridge Clay Source Rock (equivalent of Draupne Formation in the area) and extensive shallow marine sandstones, which constitutes the main reservoirs in the North Sea (Evans et al., 2003). Late Cretaceous fan and channels were deposited into the basin at time 1 (Fig. 7.6). Mudstone dewatering probably started in the mid-Late Cretaceous and these mudstones are rich in smectite (Thyberg et al., 2010). For sands to remobilize, they must be unconsolidated and sealed so that overpressure is generated (Lonergan et al., 2000). Based on the timing of intrusion emplacement, fluidization began in the Late Cretaceous which corresponds to timing of hydrocarbon generation from North Sea basin modelling (Kubala et al., 2003; Schlakker et al., 2002).

Fluid from hydrocarbon leakage and pore water, expelled during diagenetically-driven processes at this time, would have facilitated fluidization of sands at time 2 (Fig. 4.23a). Clay mineral analysis shows Paleogene mudstones are very rich in silica and smectite; and with increased burial, they are transformed and significant volume of pore water is produced (Rundberg 1991; Davies et al., 2006; Marcussen et al., 2009). All the pore water produced during diagenetic transformation will try to get out of the host rock and if it intersects an unconsolidated sand body, the sand may be entrained, when fluidization velocity is exceeded and remobilization is initiated (times 3 – 5) (Huuse et al., 2010). This process would have been repeated in the basin, to aid multiple emplacements of sandstone intrusions, as the sealed sands would have subsided through the transformation zones (Fig. 4.23a). Fluidization would also have been supported by any additional influx from deeper part of the basin, either as hydrocarbon, or water (Lonergan et al., 2000; Jolly & Lonergan 2002; Wild & Briedis 2010).

In most cases, only the present-day location of the opal A to opal CT diagenetic boundary is observed in seismic or outcrop and represented as a high-amplitude reflection in seismic, corresponding to a downward increase in bulk density and seismic velocity (Davies et al., 2006; Davies & Cartwright 2002). Most smectite to illite conversion are based on experiments, petrophysical analysis and well log response (Rundberg 1991; Marcussen et al., 2009). The present-day location of the opal A to opal CT diagenetic boundary is directly below the Oligocene-emplaced intrusions (Figs. 4.16, 4.18). The boundary is conformable to the near-base Miocene and mid-Miocene reflections, indicating the time, at which the transformation ceased and the diagentic front became fossilized (Davies and Cartwright 2002; Neagu et al., 2010). This coincides with last period of significant sandstone intrusion and extrusion in the area (Fig. 4.23a, time 5). The last episode of intrusion in the area was during the Early Pliocene and transformation ceased at about mid-Miocene times (Fig. 4.23a, time 6). It could be assumed that it was a gradual process, strong enough to still generate water to aid fluidization in the Early Pliocene. However, there is no evidence for this. Presently, we have no explanation for this, however, we mentioned earlier that estimation of rate of sedimentation was much higher during the Pliocene, (415.63 m/Ma,
compaction unaccounted for) (Tab. 3.3 & Graph 3.1) compared to other times in the area. This could have facilitated overpressure development within the unit (Fig. 4.23a, time 6).

Based on the above, we propose the main fluid sources could have driven large-scale remobilization and injection in the Northern North Sea; they are: Intraformational fluid sources, such as diagenesis of the host rock, compaction and extraformational fluid sources, such as hydrocarbon or/and water from deeper parts of the basin (Fig. 4.23b). For such scale of remobilization, a basinal event might be needed to trigger it, such as regional events like earthquakes or bolide impacts (Obermier 1989; Cartwright 2010; Huuse et al., 2010).

Earthquakes have been proposed to trigger remobilization and injection of unconsolidated sand by a process known as shear-induced liquefaction or dynamic liquefaction. These studies reveal that earthquake events may create shearing motion within the rock, which leads to grain crushing, causing significant increase in fluid pressure, weakening in overburden rocks and causing injection (Obermier 1989; Cartwright 2010). However, this is known to occur at very shallow depth (within few metres of the surface) and produces centimetres to few metres structures (Obermier 1996; Cartwright 2010). Jolly & Lonergan (2002) also noted that at greater depth, it is difficult to liquefy sediments by dynamic liquefaction, due to increase in overburden stress with depth. The scale of intrusion, depth of intrusion and magnitude of earthquake should be considered, when invoking seismically-induced liquefaction as a potential driving mechanism for intrusions (Jolly & Lonergan 2002). In the study area, the scale of intrusions is in hundreds and thousands of magnitudes larger than those formed by seismically-induced liquefaction. Depths of intrusion in the area are assumed to be within the range of 400 – 600 m, therefore too deep for dynamic liquefaction, based on the above. And lastly, no known record of earthquakes with magnitudes greater than 5 is known in the area (Huuse & Mickelson 2004). Based on the above, we do not favour earthquakes as a possible triggering mechanism in the area.

Bolide impact, which created the Silver Pit crater in the Southern North Sea and Ries impact in Germany during the mid to late Eocene and mid to late Miocene, respectively, has also been suggested in literature as potential triggers for sandstone intrusions (Cartwright 2010). Although the timing of these events coincides with timing of emplacement of some of the intrusions in the area, they occurred at great distances away from the study area and their impact is not likely to have reached the Northern North Sea making this process unlikely.

Earthquakes and bolide impacts are unlikely to be responsible to trigger formation of sandstone intrusions in the area. Detailed study of the heat flow in the area is beyond this study. The fluid budget might be sufficient in the area to facilitate fluidization and subsequent remobilization and injection without an external trigger. Experimental analysis reveals that introduction of water into the sealed system below the parent body, creates hydrofractures to the surface, which sands can migrate through till they get to the free surface (Bureau et al., in press).
Chapter 4

(a)

Time 1
Pre-Cretaceous

- Rifting, faulting, formation of horst and graben structures and deposition Jurassic sediments

Time 2
Mid-Late Cretaceous

- Mudstone dewatering probably began. Presence of occurrence of polygonal faults and deposition of Cretaceous sandstones. Hydrocarbon generation began in Late Cretaceous

Time 3
Late Cretaceous

- Cretaceous sands are remobilized. Hydrocarbon generation begins. Porewater expelled from formation and deeper parts of the basin

Time 4
Middle Paleocene

- Sandstone deposition from the basin margins. Continuous dewatering of mudstones. Sands are remobilized during the mid-Paleocene and an extrudite was formed. Extrudite formed in the mid-Paleocene

Time 5
Mid to Late Eocene

- Deposited sandstones in the Eocene time are remobilized and injected into the surrounding mudstones with increased burial

Time 6
Mid-Late Miocene

- MMU represented paleoseated at this time. Extrudites formed on the MMU. Diagenetic boundary/front stopped being active during the Late to Mid Miocene and present location below Oligocene-emplaced injectites

Time 7
Early Pliocene to Pleistocene

- Last stage of remobilization, sands are extruded during the Early Pliocene. Westward prograding of clinoforms. Pleistocene unconformity formed

Acronyms used:
- MMU -mid Miocene unconformity
- DB-Diagenetic boundary
- EO-Eocene Oligocene
- ME-mid Eocene
- TB-Top Balder
- BT-Base Tertiary
- LT-Late Turonian
- BCU-base Cretaceous unconformity
- NVG - North Viking Graben

- Depositional/Remobilized
- Injected sandstones
- Pore water
**Fig. 4.23 (a&b)** Schematic diagrams illustrating proposed model of formation of sandstone intrusions in the Northern North Sea
4.6 CONCLUSIONS

The study forms part of the North Sea intrusion province described by Cartwright (2010) with laterally and vertically extensive intrusions been emplaced forcefully within thick mudstone units. Other similar examples of large-scale intrusions are the Faroe-Shetland and Paonoche - Tumey complexes. Based on our studies, we present our conclusions below:

- Presence of series of high – amplitude, anomalies emplaced within low - amplitude background pervasively deformed by polygonal faults at multiple intervals in the area from Cretaceous to Pliocene
- Three main styles were described: (i) high-amplitude, bedding - discordant which have V, U or W-shape geometries (ii) high-amplitude bedding - concordant and (iii) steep-mounded anomalies
- Some of the anomalies penetrated by exploration wells encountered tens of metres thick sandstones and interpreted as sandstone intrusions and extrusions
- Five (5) episode of emplacement occurred from Late Cretaceous to Early Pliocene in the Northern North Sea
- Occurrence of multiple tiers of polygonal fault networks within fine-grained, smectite-rich and siliceous-rich mudstones from Cretaceous to Miocene intervals
- Evidence of silica diagenetic transformation at multiple intervals (Paleocene – Oligocene). Transformation of opal A to opal CT results in abrupt porosity loss, significant water expulsion and excessive pore pressure
- This process is proposed as a potential driving mechanism for intrusion emplacement, in combination with hydrocarbon and pore water from deeper parts of the basin
- Diagenetic transformations such as opal A to opal CT and smectite to illite transformation causes reduction in porosity and pore water expulsion
- Our propose of model such that the sealed unconsolidated sands subsided through the transformation zones with intrusions emplaced at multiple intervals through time
- Potential parent bodies are depositional sandstones in form of fans and channels also located at different stratigraphic levels
- Local occurrences between intrusions and underlying structural elements suggest they could have influence their distribution. Hydrocarbon generation in the area started in Late Cretaceous and continues till date, coinciding with timing of oldest intrusion (CSS0)

The study represents the first-ever, documentation of large-scale, sandstone intrusions and extrusions emplaced during series of episodic events in a single basin (Fig. 4.24). Main episodes proposed include: Late Cretaceous, Mid-Paleocene, Mid - Late Eocene, Mid – Late Miocene and Early Pliocene. This is useful in calibrating fluid and fluid flow history in the basin during reservoir
Fig. 4.24 Northern, Central and Southern profiles across the study area
modelling (Shoulders & Cartwright 2004; Jackson & Stoddart 2005). Therefore, there is need to incorporate them into the present Cenozoic framework in the Northern North Sea and other basins in the world (Fig. 4.24). Multiple stratigraphic occurrences in the study area could have impacted prospectivity in the Tertiary interval of the Northern North Sea as their presence is evidence of breach in the sealing rocks unlike the adjacent Outer Moray Firth, South Viking Graben and East Shetland Platform.

ACKNOWLEDGEMENTS

We wish to thank Petroleum Technology Development Fund (PTDF) Nigeria for proving full scholarship that has made this research possible. We want to thank PGS for providing the 3D MegaSurvey seismic volume which most of this interpretation was based on and TGSNOPEC for proving regional 2D seismic lines for this project. We also want to thank Norwegian Petroleum Directorate (NPD.NO) website for information on the wells used. Appreciation also goes to the reviewers for their constructive comments in the process of reviewing this paper.
REFERENCES


BUREAU, D., MOURGUES, R., CARTWRIGHT, J., FOSCHI, M., & ABDELMALAK, M.M (2013). Characterisation of interactions between a pre-existing polygonal fault system and sandstone intrusions and the determination of paleo-stresses in the Faroe-Shetland basin. Journal of Structural Geology, 46, 186-199

BUREAU, D., MOURGUES, R., CARTWRIGHT, J., & HUUSE, M (in press). Large-scale sandstone intrusion emplacement and geometry


SHOULDERS, S.J., & CARTWRIGHT, J. (2004). Constraining the depth and timing of large-scale conical sandstone intrusions. Geology, 32, 661-664


Chapter 5

5 QUANTITATIVE ANALYSIS OF SANDSTONE INTRUSIONS, POLYGONAL FAULTS AND DIAGENETIC BOUNDARY IN THE NORTHERN NORTH SEA

ABSTRACT

Cretaceous and Tertiary intervals in the northern North Sea are dominated by fine-grained mudstones. 3D seismic analysis shows presence of large-scale sandstone intrusion complexes, silica diagenetic boundaries and polygonal faults throughout the sequence. These fluid flow products occur over large areas in several sedimentary basins and sometimes co-exist. Sandstone intrusions in the study area occur at different stratigraphic levels within Cretaceous and Tertiary sediments. Quantitative analysis reveals their dip; width and height values are comparable with other published examples from the North Sea and Faroe-Shetland basins (mean values include 20 - 25°, 995 – 1050 m, 135 – 170 m for dip, width and height, respectively) but much lower for the deeper Cretaceous ones. Polygonal faults deform these intrusion-emplaced, mudstone-rich successions forming two main tiers, such that average dip measured are 46° and 36° for the upper and lower tier respectively. The polygonal faults and sandstone intrusions have different dip populations, which could suggest they formed independently. Difference in dip angles of the Cenozoic and Tertiary intrusions and the upper and lower polygonal fault tiers could be due to original difference in dips during emplacement, compaction from subsequent deposition or variation in mineralogical properties of the mudstone-dominated host rock. Silica diagenetic transformation occurred in the basin with its present day location directly below the Oligocene-emplaced intrusions suggesting a possible genetic relationship. The opal A to opal CT boundary in the area is no longer active.

Although, the North Sea has been intensely studied with respect to these post-depositional features, this represents the first quantitative analysis in the area through different intervals. Sediment remobilization, polygonal faulting and silica diagenetic transformation, however, form important processes within the northern North Sea and make up significant part of its present day configuration.
5.1 BACKGROUND

Sandstone intrusions, polygonal faults and silica diagenetic boundaries form special post-depositional products associated with fluid flow commonly observed over large areas of sedimentary basin. These 3 features have been found together in the northern North Sea (NNS), Faroe-Shetland Basin (FSB), San Joaquin Basin (SJB) and several other basins in the world at different scales; and sometimes thought to be genetically related (Davies et al., 2006; Davies & Ireland 2011; Cartwright 2011) (Fig. 5.1).

Fig. 5.1 Global distribution map showing location of sandstone intrusions, polygonal faults and sites of silica diagenetic transformation

Three-dimensional seismic data has proven more effective in revealing detailed geometries of these important post-depositional features across tens of kilometres area in the northern North Sea (Fig. 5.2a). They have been introduced in chapters 3 and 4. Similar studies have documented the interaction between sandstone intrusions and polygonal faults in detail from the FSB (Shoulders et al., 2007; Cartwright et al., 2008; Bureau et al., 2013), sandstone intrusions within single interval in the NNS (Jackson et al., 2010) and silica diagenetic transformation from the NNS (Rundberg 1991; Thyberg et al., 1999). However, this study attempts to document the dip angles, width and height from several levels and their relationship with polygonal faults and document the opal A – opal CT boundary with respect to previous studies. It also attempts to highlight any possible relationship, which may or may not occur between clay mineralogy and difference in dip population between sandstone intrusions and polygonal faults.
Fig. 5.2(a) Map of the North Sea showing the study area in red outline.

Fig. 5.2(b) Seismic section and time slice through intrusions and polygonal faults. Note present day location of opal A – CT boundary (OACB) below intrusions
5.2 DATABASE AND METHODS

3D seismic data was used for the study (Fig. 5.2a). Detailed information about the seismic data and methodology is provided in chapters 1, 3, 4 & appendix. This study is focused on intrusions emplaced within CSS0 – CSS4, dated Late Cretaceous, Middle Paleocene, Middle-Late Eocene and Middle-Late Miocene. Average velocity was calculated for each CSS unit and used for depth conversion of measured values. True dip measurements were taken across the sandstone intrusions and polygonal faults with no vertical exaggerations. 140 dip values were taken for polygonal faults; and 130 and 100 values for Tertiary and Cretaceous intrusions, respectively. The measurements were taken across the area and on the best resolved intrusions. Dip angles of fault planes were measured on cross sections orthogonal to fault strikes as observed in plan view. To analyse the silica diagenetic boundary, 22 wells were utilized to estimate the geothermal gradient and present day temperature at the opal A – CT boundary.

![Diagram of sandstone intrusions](image)

**Fig. 5.3** Measured parameters for sandstone intrusions (not to scale)

5.3 QUANTITATIVE MEASUREMENTS

5.3.1. Sandstone intrusions

Numerous sandstone intrusions are observed from multiple intervals in the NNS (Fig. 5.2b). Quantitative data shows large variability between dip angles, width and height measurements for the Cretaceous and Tertiary-aged intrusions in the area (Figs. 5.4-5.7). The Late-Cretaceous intrusions have smaller dips; and average values for their width and height are smaller than the Tertiary intrusions (Tab. 5.1). The values measured for the younger intrusions are comparable with other parts of the North Sea and FSB. Some trends are observed from cross plotting of the parameters.
Fig 5.4 Late Cretaceous-aged intrusions (values from Jackson et al., 2010)
Fig. 5.5 Middle Paleocene-aged intrusions. Depth values are from the present day seabed.
Fig. 5.6 Middle to Late Eocene-aged intrusions
Fig. 5.7 Middle-Late Miocene-aged intrusions
Fig. 5.8. Measurements for Tertiary intrusions
Fig. 5.9. Measurements for all intrusions
5.3.2. **Polygonal faults**

Two tiers are observed from the polygonal faults in the area based on increase in fault density at the base of each tier, preferred dominant orientation and presence of a potential sand body (Fig. 5.10). However, the possibility of more than two tiers is likely based on the regional extent of the area is, fault pattern can change considerably across the area.

*Fig. 5.10. Characteristics of polygonal faults in the area*
The measured values for polygonal fault dips measured show higher values for the upper or tier 2 with an average of 46° while the lower or tier 1 has average of 36° (Fig. 5.11, Tab. 5.1). Similar decrease in dips was also observed between upper and lower faulted intervals from the Central North Sea (Lonergan & Cartwright 1999). Considering tier 1 are located deeper than tier, 2 this could suggest the faults get shallower with increased depth, as observed in FSB (Shoulders et al., 2007). Fault lengths range between 583 – 3404 m and higher than those measured in the CNS but similar to the More Basin (Tab. 5.1). No systematic correlation is observed between fault lengths and orientation (Fig. 5.12).

Because sandstone intrusions often occur within polygonally faulted units, they are often thought to have control on the intrusion geometry (Lonergan et al., 2000). Figure. 5.2b shows that sandstone intrusions cross cut polygonal faults and not necessarily along the fault plane, suggesting they might not be directly related, as previously thought (Huuse et al., 2004). This was also confirmed from the FSB and supported by difference in dip angles with polygonal faults having high dip angles that get shallower with depth (Shoulders et al., 2007). In the study area, we also observed this difference in dip population between the sandstone intrusions at all levels and polygonal faults (Fig. 5.11).

![Fig. 5.11. Dip populations of sandstone intrusions and polygonal faults](image-url)
Figs. 5.12. Fault length vs orientation for all maps in 5.10. No correlation between them.
5.3.3. **Silica diagenetic boundary**

Opal A is rich diatoms and transforms to opal CT during burial, both of which are present in the mudstones of the northern North Sea (Fig. 5.13) (Rundberg 1991; Thyberg et al., 1999). In addition to the changes in chemical properties of sediments during transformation, changes also occur in the physical properties, such as up to 30 % porosity reduction, collapse of pore framework causing a downward increase in bulk density and seismic velocity which creates an increase in acoustic impedance of the rock and represented by a hard-kick reflection (similar to the seabed) on seismic data (Fig. 5.13) (Davies & Cartwright 2002). The reflection was mapped over a large area, but mapping was less confident in the western part due to chaotic nature of seismic and intense deformation (Fig. 3.5g).

**Fig. 5.13. Synthetic seismogram generated for well 30/3-3 to show diagenetic boundary**

The opal A – CT boundary is not parallel to the present day seabed; instead it is more parallel to the base Miocene surface and mid-Miocene unconformity (Fig. 5.14). TWT thickness map between the boundary and the present day seabed shows it occur between 600 – 1300 ms below the seabed, therefore, cannot represent a bottom simulating reflection (Neagu et al., 2010). Its parallelism with the base and mid Miocene reflections is significant as this represents time when the upward migration of the boundary ceased or became fossilized (Davies & Cartwright 2002), hence no longer active. Average geothermal gradient estimated at the boundary is 34° and temperature at the boundary using specific geothermal gradient from each well is 22 - 45° (Appendix 5.1).
Fig. 5.14. Seismic section across diagenetic boundary showing relationship with overlying surfaces (b&c) TWT structure map of boundary and thickness map with the present day seabed. Mapped area represents areas of high confidence mapping of the boundary.
Fig. 5.15. Simplified correlation across wells from the N&S parts of the study area showing concentration of Opal CT measured from XRD within Paleocene to Oligocene units (values from Rundberg 1991)
### Table 5.1 - Summary table of sandstone intrusions, polygonal faults and silica diagenetic boundaries

<table>
<thead>
<tr>
<th>Study</th>
<th>Basins</th>
<th>Remobilized sands and sand injectites</th>
<th>Polygkonal faults</th>
<th>Silica diagenetic boundaries</th>
<th>Unit/Age/Timing</th>
<th>References</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>NNS</td>
<td>25 40 50 250 ms</td>
<td>Opal A-CT</td>
<td>-</td>
<td>Lower-Mid Eocene*</td>
<td>Huuse &amp; Mickelson 2004</td>
</tr>
<tr>
<td>2</td>
<td>OMF</td>
<td>5 25 100 300 500 2000</td>
<td>-</td>
<td>Lower Eocene*</td>
<td>Molyneux et al., 2002</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>NNS</td>
<td>1 20 7 90 50 150 1740 500</td>
<td>&lt; 50</td>
<td>Late Cretaceous*</td>
<td>Jackson et al., 2010, 2014</td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>NNS</td>
<td>150 1500</td>
<td>Pleiocene*</td>
<td>Li-esth et al., 2012, 2013</td>
<td></td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>SVG</td>
<td>20 40 35 250 2000</td>
<td>Early Eocene*</td>
<td>Huse et al., 2004</td>
<td></td>
<td></td>
</tr>
<tr>
<td>6</td>
<td>SVG</td>
<td>20 40 50 200 500 1000</td>
<td>Middle Eocene*</td>
<td>Huse et al., 2004</td>
<td></td>
<td></td>
</tr>
<tr>
<td>7</td>
<td>CG</td>
<td>80 ms 1400</td>
<td>Middle Miocene*</td>
<td>Andrewes et al., 2009</td>
<td></td>
<td></td>
</tr>
<tr>
<td>8</td>
<td>ENS</td>
<td>10 20 15 150 300 2700</td>
<td>Oligocene*</td>
<td>Andrewes et al., 2014</td>
<td></td>
<td></td>
</tr>
<tr>
<td>9</td>
<td>CNS</td>
<td>18</td>
<td>Eocene*</td>
<td>Lonergran &amp; Cartwright 1999</td>
<td></td>
<td></td>
</tr>
<tr>
<td>10</td>
<td>CNS</td>
<td>30 70 45</td>
<td>Pal-Lower Miocene*</td>
<td>Lonergran et al., 1998</td>
<td></td>
<td></td>
</tr>
<tr>
<td>11</td>
<td>CNS</td>
<td>30 70 45</td>
<td>Late Cretaceous**</td>
<td>Stuevold et al., 2003</td>
<td></td>
<td></td>
</tr>
<tr>
<td>12</td>
<td>BAREN SEA</td>
<td>200 400 500 2000</td>
<td>Opal A-CT</td>
<td>Middle Miocene*</td>
<td>Safonova et al., 2012</td>
<td></td>
</tr>
<tr>
<td>13</td>
<td>FAROE-SHETLAND</td>
<td>7 33 22 90 340 190 400 1700 855</td>
<td>Opal A-CT-Y</td>
<td>Early Pliocene</td>
<td>Davies &amp; Cartwright 2002</td>
<td></td>
</tr>
<tr>
<td>14</td>
<td>MID-NORWEGIAN RIDGE</td>
<td>8 22 24 147 875 68</td>
<td>Opal A-CT-Q</td>
<td>Olgo-Pliocene***</td>
<td>Ireland et al., 2011</td>
<td></td>
</tr>
<tr>
<td>15</td>
<td>MID-NORWEGIAN RIDGE</td>
<td>6 37 26 250 350 55</td>
<td>Opal A-CT-Y</td>
<td>Olgo-Pliocene***</td>
<td>Neagu et al., 2010</td>
<td></td>
</tr>
<tr>
<td>16</td>
<td>MID-NORWEGIAN RIDGE</td>
<td>3 20 7 90 50 150 1740 500</td>
<td>Opal A-CT-Q</td>
<td>Late Cretaceous*</td>
<td>Olobayo et al., 2015 Chapters 3-8</td>
<td></td>
</tr>
<tr>
<td>17</td>
<td>MID-NORWEGIAN RIDGE</td>
<td>17 32 25 90 210 140 440 1200 825</td>
<td>Opal A-CT-Q</td>
<td>Early-Mid Miocene 24-41 22-45</td>
<td>Middle Paleocene*</td>
<td></td>
</tr>
<tr>
<td>18</td>
<td>MID-NORWEGIAN RIDGE</td>
<td>15 38 25 120 215 170 490 1800 1050</td>
<td>Opal A-CT-Q</td>
<td>Mid-late Eocene*</td>
<td>Olobayo et al., 2015 Chapters 3-8</td>
<td></td>
</tr>
<tr>
<td>19</td>
<td>MID-NORWEGIAN RIDGE</td>
<td>12 35 20 60 215 135 315 1940 995</td>
<td>Opal CT-Q</td>
<td>Not studied in detail</td>
<td>Middle Miocene*</td>
<td></td>
</tr>
</tbody>
</table>
Results from previous analysis show concentration of opal CT within Paleocene to Oligocene intervals (Rundberg 1991). This is represented graphically using the wells analysed from his work (Fig. 5.15). Wells from the NNS also show relative abundance of diatoms in the mudstones in the upper part of the Oligocene interval (Thyberg et al., 1999). Based on the above and interpretation from seismic and well data, there are strong evidences of regional diagenetic transformation in the area. Occurrence of CT within sediments at multiple intervals, suggests transformation would have occurred at different times and the diagenetic boundary migrated upwards with increased burial till it became fossilized during Late to Middle Miocene time (Davies & Cartwright 2002).

5.4 DISCUSSION

Shoulders et al., (2007) suggested two possible scenarios for post compaction effect based on single and multiple emplacements of intrusions. We have evidences to show the NNS sandstone intrusions were emplaced during multiple episodes, therefore, the older intrusions (Cretaceous) will likely have smaller dips as they would have undergone greater level of compaction (Fig. 5.11).

Clay mineralogy of Cenozoic mudstones in the Northern North Sea has been well documented but not so much in the Cretaceous succession. SEM analysis on samples from the Tertiary interval in the NNS show in most cases, higher percentage of smectite with respect to other clay minerals (Appendix 5.2) (Rundberg et al., 1991; Thyberg et al., 2000; Marcussen et al., 2009). In the Cretaceous, however, smectite content is often low with higher concentration of other clay minerals (Tab. 5.2) (Pearson1990; Thyberg et al., 2010). This relationship is also observed from wells in the Voring and More basins such that smectite content decreases with increasing depth and corresponds to a marked change in velocity (Peltonen et al., 2009). Mudstones rich in smectite content are less compressible compared to those low in smectite, such that the latter have higher velocity and bulk densities (Marcussen et al., 2008; Marcussen et al., 2008). This variation in mineralogical and physical properties of the mudstones could have reflected on the dip angles of Cretaceous intrusions and lower tier polygonal faults (Fig. 5.11); however compositions of mudstone vary across the area and requires more detailed analysis in order to constraint it.

Table 5.2 Clay mineralogy of Upper Cretaceous to Oligocene. Note higher smectite content in Cretaceous than Tertiary strata Adapted from Pearson 1990). Velocity increases with depth

<table>
<thead>
<tr>
<th>CSS UNIT</th>
<th>STRATA</th>
<th>I-S</th>
<th>C</th>
<th>K</th>
<th>I</th>
<th>% S IN I-S</th>
<th>Interval velocity (km/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>CSS0</td>
<td>U. Cretaceous</td>
<td>31</td>
<td>21</td>
<td>18</td>
<td>30</td>
<td>20 - 70</td>
<td>2.840</td>
</tr>
<tr>
<td>CSS1</td>
<td>Paleocene</td>
<td>79</td>
<td>8</td>
<td>7</td>
<td>6</td>
<td>60 - 100</td>
<td>2.3</td>
</tr>
<tr>
<td>CSS2</td>
<td>Eocene</td>
<td>79</td>
<td>8</td>
<td>7</td>
<td>6</td>
<td>60 - 100</td>
<td>2.130</td>
</tr>
<tr>
<td>CSS4</td>
<td>Oligocene</td>
<td>79</td>
<td>8</td>
<td>7</td>
<td>6</td>
<td>60 - 100</td>
<td>2.05</td>
</tr>
</tbody>
</table>
Fluid expelled during both transformation processes is proposed as fluid source that facilitated fluidization in the area. This in combination with upward migration of hydrocarbon from deeper depth and pore water from sediments during compaction.

5.5 CONCLUSIONS

- Measurements of dip angle, width and height of sandstone intrusions from the study area are comparable to other parts of the North Sea and FSB (Tab. 5.1)
- Late Cretaceous-aged intrusions have smaller values than Tertiary intrusions
- Polygonal faults in the area have higher dip values than intrusions
- Evidence of silica diagenetic transformation at multiple intervals
- Difference in dip populations could be due to subsequent compaction or clay mineralogy
- Fluid expelled during diagenetic transformation is proposed as source of fluid that facilitated fluidization of sands in the area in combination with hydrocarbon from underlying intervals and pore water from compaction of sediments

REFERENCES

BUREAU, D., MOURGUES, R., CARTWRIGHT, J., FOSCHI, M., & ABDELMALAK, M.M (2013). Characterisation of interactions between a pre-existing polygonal fault system and sandstone intrusions and the determination of paleo-stresses in the Faroe-Shetland basin. Journal of Structural Geology, 46, 186-199


ABSTRACT

High-resolution 3D seismic data covering an area of 2,845 km² aided the investigation of investigating the Cenozoic slope deposits and fluid-flow phenomena along the Nigeria Transform Margin. The survey was acquired to highlight the hydrocarbon potential of Cretaceous plays that form significant hydrocarbon reservoirs in the northern part of the study area; Aje field and Ogo discovery and in the Hilon and Fifa fields located on the western part. The studied interval, which encompasses the Cenozoic succession and part of the post-transform succession, consists of ~ 2 km thick overburden for the underlying Cretaceous plays. The study focuses on large-scale buried and active mass-transport complexes deposited with deep-water channel complexes and sediment waves and wide range of fluid flow phenomena formed from fluid migration within the basin. The fluid flow phenomena, which includes; pockmarks, vertical pipes, seabed mound and gas-hydrates related bottom simulating reflections were mapped both on the seabed and overburden. They are observed from Pliocene-aged sediments and distributed above structural highs, regional faults and active and paleo deep-water channels in the eastern part of the study area (area 1). If fluids responsible for formation of identified fluid flow features are thermogenic in origin, the features could be indicative of presence of an active petroleum system in the deeper interval, and fluids could have migrated along planes of deep-seated, regional faults. Hydrocarbon generation in the basin started in Late Miocene and continued till the present-day. This coincides with the presence of the fluid flow phenomena suggesting they could have been formed during hydrocarbon generation. The mass-transport deposits are mapped at multiple levels and volume of failed sediments increased through time such that they constitute very significant portion of the entire stratigraphic succession (up to 25 %) within area 2. Mechanism for formation of repeated and increased volume of mass transport deposit in the area is attributed to increased rate of sedimentation through time, slope gradient and probably sea level change. The presence of repeated mass-transport deposits and fluid flow phenomena on the Nigeria Transform Margin has implications for installations of offshore facilities; as they constitute potential geohazards and must be properly evaluated at the early stage of exploration and production. Presence of fluid flow phenomena will also aid in understanding location and distribution of potential reservoirs and fluids along the margin. The study also presents the first documentation of polygonal faults from offshore Nigeria. Fault throws are smaller than those recorded in the North Sea and Faroe-Shetland basins but have similar dip angles.
6.1 INTRODUCTION

Significant interest and exploration activity along the equatorial conjugate margins led to acquisition of a 2,845 km$^2$ of GeoStreamer. 3D high-resolution seismic data from the Nigeria Transform Margin in 2010 by Petroleum Geo-Services (PGS) in cooperation with the Department of Petroleum Resources (DPR) of Nigeria. It was acquired, to confirm the presence of Cretaceous play fairways already discovered along the West African Transform and Brazilian margins (Fig. 6.1). The survey area falls within the Dahomey-Benin basin, part of the east-west aligned sedimentary basins formed during the Late Cretaceous rifting of the African and South American plates (Fig. 6.2a) (Brownfield & Charpentier 2006; Greenhalgh et al., 2011).

All the basins on both sides of the continents have similar structural and stratigraphic features; exploration activities in the basins have increased significantly in the last few years due to successes from recent discoveries such as the world-class Jubilee field in Offshore Ghana, Venus and Odum fields (Brownfield & Charpentier 2006). Although, exploration activities started in the area much earlier following the discovery of bitumen and tar sands in Late Cretaceous outcrops along the African Equatorial conjugate margin; this did not yield desired commercial accumulations (Greenhalgh et al., 2011). However, continuous exploration with the use of better resolved seismic data and data gathered from initial wells drilled revealed presence of two main petroleum plays, which includes; the older syn-transform Aptian-Albian fields such as Hihon, Fifa, Tano and the younger, post-transform Upper Cretaceous fields such as Aje, Panthere, Belier (Greenhalgh et al., 2011).

The study area is located in the western part of Nigeria within the West Africa Transform Margin (WATM) covering Oil Prospecting License 312, 313 and 314 (OPL) (Fig. 6.1b). It is bounded to the north by Aje field and Ogo discovery within OML 113 and OPL 310 respectively, to the west by the Hihon and Fifa fields and to the east by the Niger-Delta basin (Fig. 6.1a). Water depths recorded in the area is between 1.5 and 3.8 km. The studied interval is bounded at the base and top by the Top Albian unconformity and present-day seabed respectively, which formed the thick overburden for underlying Cretaceous source and reservoir rocks (Figs. 6.2c). High-resolution, three-dimensional (3D) seismic data facilitated detailed study of series of seabed and subsurface features. These features include; soft-sediment deformation and remobilization products (MTDs), depositional elements and fluid-flow features, which represent significant part of the basin evolution and fluid-flow history.

Mass-transport deposits (MTDs), deep-water channels, and sediment waves form important components of the continental slope of the Nigeria Transform Margin. Mass-transport deposits (MTDs) are common in deep-water settings and easily recognised on seismic sections due to their chaotic internal character, large size, extensive nature and distinctive external geometry (Shipps et al., 2011). Integration of 2D, 3D seismic data, side-scan sonar, multibeam bathymetry, well data and outcrop studies have improved understanding of MTDs in the last few decades. This has helped the study of their geometries, distribution, evolution and relationship with other depositional elements.
The MTDs form up to 40% of the entire succession studied with high-level of preservation of most of its components such as head scarps, lateral margins, deformed blocks, ramps etc, used as kinematic indicators to unravel the evolution and direction of translation of failed sediments (Bull et al, 2009). Repeated occurrence of mass-transport deposits in the area suggests an unstable slope throughout the Cenozoic and as such very critical to exploration and production as they would form potential geohazards for offshore facilities installations and subsequent drilling (Martinez et al., 2011; Posamentier & Martinsen 2011). The association of MTDs with turbidites, which constitute significant target for deep-water drilling, suggest the need to map their lateral and vertical distribution and also to understand their morphology (Shipp et al., 2011; Nelson et al., 2011).

Fluid flow features are formed as a result of fluid movement within the sedimentary basin; this could be water, gas or oil or a combination of the three; represented as high or low amplitude anomalies on the seismic data (Judd & Hovland 2007; Cartwright et al., 2007; Løseth et al., 2009). A wide range of fluid flow features occur in the geologic record either on the present-day seabed or in the subsurface; they include sandstone intrusions, mud volcanoes, pockmarks, pipes, chimneys, bottom simulating reflections (BSRs), carbonate mounds, diageneric boundaries and polygonal faults (Shipley et al., 1979; Cartwright 1994; Cunningham & Lindholm 2000; Graue 2000; Løseth et al., 2001; 2011; Davies 2003; Cartwright 2007; Huuse et al., 2010; Andersen 2012). Fluid source could be either thermogenic, biogenic or both (Gay et al., 2006a; Judd & Hovland 2007). We observe both seabed and overburden fluid flow features such as pockmarks, pipes and BSR, along the Nigeria Transform Margin and these could be indicative of active petroleum system in the area. Hydrocarbon generation within the basin began in the Late Miocene and continued till date, although generation started much earlier in neighbouring basins (Brownfield & Charpentier 2006) (Fig. 6.2b).

The aim of this paper is to document the occurrence of mass-transport deposits and other depositional elements and fluid flow features along the Nigeria Transform Margin. This includes details of their spatial distribution, mode of occurrence as well as their usefulness in understanding the evolution and fluid flow of the basin. Main results from the analysis of 3D seismic data include; (1) sub-division of the post-transform section into five (5) main seismic units separated by major unconformities and surfaces; (2) spatial and temporal distribution of mass transport deposits through time; (3) documentation of fluid-flow features which includes pockmarks, pipes, furrows, BSRs restricted in the eastern part of the area and their relationship with structural highs, deep-water channels and regional faults; and (4) presentation of the first documentation of polygonal faults along the Nigeria Transform Margin.
Fig. 6.1(a) Gulf of Guinea Province (7183) with location of oil and gas fields shown in red outline (b) map showing the structural zones along the West African transform Margin and location of study area. The area covers OPL blocks 312, 313 and 314 as show in red. Yellow and blue boxes represent location of soft-sediment deformation features and fluid flow pipes by Davies 2003 & Laseth et al., 2011 respectively. Aje field and Ogo discoveries also shown. Area falls within the frontal deformation zone. Inset shows location with the Atlantic (Redrawn from Brownfield & Charpentier 2006; Techlink, PGS 2006)
6.2 GEOLOGIC SETTING AND PETROLEUM SYSTEM

The study area is located within the Dahomey-Benin basin, which stretches from southeastern Ghana to southwestern Nigeria (Obaje 2009). The basin is separated from the Niger Delta by the Okitipupa ridge (Obaje 2009). This basin forms part of the east-west aligned basins within the Gulf of Guinea that consists of Cote d’Ivoire, Ghana, Togo, Benin, western part of Nigeria coast and for the West African Margin and Guyana, Suriname, French Guiana and northern Brazil on the South American margin (only the African margin shown in Fig. 6.1a) (Brownfield & Charpentier 2006). These basins were initiated during the Late Jurassic rifting between the African and South American plates; and are characterized by transform and wrench faults formed during the separation. Which results in similarities between the structural and stratigraphic elements within these basins (Fig. 6.2a) (Greenhalgh et al., 2011). The Nigerian Transform Margin (study area) and the other basins within the Gulf of Guinea are in contrast to other passive-margin basins such as the Lower Congo and Angola basins mainly by influence of transform tectonics, which dominated during basin evolution, and by the absence of salt tectonics (MacGregor et al., 2003).

![Paleogeographic map showing stages in the separation of Africa and South America during the Cretaceous (Brownfield & Charpentier 2006)](image)

**Fig. 6.2 (a).** Paleogeographic map showing stages in the separation of Africa and South America during the Cretaceous (Brownfield & Charpentier 2006)

Basin evolution along the margins experienced complex tectonic history, which occurred in three phases, separated by major unconformities (Fig. 6.2c). These include; pre-transform or pre-rift (Late Proterozoic to Late Jurassic), syn-transform or syn-rift (Late Jurassic to Early Cretaceous) and post-transform or post-rift (Late Cretaceous to Holocene) (Brownfield & Charpentier 2006). The Gulf of Guinea formed at the end of Late Jurassic to Early Cretaceous time was characterized by transform
and block faulting above regionally, extensive Paleozoic basin during the breakup of the north Atlantic (separation of North America from Europe and Africa) that started during the Late Permian to Early Triassic time (Ziegler 1988). Thick continental crust of the African and South American continental plates began to breakup in the Early Albian time and formed the basins separated by transform faults (Blarez & Mascle 1988). The culmination of transform tectonism in the middle to Late Albian time coincided with initial breakup of oceanic crust along the continents and formed the Gulf of Guinea initially as an anoxic oceanic basin; but by the beginning of Campanian, the Gulf of Guinea and the rest of the Atlantic Ocean had become completely oxic seaway (Brownfield & Charpentier 2006).

The stratigraphic section of the basin has been divided based on the three stages of tectonic evolution which includes; Precambrian to Lower Cretaceous rocks for pre-transform, Lower Cretaceous to Late Albian rocks for syn-transform and the Cenomanian to Holocene rocks representing the post-transform stage (Brownfield & Charpentier 2006). For the purpose of this study, we will only summarize the post-transform succession, which the studied interval encompasses (Fig. 6.2c). The Top Albian unconformity marked the end of the syn-transform phase, followed by thermal subsidence that continued till present day (Greenhalgh et al., 2011). In the middle to Late Cretaceous, deeply incised canyons were eroded into the shelf during relative sea-level falls and transported sediments into the basin as large turbidite fans, which are main reservoir targets along the transform margin (Fig. 6.2b & c) (Brownfield & Charpentier 2006; Greenhalgh et al., 2011). These sandstones were deposited within the Araromi and Agwu Shale Formation, which may have formed source rocks and seals for the reservoirs (Fig. 6.2c) (Borsato et al., PGS).

Non-marine to marginal marine conditions prevailed during the middle Cretaceous and is expected to contain gas-prone source rocks (MacGregor 2003; Brownfield & Charpentier 2006). Sediments deposited during the Late Cretaceous in the basin were divided two main stratigraphic units; the Abeokuta and Araromi Formations (Obaje 2009). Sandstone of the Araromi Formations forms the reservoir sands of the Aje and Seme fields in Nigeria and Benin respectively (Fig. 6.2c). Tertiary rocks unconformably overlie Cretaceous rocks and comprises of Paleocene to Eocene marine shales of the Imo Shale Formation and interbedded with Ameki Formation sandstones in the study area (Fig. 6.2c). A major Oligocene-Miocene unconformity separated the Early Tertiary succession from Miocene marine rocks (Fig. 6.2c) (Brownfield & Charpentier 2006; Borsato et al., PGS). Fluid flow features observed are concentrated within Pliocene to Recent sediments.

Generation and migration of hydrocarbon within the Dahomey-Benin basin started during the Late – Miocene (X2 in fig. 6.2b), and continued till present-day, though started in the Late Cretaceous in neighbouring basins (Fig. 6.2b) (MacGregor 2003; Brownfield & Charpentier 2006).
6.3 DATASET AND METHODS

6.3.1 Dataset

A 2,845 km$^2$ of GeoStreamer, 3D high-resolution seismic data from the West African Transform Margin was provided by Petroleum Geo-services (PGS). Seismic data covers Oil Prospecting Licence (OPL) 312, 313 and 314 (Fig. 6.3). The 3D seismic data is pre-stack time migrated with a bin size (inline and crossline spacing) of 12.5 m x 12.5 m. Data quality is very good except interval below the channel complex in the eastern part of the study area. Water depth ranges between 3000 – 3800 ms two-way-time (TWT) and seismic data goes down to six seconds TWT. The seismic data is zero-phase processed with normal SEG polarity such that an increase in acoustic impedance is represented by positive amplitude = red peaks = hard reflections. Frequency, horizontal and vertical resolutions were calculated for each unit assuming an average seismic velocity ($V$) of 2000 m/s (Tab. 6.1). Unfortunately, no well data was available for the study making it difficult to ascertain actual lithology and horizon and sequence ages where based on nearby field (Aje Field) (Appen 1.2 & 1.3).

6.3.2 Methods

The study area was divided into two areas for ease of description: area 1 - the eastern part (fluid flow zone) and area 2 (mass-transport deposit zone). Each of the areas represents approximately the limits of these features (Fig. 6.3). 6 major horizons were mapped using 2D and 3D tracking using Schlumberger Petrel. These horizons were matched from horizons in the survey north of the study area in OML133 (Aje field) therefore ages of horizons are based on previous interpretation (Fig. 6.1b; Appendix 1.2 & 1.3). Seismic stratigraphic techniques based on seismic facies, reflection continuity and terminations was also applied to map the area (Mitchum et al., 1977).
Fig. 6.2 (c). Simplified stratigraphic column and petroleum systems along the West African Transform Margin (adapted from Borsato et al., PGS). Also shown is the occurrence of MTDs and fluid flow features observed from the study area.
Fig 6.3 TWT structure map of the seabed topography showing the extent of the 3D seismic data used for study. Entire study area is divided into 2 areas for ease of description and discussion. Division is based on approximate extent of MTDs and fluid flow deposits.

Tab. 6.1 Key seismic data parameters such as frequency, velocity, horizontal and vertical resolution for each of the seismic units.

<table>
<thead>
<tr>
<th>SEISMIC UNITS</th>
<th>FREQUENCY (hz)</th>
<th>INTERVAL VELOCITIES (km/s)</th>
<th>HORIZONTAL RESOLUTION (m)</th>
<th>VERTICAL RESOLUTION (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>SU1</td>
<td>25</td>
<td>2</td>
<td>42</td>
<td>20</td>
</tr>
<tr>
<td>SU2</td>
<td>48</td>
<td>2</td>
<td>21</td>
<td>10</td>
</tr>
<tr>
<td>SU3</td>
<td>30</td>
<td>2</td>
<td>33</td>
<td>17</td>
</tr>
<tr>
<td>SU4</td>
<td>40</td>
<td>2</td>
<td>25</td>
<td>13</td>
</tr>
<tr>
<td>SU5</td>
<td>50</td>
<td>2</td>
<td>20</td>
<td>10</td>
</tr>
</tbody>
</table>

Several horizons between the main horizons were also produced from horizon stacking using Paleoscan to image features of interest on individual horizons. Time surface maps were generated from the horizons and used to create two-way-time (TWT) thickness and attribute maps. Attribute maps such as variance, root mean square (RMS), maximum amplitude, dip angle, dip azimuth and exact value were applied to image and investigate morphology of distinct features of interests such as mass-transport complexes, channels, regional and normal faults, pockmarks, furrows e.t.c observed in the area. Time slices and horizon mapping through the volume was useful for polygonal faults investigation. Iso-proportional slices were generated using a frequency decomposition volume in SVIPRO to image the deep-water channels in the eastern part of the study area (area 1). Bright spots for possible gas accumulation were defined from their anomalous high-amplitude reflections and reverse polarity produced as a result of presence of gas. Lithology is poorly constrained due to lack of well data.
6.4 OBSERVATIONS AND RESULTS

6.4.1 Sequence Stratigraphic Units

The studied interval encompasses the entire Cenozoic and Cretaceous successions bounded below by the Late Albian unconformity and top by the present-day seabed, which represents the post-transform interval (Figs. 6.2c, 6.4a-e). 3D seismic interpretation indicates presence of up to 2000 ms TWT (2 Km) thick post-transform interval assuming a velocity of 2 km/s (Fig. 6.4a-e). The tectono-stratigraphic framework of the interval is controlled by transform faulting that terminated in the Late Albian with deposition of thick post-transform sediments above the Top Albian unconformity above the faults (MacGregor et al., 2003). Unconformity is represented by a strong positive amplitude reflection mapped only in the northern part due to limitation in the part of the data available data. The post-transform interval was divided into five (5) seismic units bounded by Six (6) surfaces traced from the Aje field and the use of seismic stratigraphic techniques is based on reflection terminations and seismic facies (Mitchum et al., 1977). Units are described here as SU1 through to SU5 with the oldest being SU1 and youngest as SU5 (Figs. 6.4a-e, 6.5).

SU1 is characterized by transparent reflections and forms the entire Cretaceous section (Figs. 6.4). The unit is bounded at the top and base by the top Cretaceous and top Albian unconformities respectively (Fig. 6.2c). Although no well data is available to determine lithology within the unit but previous studies confirmed the unit is dominated by sandstone and shale (Brownfield & Charpentier 2006). The Late Cretaceous-aged sandstones form the reservoirs for the Aje and Seme fields and equivalent of the Jubilee field in Ghana (Fig. 6.2c). Unit thickness reaches up to 800 ms along the western part but totally absent where the top Cretaceous unconformity merges with the top Albian unconformity (Fig. 6.5a). SU2 consists of variable reflections from low to high amplitudes. Reflections are very continuous and undulating especially in the centre (Fig. 6.4b). Occasionally, reflections are also very chaotic within the unit. Chaotic reflections are due to presence of mass transport deposits within the unit (Posamentier & Martinsen 2011). This unit encompasses Paleocene to Eocene-aged sediments, bounded above by a major unconformity (Eocene-Oligocene?). Sediment thickness within the unit reaches up to 1100 ms. TWT (Fig. 6.5b). Presence of thrust structures is observed within this unit (Fig. 6.4c).

The SU2 is overlain by the SU3 (Fig. 6.4). Internally, it is characterized by low to moderate amplitude reflections. Chaotic reflections are also prominent within the unit. It is bounded above and below by the Oligocene-Miocene and Eocene-Oligocene unconformities respectively (Fig. 6.2c). The lower surface erodes into the underlying unit (Fig. 6.4a). Thickness map of the unit reveals series of N-S oriented, elongated anticlines separated by alternating lows (Figs. 6.4b & 6.5c). Thickness reaches up to 700 ms TWT in the western part where large-scale deformed blocks were pushed down the slope (Fig. 6.5c). SU4 is characterised by very transparent, parallel reflections bounded at the base by the Oligocene-Miocene unconformity. The top was placed below overlying unit characterised by low to high-amplitude, reflections belonging to SU5 (Fig. 6.4).
Fig. 6.4a. Dip line across the study area showing major surfaces and units. Surfaces extended from Aje field towards the northern part of the survey (PGS). Location of line shown on seabed map

SU4 is relatively thin in the centre of the study area (Fig. 6.5d). We interpreted the top of the SU4 as the base Pliocene interval based on change in seismic facies from underlying low-amplitude, transparent reflections to overlying low to high-amplitude reflections.

SU5 represents the youngest unit described in the study. It is characterised by low to high-amplitude reflections and often very chaotic (Fig. 6.4). The unit is bounded below and above by what we picked as the top of the Miocene section and seabed respectively. SU5 is dominantly characterised by mass transport deposits in area 2 (Figs. 6a, c & d). Area 1 within the unit is defined by series of high-amplitude, continuous to semi-continuous reflections associated with presence of deep-water channel complexes and fluid flow phenomena (Fig. 6.2e). Structural framework of the basin is dominated by N-S elongated anticlines and NW-SE regional faults.
Chapter 6

Fig. 6.4b-e. Strike and random dip lines across the study area showing seismic units and surfaces. Units are defined based on seismic facies and terminations. Units are extensively deformed into mass transport deposits.
Fig. 6.5. TWT thickness maps of the mapped seismic units
6.4.2 Seabed morphology

The morphology of the seabed in the study area is very irregular and imaged exceptionally in detail from time structure and attribute maps (Figs. 6.6 & 6.7). Dip angle and variance attribute on the seabed surface highlights key seabed features and provides an overview of related shallow, overburden features discussed in this paper. Both the seabed and sub-surface features are classified under depositional and fluid-flow products such as mass-transport deposits (MTDs), channels, sediment waves; and fluid flow elements include pockmarks, pipes, furrows, mound, bottom simulating reflector (BSRs) and polygonal faults. These features shape the seafloor bathymetry and would likely influence location of seafloor infrastructures. Structural highs and linear depressions created by faults were also well imaged (Fig. 6.6).

Area 1 is mainly characterized by seabed and overburden fluid flow features such as pockmarks, pipes, mound, furrows, BSRs and channels and some seafloor MTDs (Figs. 6.6 & 6.7). The headwall scarps and lateral margins of the MTDs are often well preserved on the seabed due to lack of subsequent deposition (Fig. 6.7) (Bull et al., 2009). Two types of channels are observed on the seabed in this area, and defined based on their level of sinuosity (Fig. 6.6). The main channel complex is highly sinuous and well imaged on the seabed maps (Figs. 6.6 & 6.7). A less sinuous channel is observed close to the end of the survey and the channel width increases down slope (Fig. 6.7). Both channels flow from NE-SW. Sediment wave train occur west of the main channel and has a similar flow direction. The channels, MTDs and sediment wave train have similar flow direction (Fig. 6.7). Isolated pockmarks, although randomly distributed on the seafloor are associated with underlying structures. They are represented as circular to elongate depressions in plain view and on seismic section (Figs. 6.7a & c).

Area 2 is characterized by structural highs, MTDs and very straight and linear channels (Fig. 6.6). The channels and MTDs have a N-S and NW-SE flow direction respectively. Fluid-flow features were not observed on the seafloor within this area. Series of MTD blocks are observed on the seafloor in the southwest corner of area 2 close to the end of the survey (Fig. 6.6). These blocks are up to 120 ms high and 150 m wide. These blocks are very protruding and form positive topography on the seabed, and internal reflections terminate against the upper wall of the block. Hummocky relief is observed on the seabed due to presence of near seabed mass transport complexes.

Understanding the distribution of these seabed features, which includes soft-sediment deformation, and fluid flow features, is useful, as they constitute geohazards and should be evaluated before installation of offshore facilities. Presences of seabed and overburden fluid-flow features are possible indications of active petroleum system in the area 1.
Fig. 6.6 Dip angle and variance attribute maps to show the topography of seabed. Depositional, soft-sediment deformation and fluid flow features such as, submarine channels, sediment waves, mass transport deposits, pockmarks and mound are well imaged. Sediments are transported down the slope.
6.4.3 Mass Transport Deposits (MTDs)

MTDs are important products of soft-sediment deformation in our basins in which very large volumes of sediments are transported down the slope during failure (Morscadelli & Wood, 2008; Bull et al., 2009; Shipp et al., 2011). They are often characterised by unique kinematic indicators well imaged from seismic data. Three main domains are commonly recognised in a mass-transport deposit. They are headwall, translational and toe domain (Fig. 6.7). Numerous and large-scale MTDs were identified vertically and laterally along the Nigeria Transform Margin and constitutes up to 50% of the entire stratigraphic section. This estimate may be low due to seismic resolution as smaller MTDs may be present. We adopt the general terminologies used by Bull et al., (2009) to define these MTD’s; these include headwall scarps, lateral margins, deformed blocks, pressure ridges, ramps and outrunner blocks (Shipp et al., 2011 & references there in). Internally, MTDs are characterized by very low-amplitude, chaotic and discontinuous reflections (Posamentier & Kola, 2003; Posamentier & Martinsen, 2011); occasionally reflections could exhibit high-amplitude character as in sand-prone, submarine MTDs (Meckel, 2011).

6.4.3.1 Headwall domain

The headwall domain consists of the upslope region dominated mainly by extensional processes (Bull et al., 2009). They include headwall scarps and extensional ridges and blocks (Fig. 6.7). The former is easily recognised from the seismic data both in seismic cross section and platform, and represents the position of initiation of deformed unit (Figs. 6.8a & 6.9b). In cross sections, they are often observed as a normal fault displacement that separates the MTD from the undeformed strata behind the headwall scarp (Fig. 6.9b). Series of headwall scarps ranging from few to tens of kilometres were identified in the area both on the seabed and from buried MTDs (Fig. 6.8a). The best-imaged ones are from the present-day seabed that have only recently occurred and no overburden deposition, although harder to see in seismic cross section (Fig. 6.8) (Frey Martinez et al., 2005; Bull et al., 2009). The headwall scarp exhibit an actuate geometry and provides information on direction of movement of the sediments. In our case, sediments moved from northeast to southwest (Fig. 6.8a).

6.4.3.2 Translational domain

This region forms the main body of the MTD (Fig. 6.7). They are grouped under lateral margins (scarps; strike slip deformation), basal shear surface (ramps and flats; grooves and striations), internal body of MTD (translated and outrunner blocks; slump folds) and top slide surface (longitudinal shears; secondary flow fabrics). Lateral margins are easily identified from the seabed MTDs (Fig. 6.7a). Lateral scarps/margins forms the sides of the MTDs and parallel to slope direction processes (Bull et al., 2009).
<table>
<thead>
<tr>
<th>Domain</th>
<th>Component</th>
<th>Image</th>
</tr>
</thead>
<tbody>
<tr>
<td>Headwall domain</td>
<td>Headwall scarps</td>
<td><img src="image1" alt="Headwall scarps" /></td>
</tr>
<tr>
<td></td>
<td>Extensional ridges and blocks</td>
<td><img src="image2" alt="Extensional ridges and blocks" /></td>
</tr>
<tr>
<td>Lateral margin</td>
<td>Ramps and flats</td>
<td><img src="image3" alt="Ramps and flats" /></td>
</tr>
<tr>
<td></td>
<td></td>
<td><img src="image4" alt="Ramps and flats" /></td>
</tr>
<tr>
<td>Translational domain</td>
<td>Remnant block</td>
<td><img src="image5" alt="Remnant block" /></td>
</tr>
<tr>
<td></td>
<td>Longitudinal shear</td>
<td><img src="image6" alt="Longitudinal shear" /></td>
</tr>
<tr>
<td></td>
<td>Glide tracks and outrunner blocks</td>
<td><img src="image7" alt="Glide tracks and outrunner blocks" /></td>
</tr>
<tr>
<td>Translated/rotated/Deformed blocks</td>
<td></td>
<td><img src="image8" alt="Translated/rotated/Deformed blocks" /></td>
</tr>
<tr>
<td>Toedomain</td>
<td>Fold and thrust systems</td>
<td><img src="image9" alt="Fold and thrust systems" /></td>
</tr>
<tr>
<td></td>
<td>Pressure ridges</td>
<td><img src="image10" alt="Pressure ridges" /></td>
</tr>
<tr>
<td></td>
<td>Eroded block</td>
<td><img src="image11" alt="Eroded block" /></td>
</tr>
</tbody>
</table>

**Fig. 6.7** Summary diagrams of key components of the mass transport deposits along the Nigeria Transform Margin often used for kinematic indication
(It separates the undeformed strata from the deformed or failed strata (Fig. 6.9b). Lateral margins trend N-S suggesting overall flow direction in from northeast to southeast. A very important part of an MTC is the basal shear or detachment surface which underlies the entire failed unit or body (Zhu et al., 2011). They are easily identified in seismic data and also in outcrops (Posamentier & Martinsen 2011). N-S seismic section across the area shows at least 10 MTDs that lie on basal shear surfaces (Fig. 6.9a). They are often continuous but may be affected by ramps, faults or other forms of displacements within the body of the MTD (Figs. 6.7, 6.9a & b). Ramps cuts down or upwards on the basal shear surface (Frey Martinez et al., 2005) and observed as a deep cut on the surface map (Fig. 6.9e). The most prominent ramps identified along the Nigeria Transform Margin occur on the base of SU5 and cut deeply into the SU4 (Figs. 6.9a & b). They vary in size, ranging from 3 Km to 20 Km and could be as deep as 150 ms TWT (Fig. 6.9a & e). Another major part of the MTD common in the area are translated and outrunner blocks (Figs. 6.7 & 6.9a-d).

Deformed blocks as high as 350 ms TWT and ~ 2 km in length are observed within SU 3 and 4 (Fig. 6.9a). They are similar in height to rafted blocks observed in Hinlopen Slide on the northern Svalbard Margin in the Arctic Ocean which are 450 m high and more than 5 km wide (Vanneste et al., 2006). Reflections within the blocks, if preserved are rotated to near vertical and often chaotic. Individual blocks form pyramids, which tapers to the top with a flat or rugose base (Fig. 6.9a - c). They decrease in size down the slope (Fig. 6.9b) and surface mapped above the blocks reveals circular to oval-shaped, isolated features (Fig. 6.9c). Alternating depressions occur between the blocks and could form mini basins (Fig. 6.9c). Long, linear features often interpreted as glide tracks with outrunner blocks at the end are observed on the top surface map of the blocks (Figs. 6.9b) (Nissen et al., 1999). A prominent eroded block is observed within SU5 (Figs.6.4b & 6.7). Internally, reflections are chaotic and transparent but surrounding reflections are characterised by high-amplitude, continuous reflections. It erodes into the underlying continuous, low amplitude unit SU4 (Fig. 6.7).

**6.4.3.3 Toe domain**

This represents the downslope part of a mass transport deposit, where it terminates or the region at which the movement stopped (Fig. 6.7) (Frey Martinez et al., 2005; Bull et al., 2009). It is made up of compressional structures at the downslope of the MTD such as thrusts, folds and pressure ridges (Fig. 6.7). Pressure ridges are semi-circular features associated with the end of a failed mass. Identifying these components of the MTDs helps to know what part of the system is been observed, and to make predictions the distribution of the MTD and its influence of other deep-water systems.

Utilizing combination of time surface maps and attribute extraction on the basal surfaces helped to investigate the presence and distribution of mass transport deposits. Based on this, we have mapped large-scale MTDs from seismic units 2 to 5 (Fig. 6.10). They are mostly concentrated in
area 2. Amount of failed sediments that formed the MTDs also increases through time. Figure 6.10 highlights the MTDs mapped based on the basal surfaces from each one. In total, 22 mass transport deposits with varying sizes. Individual MTDs range from few kilometres to tens of kilometres in length and between 50 to 450 m thick. Individual volumes are not calculated but sizes should give an idea on the volumes of failed sediments along the slope during the Cenozoic. MTDs are not mapped in area 1 (Fig. 6.10). Seismic quality is very poor in within SU2 to SU4 in area 1 and often transparent. Locally where seismic is good, they are characterised by continuous reflections that are sometimes displaced by faults. SU5 in area 1 consists of entirely fluid flow features and deep-water channels (Fig. 6.6). Failed sediments are transported down the slope in the area.

### 6.4.4 Deep-water channels

Series of channels are observed along the Nigeria Transform Margin from 3D seismic data (Figs. 6.11 & 12) and generally form an important component of continental slopes. They include both active and buried channels and are well imaged on the seabed. Three main geometries are observed in the area based on the level of sinuosity.

#### 6.4.4.1 Highly-sinuous channels

These include highly sinuous channels active and paleo-channels (Fig. 6.11). The main channel complex (CC1) trends from northeast to southwest for about 20 km across the area. The full length both in up dip and down dip direction cannot be determined due to seismic data limit. It is highly sinuous and erosionally confined. Channels are represented as series of high-amplitude packages with strongly incised erosional bases (Fig. 6.11). Mapping of the channels in area 1 was important as they form an important part of the fluid flow history in the area. Iso-proportional slices from the seabed (t10) to the base of the high-amplitude, reflection package (t1) revealed the channel geometry and other buried channels (Fig. 6.11). The slices show the evolution of the channels through time. Five channel complexes are revealed. CC1 and CC5 are active channels while CC2-CC4 are paleo-channels. Lithology within the channels cannot be ascertained without well data but based on high-amplitude character; channels are likely to be sandstone-rich. CC1 becomes more confined with time and occur in close relation with sediment waves (time 10). CSS5 is less sinuous and looks more like a levee of another channel but its location at the end of the survey makes it challenging to confirm this (Fig. 6.6). Circular depressions are observed along channel margin and within channel axis of the both active and buried channel complexes.
Fig 6.8. Mass transport deposits in the area (a) seafloor topography showing components of series of mass transport deposits. At least 3 are identified. Image also reveals other seafloor features such as meandering and straight channels, pockmarks, faults and mound. Red arrow shows transport direction of failed sediments down south (b) seismic section through the headwall scarp of MTD 2. Note how fault cuts through the sediments (c) dip seismic line revealing all three MTDs on the seafloor. Headwall scarps and lateral margins are well imaged. High-amplitude reflections observed directly beneath the seabed and above the faulted structural high. Line locations for b and c shown in a.
Fig. 6.9. (a&b) Seismic profile showing well-preserved, deformed MTD blocks and other features (c) variance extracted on top surface of deformed blocks (d) time structure map of base of SU5 showing MTD ramps
Evolution and distribution of MTDs along the Nigerian Transform Margin during the Cenozoic. Coloured patches represent single MTD drawn from its basal surface in petrel. Deformation increases with time. Note that outline of seabed MTDs are not included.
Fig 6.11. Iso-proportional slicing through a frequency decomposition colour blend volume (a) W-E seismic section showing location of slices (time 10 – time 1) from the seabed to the base of the channel complexes, Cc (b) individual iso-slice to image channels. At least five channel complexes/belts are observed. Cc1 is meandering and confined within the belt but Cc2 - 4 are disorganised. Cc5 forms a linear channel complex belt. Note location of seabed mound above paleo channels. MTDs are also observed.
6.4.4.2 **Linear channels**

Series of depressions are observed on the seafloor within areas 2 and 3 (Figs. 6.5 & 12). Seismic profiles show the depressions are only between 10 – 15 m deep and up to 250 m wide (Fig. 6.12). Time structure map and attribute extraction on the seafloor reveals that depressions are often continuous and forms linear and narrow features, which are clearly seen on the seabed (Figs. 6.11a, d & h). The long and linear features are only observed within areas 2 and 3 and have N-S and NE-SW orientation respectively. They are interpreted as linear channels with no sinuosity similar to those observed offshore Angola (Gee & Gawthorpe 2007). According to them, they suggested the linear channels were formed from erosional lineation on the slope created by large and infrequent turbidity current and often affected by complex topography. Azimuth map of the seabed in the study area shows how these linear channels are deflected around the structural high and MTD blocks such that channels are compressed close to the structures and then bifurcates forming newer channels (Fig. 6.12a&b). We describe 3 phases, which includes the normal phase, where channels have not been affected by structural high or MTD blocks. Seismic profile c shows only 3 channels (1 – 3) (Fig. 6.12c), but close to the structural high the channels are compressed and deflected by the high, which represents the second phase. Finally, the bifurcation phase where channels 1 and 2 bifurcates and forms additional channels 5 and 4 respectively (Figs. 6.12). Width of individual channel also decreases towards the structural high. Based on this we support earlier interpretations from offshore Angola by Gee & Gawthorpe (2007), that these linear channels are affected by complex topography.

6.4.5 **Sediment waves**

RMS attribute at -50 ms below the seabed reveals a 25 km long linear feature in the eastern part of the study area (Fig. 6.13a). Average width across the feature is 2 km, which increases abruptly in the southern part and forms a lobe similar to terminal lobes within deep-water environments. It has the same NE-SW orientation as the main channel system but terminates before the end of the survey. The attribute map shows that the bright amplitudes imaged within the feature correlates to high-amplitude, anomalous reflections on seismic cross section across the feature (Fig. 6.13b). Seismic profile through the lobate part of the feature shows the anomalies are constrained with looks like a cut-off loop of the channel and interpreted as a sediment-wave train (Fig. 6.13c).

This pattern of sediment waves is very unique as it develops within what could have been an abandoned channel, hence the shape (Fig. 6.13a). The down-dip lobate part of the sediment wave could have represented the cut-off loop of the old channel (Fig. 6.13a & c). We assume the sediment waves were formed by turbidity current. Sediment waves within leveed channel complex and channel overbank have been interpreted in the Niger Delta basin (Posamentier & Kolla 2003; Sutton & Mitchum, 2011). Relationship of sediment waves observed in the area with gravity-induced processes suggests they were created by turbidity currents.
Fig. 6.12 (a&b) TWT surface and RMS attribute map of the seabed showing linear channels. Channels react near structural high; they merge and bifurcate downslope forming two more channels (c-f) seismic profiles downslope across channels (g) dip map of the seabed showing the linear channels.
Fig. 6.13. Sediment waves (a) RMS amplitude map @ 50 ms TWT below the present day seabed showing morphology of sediment wave. Transport direction is NE – SW as the channels (b) cross section through the train of sediment wave (c & d) dip and random lines showing how the reflections interpreted as sediment waves are constrained within the channel margin. Note presence of polygonal faults. Location of lines shown in “a”
6.4.6 Fluid Flow Phenomena

6.4.6.1 Pipes and high-amplitude reflections

Vertical and narrow columns in form of pipes are clearly visible from seismic cross section in the upper stratigraphic seismic unit 5 of the study area. They are between 50 – 80 m wide and extend about 400 ms below the seabed (Fig. 6.14a). Within the features, seismic response is slightly distorted and reflections are either concave downwards inform of stacked intervals of pull-up structures or concave upwards inform of stacked cones (Figs. 6.14c-g). Surrounding reflections are normal and continuous. They are often located below seabed depressions and have a circular to oval shape on time slice (inset of fig. 6.14a). In the northern part of area 1, these vertical columns terminate above a structural high at about 2150 ms TWT below the present day seabed. Similar features have been interpreted as blow-out pipes formed as a result of fluid migration through the stratigraphic succession (Løseth et al., 2001; 2011; Gay et al., 2007; Cartwright et al., 2007; Moss & Cartwright 2010; Huuse et al., 2010). In the study area, the structural high is faulted at the crest by series of normal faults (Fig. 6.14a). Amplitude quality diminishes with the vertical columns and increase towards the top of the structural high. Amplitude anomalies are often observed either directly below the column (Fig. 6.14d) or adjacent to it at the level at which the columns terminate (Fig. 6.14a & f). In most cases, the high-amplitude reflections are characterized by high-amplitude, reflection packages with reversed seabed polarity, such that a hard kick is overlain by a soft kick (Fig. 6.13a) (Schroot & Schuttenhelm, 2003; Andreassen et al., 2007). These amplitude anomalies form bright spots and could be associated with gas accumulation. Occasionally, the bright spots also terminate against the fault plane (Fig. 6.14f). Similar bright amplitude or bright spots beneath or along vertical zones have also described in other parts of the deep-water Niger Delta basin (Loseth et al., 2001; 2011) and Barent Sea (Andreassen et al., 2007). They are often interpreted to be associated with gas accumulations such as gas charged sands within deep-marine reservoir channels or fans. Based on the observations presented above, the vertical columns are interpreted as pipes. These pipes as well as faults can act as pathways for underlying fluids to migrate and be expelled onto paleo or present day seafloor (Gay et al., 2004; Ligtenberg 2005; Loseth et al., 2009; Ho et al., 2012).

6.4.6.2 Pockmarks

Numerous depressions are identified on the seabed from seismic cross section (Fig. 6.14a). They exhibit circular, oval or elongate geometries in plain view and are randomly distributed (Fig. 6.14b). These depressions have been observed both on the present-day seabed and paleo seabed. They are interpreted as pockmarks (Hovland & Judd 1988; Heggeland 1998; Judd & Hovland 2007; Gay et al., 2006a, 2006b). Since their first recognition on the Scotian shelf from sidescan records by King & MacLean (1970), these fluid flow features have been documented in several basins in the world (Rise et al., 1999; Ligtenberg 2005; Judd & Hovland 2007; Gay et al., 2007; Andresen, 2012;
Reiche et al., 2011; Ostanin et al., 2012). Original simple geometries of pockmarks can be altered through merging of individual pockmarks, carbonate precipitation and bottom current erosion to produce more diverse range of geometries such as elongated, bulls-eye, composite and complex (Andresen et al., 2008). Pockmarks identified along the Nigeria Transform Margin are classified based on geometry, occurrence and location and are observed within area 1 (Fig. 6.6)

Fig. 6.14. Isolated pipes and pockmarks above a structural high in the northern part of the study area (a) seismic section through vertical columns and depressions on the seafloor interpreted as pipes and pockmarks respectively. Inset shows the circular to oval planform geometry @ -1808 ms twt (b) Dip angle map of the seafloor reveals the distribution of pockmarks (c-g) isolated pockmarks and underlying pipe anomalies. Locations shown in b. Note the occurrence of high-amplitude anomalies below pipes, along fault planes and above structural. Anomalies are possible gas accumulations
Isolated/Scattered and pipe-related pockmarks

In seismic cross sections, they are observed as V or U-shaped depressions on the present day seabed. They are up to 15 ms deep and up to 60 m wide, isolated depressions and scattered randomly on the seabed above a structural high in the northern part of area 1 (Fig. 6.14). Spacing between individual pockmarks is irregular and they occur directly above underlying vertical columns interpreted as pipes (Fig. 6.14a). The isolated pockmarks and vertical pipes are likely to be genetically related. Relationship between pockmarks, pipes and sandstone reservoir was identified in the deep-water Niger Delta (Loseth et al., 2001; 2011). It was suggested that crater-like depressions on the seabed formed from gas expulsion from underlying hydrocarbon-charged reservoir unit.

Stacked pockmarks

Five horizons were interpreted locally around what appears to be vertically, stacked depressions between 1975 – 2275 ms TWT in the eastern part of the study area (Fig. 6.15a). In plain view, depressions exhibit circular geometry on each of the horizons (Fig. 6.15b). Depth of individual depression and width varies between 10 – 35 ms and 270 – 480 m from shoulder to shoulder respectively (Fig. 6.15b). Depth and width of the stacked pockmarks increases with depth (Figs. 6.15bi-iv). This relationship changes on the last horizon mapped (Fig. 6.15bv). It is unclear as to what is controlling the change in dimensions but we observe the deepest depression also coincides with presence of an increase in amplitude (Fig. 6.15a). The stacked depressions are associated with the hanging wall of the faults and the high-amplitude, soft-kick reflections (possible gas accumulation) terminate against the fault plane (Fig. 6.15a & d). They are interpreted as stacked pockmarks similar to those from the Lower Congo Basin and other sedimentary basins and indicative of repeated fluid expulsion within the sedimentary column (Cartwright et al., 2007; Andresen & Huuse 2008; Frey-Martinez et al., 2011).

Fault-related pockmarks

Circular or elongated depressions observed with normal faults along the Nigeria Transform Margin are interpreted as pockmarks (Fig. 6.15a-e) (Hovland & Judd, 1988). The seismic profile and attribute maps below the seabed shows presence of pockmarks along and above faults (Fig. 6.15e & f). The faults are oriented NW-SE, perpendicular to the channels and MTDs on the seabed (Fig. 6.6). Occasionally, the faults offset the present day seabed and create linear depressions on the seafloor (Fig. 6.15f). This suggests faults are likely active. These pockmarks occur either along the hanging wall of the faults (Fig. 6.15d) or directly above fault planes (Fig. 6.15e) as in fault-hanging wall and fault-strike pockmarks respectively similar to those observed in other parts of the West African margin (Pilcher & Argent, 2007). Presence of pockmarks along faults is likely indication of fluid leakage through the fault (Ligtenberg, 2005). Pockmark and fault relation is well documented from the Lower Congo Basin; the faults create curved depression on the sea floor and served as pathways for fluid migration (Gay et al., 2007).
Fig. 6.15. Seismic expression of pockmarks (a) stacked pockmarks and schematic diagram (b) surface of individual level of stacked pockmarks. Note how it deepens and widens with depth (c) another example of stacked pockmarks (d-f) pockmarks associated with fault, (d) above the fault plane (e) along hanging wall of fault (f) TWT and attribute maps on the seabed showing planview expression of pockmarks and faults
Channel-related pockmarks

Variance attribute extracted on the seabed shows large number of depressions (red arrows) similar in size and depth as those described above within the channel axis and along margins of both active and buried channel complexes and interpreted as pockmarks (Fig. 6.16) (Hovland & Judd 1988). These pockmarks are 200 – 300 m wide and depth of ~ 50 ms TWT. They are mostly circular in plain view and more regularly spaced about 1 km than those observed above the structural high (Fig. 6.14b). The pockmarks follow the meandering geometry of the channels (Fig. 6.15). The paleo-channels are located at about 200 – 250 ms below the seabed where the pockmarks occur (Figs. 16d & e). The channels are characterised by high-amplitude reflections suggesting sandstone lithology. Presence of pockmarks above stacked turbiditic paleo-channels has been well documented in the Lower Congo basin (Gay et al., 2003, 2004, 2006, 2007). Pockmark formations have been attributed to fluid expulsion from these active and buried channels with the fluids sourced either directly from the channels or from deeper intervals and the channels acted as permeable conduits for fluid migration (Gay et al., 2006, 2007). Variance attribute on the seabed shows presence of small faults above buried channels, these faults could have enhanced upward fluid migration from underlying buried channels forming pockmarks on the present day seabed (Fig. 6.16a). Fluid expulsion from deep-water channels has also been associated with emplacement of sandstone injectite in the deep-water Niger delta towards the eastern part of the study area (Davies, 2003).

Elongated pockmarks

Series of high-amplitude, wedge-shaped anomalies are observed at ~ 25 ms below the seabed (Fig. 6.17). These anomalies are characterized by two full reflection cycles starting with a hard kick at the top and a soft kick at the base. They are isolated packages, about 25 ms thick and terminate against fault planes (Fig. 6.17b). Thickness of each reflection package increases towards the fault plane and wedges away from it. Amplitude diminishes away from the fault plane into continuous reflection like surrounding strata (Fig. 6.17a, b & d). The high-amplitude packages are layer-bound and occur continuously for about 15 km. RMS attribute extracted on the yellow horizon located ~ 100 ms below the seabed with a window length of 75 ms revealed the plan view geometry and distribution of these wedge-shaped, high-amplitude anomalies (Fig. 6.17a & c). The map reveals several randomly spaced, circular-oval or elongated shaped depressions oriented in NW-SE or W-E direction (Fig. 6.17a). Based on their geometries, they are interpreted as circular pockmarks and elongated pockmarks respectively. These elongated pockmarks are up to 1500 m long and 200 m wide. Similar features have been interpreted as furrows along the mid-Norwegian margin (Reiche et al., 2011) and Lower Congo basin (Gay et al., 2004); they are related to normal faults.
Fig. 6.16. Presence of pockmarks above active and paleochannels. (a) variance attribute extracted on the present day seabed. Pockmarks (red arrows) are randomly distributed within the present day channel-belt complex and above paleochannels. Location of seismic sections shown (b) line through the main channel-belt complex. Pockmarks occur above channel margins (c) seismic line across the main channel-belt. Pockmarks occur within and away from it (d & e) pockmarks on the seabed above paleochannels. Fluids could have migrated through porous sands within the channels or along faults to the seabed to create pockmarks.

We observe a unique relation between underlying normal faults, high-amplitude, wedge-shaped features and furrows (Fig. 6.17). Where underlying regional faults propagate through shallower sediments and wedge-shaped anomalies terminate against the fault plane, elongated pockmarks are formed in contrast to normal circular pockmarks formed where such relationship is not defined. This is clearly observed in furrows number 7, 8 and 9 as opposed to pockmarks 3 and 4 (Fig. 6.17).
This relationship could also suggest a transition from individual circular to elongated pockmarks created due to subsequent remodification of the pockmark geometry by deep-seated faults (inset in Fig. 6.17d). Suggesting they could have been formed initially as circular depressions but remodeled by faulting to create present elongate or linear geometries. Similar transition model from circular pockmarks to elongated pockmarks (furrows) was proposed in the central North Sea and elongation was attributed to bottomcurrent (Kilhams et al., 2011). The interval at which high-amplitude, wedge-shaped feature occur is highly faulted with smaller extensional faults (Fig. 6.17). Some of the planes of these faults coincide with the regional faults, and as such associated with the pockmarks.

Fig. 6.17. (a) 3D image with seismic cross section and RMS attribute extracted on the yellow horizon with a window length of 25 ms to reveal circular and elongate plan view geometries of high-amplitude, wedge-shaped anomalies (b) profile through isolated pockmarks (c) plan view geometry showing relationship between circular and elongated pockmarks and location of seismic profiles.
Seismic profile in 6.16a showing relationship between the deep-seated, regional faults and high-amplitude, wedge-shaped anomalies. Shallow interval also affected by polygonal faults. Inset shows transition from circular pockmark to elongated pockmarks due to fault interaction. Note presence of BSR.

6.4.6.3 Gas-Hydrate Bottom Simulating Reflector (BSR)

The seismic cross section shows the presence of a continuous reflection with negative polarity at about 300 ms below the seabed within SU5 (Fig. 6.18). The reflection tracks the seabed reflection but exhibit a cross cutting relationship with surrounding stratigraphic reflections (Fig. 6.18c). The reflection is consistently located at the same depth below the present day seabed (Fig. 6.18a). Below the reflection are series of high-amplitude packages with reverse seabed polarity. These packages have been interpreted as free gas accumulations. Based on geometry, reflection character, depth below the seabed and location of possible gas accumulation in the underlying interval, the reflection is interpreted as a bottom simulating reflector (BSR) (Shipley et al., 1979). BSRs are often observed in deep-water settings and associated with low temperature and high pressure (Shipley et al., 1979). They are primarily associated with gas hydrates and represent the bottom of a gas hydrate stability zone GHSZ (Gay et al., 2007; Serie et al., 2012). The negative acoustic response is formed from contrast between over lying; high-velocity gas hydrate zone and underlying; low-velocity free gas-saturated sediments (Gay et al., 2003; Berndt et al., 2004). Numerous gas hydrates have been documented on the continental in Nigeria down to southern Angola (Cunningham & Lindholm, 2000). Their occurrence with channels, faults and mobile substrate structures have also been documented along these margins.
BSR was mapped only where cross cutting relationship is observed. It is locally present and restricted to area 1 as with other fluid flow features described in previous sections. A relationship is observed between BSR occurrence and faults in the study area such that the mapped limit of the BSR correlates to location of regional faults in the area suggesting a genetic relationship (Fig. 6.18c). Some of the deep-seated faults terminate below the gas hydrate stability zone while others propagate further into the shallower section (Fig. 6.18a & b). Extent of the BSR mapped in the area suggests extent of gas hydrates present within the SU5, although this could have been underestimated or overestimated as previous drilling through BSR have not penetrated any gas hydrates and gas hydrates have also been encountered without evidence of BSR (Hovland, 2005). Pockmarks are observed on the present day seabed above gas hydrates (Fig. 6.18e & d). Previously, presence of gas hydrates and BSR was thought to impede upward flow of fluid through the gas hydrate stability zone but continuous identification of fluid flow phenomena such as pockmarks, pipes, gas hydrate pingoes above BSRs suggests otherwise (Cummingham & Lindolm 2000; Hovland 2005; Gay et al., 2006a; Ostanin et al., 2012; Serie et al., 2012). The interval above BSR is faulted by small extensional faults and these faults could have permitted migration of gas through the sedimentary column to the seabed as pockmarks. Hydrate dissolution have also been proposed as a potential mechanism for pockmark formation in the Niger Delta due to excessive overpressure generated during dissolution process (Sultan et al., 2010).

6.4.6.4 Seafloor Mound

In the south-eastern part of the study within area 1, a 30 ms high and 500 m wide positive feature is observed on the seabed (Fig. 6.19). This is well imaged from the attribute maps and frequency decomposition map of the seabed as an isolated dome-shaped structure in form of a mound (Figs. 6.6 & 6.11). At about 20 ms TWT below, there is a marked increase in amplitude in the reflection followed by a soft reflection event (Fig. 6.19b & c). Below the high-amplitude zone is a cylindrical-shaped, vertical feature well imaged on the seismic cross section and characterised by very low to transparent or distorted amplitudes. The cylindrical-shaped feature is ~ 300 ms long between 2425 and 2725 ms with different reflection character from surrounding strata. Internally, reflections form series of stacked pull-up geometries about 20 ms high suggestive of a high-velocity mound fill. Using a background velocity of 2 km/s, the velocity within the mound was estimated as ~ 3.3 km/s.
Fig. 6.18a&b. Seismic and interpreted section showing BSR (c&d) pockmarks occur above BSR and interval is polygonally faulted. Note presence of free gas below.
Although surrounding reflections can be traced within the vertical column but reflection are very weak with variable continuity. The transition between the surrounding strata and vertical column is abrupt and clearly imaged in cross section (Fig. 6.19b). In time slice, the feature forms a circular geometry and is located about 5km close to the main channel complex. Gay et al., (2007) described a similar feature on the seabed from Lower Congo Basin and core analysis suggested carbonate-rich sediments with cold-water corals interbedded with hemipelagic muds. A single mound was also described on the mid- Miocene unconformity that represented a paleo-seabed in the Norwegian-Danish basin and Northern North Sea; they were interpreted as sand extrudite (Andresen et al., 2009; Olobayo et al., 2015b). Other possible origins for the dome-shaped or circular feature on the seabed or in the sub-surface are mud volcano, shale diapir, salt body, carbonate mound, (Stewart 1999). No well or core information is available in the area to ascertain the lithology within the mound. A salt origin is discarded, as there is no evidence of halokensis in the area. Seismic amplitude character below the mound is similar to those described from the Angola Margin as gas hydrate pingoes (Serie et al., 2012).

The vertical column is rooted within high-amplitude, semi-continuous to discontinuous reflection packages interpreted as sandstone-rich channel (Fig. 6.19b & c). Opacity rendering was applied on a cropped volume to show relationship between the seabed mound, vertical column and
underlying sandstone-rich channel (Fig. 6.19d). Time slices through the vertical column below the mound shows circular geometry of the column and a neighbouring pockmark (Fig. 6.19e). Mound volcanoes have been described from the Niger-Delta basin but location of mound above a possible sandstone-rich channel makes a mound lithology unlikely (Graue 2000). However, due to the very high velocity within the mound (~3.3 km/s) a sandstone origin is also unlikely. Lithologies known to produce such high seismic velocities are often carbonates (Anselmetti & Eberli, 2012). We therefore propose a methane-derived carbonate mound origin formed from fluid sourced from underlying channel sands through the vertical column (Fig. 16d & e) (Cauquil & Adamy 2008, OTC).

6.4.6.5 Polygonal Faults

The seismic data reveal presence of networks of small, extensional normal faults in the area (Fig. 6.20). These faults are well imaged in the first 400 ms TWT below the seabed (Fig. 20 a & c). Fault throws measured are less than 12 m (between 3 – 11 m, 6 m average) and dip angle range of 41 – 50º (46º average) assuming a velocity of using 2000 m/s (Tab. 6.2). Time structure map, original amplitude and variance attribute extraction on horizons through the highly faulted succession shows faults form polygonal geometry in plain view (Fig. 6.20 b & d). Similar faults have been interpreted as polygonal faults, which was first recognised within Eocene succession of the North Sea basin and defined as layer-bound faults formed from dewatering of fine-grained sediments particularly mudstones during early burial (Cartwright 1994; Lonergan & Cartwright, 1999; Lonergan et al., 1998; Goulty 2001; Stuevold et al., 2003). They have since then been interpreted in several basins in the world within mainly fine-grained mudstones (Appendix 1.1). Other mechanisms recognised to cause shear failure in fine-grained sediments and attributed to their formation include gravity loading, alteration of volcanic ash, silica diagenetic reactions (Cartwright, 2011).

Based on observations above, we interpret these faults as polygonal faults and this study presents the first-ever documentation of polygonal faults in the deep-water settings of Nigeria. These polygonal faults have similar dip angles with those recorded in the North Sea and Faroe-Shetland but smaller fault throws (Tab. 6.2). They deform the SU3 - SU5 and occur in two tiers separated by a non-polygonally faulted interval; the upper tier tip terminates about 50 ms below the seabed and better imaged than the lower tier in SU3. The polygonal faults are randomly oriented in most parts the study area but close to the regional faults, the faults become linear and preferentially aligned with the NE-SW regional faults but perpendicular to the NW-SE regional faults (Fig. 6.20b & d).

Presence of polygonal faults within Pliocene to Holocene sediments suggests they are still fairly recent and could explain why they have very small throws compared to those documented in the
Fig. 6.19. Seabed mound (a) variance extraction on the seabed showing mound and other seafloor features (b) dip seismic line across the mound. Vertical column with distorted internal facies below the mound. Surrounding strata is unaffected by distortion (c) strike seismic line across the mound. High-amplitude intervals below the vertical column are paleo or buried channels (d) 3D image illustrating the relationship between the mound, underlying vertical column and sand-filled channels (e) time slices @ -2380, -2392 and -2404 ms TWT through the vertical column.
Table 6.2. Similarities and differences between polygonal faults in this study and other basins

<table>
<thead>
<tr>
<th>BASIN EXAMPLE</th>
<th>2D GEOMETRY</th>
<th>PLAN VIEW GEOMETRY</th>
<th>FAULT THROW (M)</th>
<th>RANGE/AV FAULT DIP (º)</th>
<th>AUTHORS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Central North Sea</td>
<td>Normal faults</td>
<td>Distinctly Polygonal</td>
<td>NA</td>
<td>30 – 70 (45)</td>
<td>Cartwright &amp; Lonergan 1996</td>
</tr>
<tr>
<td>Central North Sea</td>
<td>Normal faults</td>
<td>Distinctly Polygonal</td>
<td>8 – 100</td>
<td>27 – 67 (45)</td>
<td>Lonergan et al., 1998</td>
</tr>
<tr>
<td>Northern North Sea</td>
<td>Normal faults</td>
<td>Distinctly Polygonal</td>
<td>8 – 30</td>
<td>31 – 56</td>
<td>Olobayo et al., 2015</td>
</tr>
<tr>
<td>Faroe-Shetland Basin</td>
<td>Normal faults</td>
<td>Distinctly Polygonal</td>
<td>NA</td>
<td>55 – 85 (58 +/-2)</td>
<td>Shoulders et al., 2007</td>
</tr>
<tr>
<td>Faroe-Shetland Basin</td>
<td>Normal faults</td>
<td>Distinctly Polygonal</td>
<td>NA</td>
<td>Type 2a – 63 Type 3 - 68</td>
<td>Bureau et al., 2013</td>
</tr>
<tr>
<td>More Basin</td>
<td>Normal faults</td>
<td>Distinctly Polygonal</td>
<td>Few metres to 80</td>
<td>25 - 50</td>
<td>Stuevold et al., 2003</td>
</tr>
<tr>
<td>Lower Congo Basin</td>
<td>Normal faults</td>
<td>Distinctly Polygonal</td>
<td>5 - 20</td>
<td>NA</td>
<td>Gay et al., 2004</td>
</tr>
<tr>
<td>Nigeria Transform Margin</td>
<td>Normal faults</td>
<td>Slightly polygonal</td>
<td>3-11</td>
<td>41 – 50 (46)</td>
<td>This study</td>
</tr>
</tbody>
</table>

North Sea and Faroe-Shetland basins formed within much older sediments and terminate at the mid-Miocene and Intra-Oligocene unconformities respectively (Lonergan et al., 1998; Shoulders et al., 2007; Olobayo et al., 2015; Chapters 3-5). In the Lower Congo basin, similar faults are documented within Pliocene-aged sediments below the seabed and have similar throws as those observed along the Nigeria Transform Margin (Tab. 6.2). Another characteristic feature observed between the faults along both margins is occurrence of alternating layers with low and high-amplitude anomalies through the faulted interval (Gay et al., 2004). Where this is observed in the study area, the polygonal faults are more visible in seismic cross sections and this could be related to lithological characteristics. Polygonal faults observed along the Nigeria Transform Margin are more extensive than other fluid flow features and present within areas 1 and 2 (Figs. 6.4b-d & 6.20). Their occurrence along the margin and in the south within the Lower Congo basin and similarity in characteristics could suggest regional occurrence of these layer-bounded faults along the entire margin.
Fig 6.20. Seismic profile showing presence of polygonal faults networks with SU3-5 (b) twt map of the green horizon showing polygonal geometry of the faults from paleoscan (c&d) same line and variance on the green horizon from petrel. Note how the faults are better imaged using paleoscan. Polygonal fault orientation changes close to the major regional faults (e) time structure map and variance attribute from the shallower section to show polygonal faults.
6.5 DISCUSSION

This section summarizes the mechanism of MTD formation, controls on fluid flow distribution and fluid source. A summary diagram highlights all the deep-water depositional elements and fluid flow phenomena interpreted in the study area (Fig. 6.21).

Fig. 6.21 Summary of depositional, soft-sediment remobilization/deformation and fluid flow elements observed along the Nigerian Transform Margin
6.5.1 **Mechanism of MTD formation**

Mass transport deposits can be recognized at a variety of scales ranging from small-scale as in cores, medium-scale in outcrop and to regional seismic scales such as the Storegga slide offshore Norway (Bull *et al.*, 2009; Shipp *et al.*, 2011; Dykstra *et al.*, 2014). Regardless of the scale at which they occur, MTDs are direct response to slope instability in sedimentary basins (Posamentier & Martinsen 2011). We presented in the previous section, multi-event MTDs from the Nigeria Transform Margin. They include both buried and active MTDs from SU2 to present day suggesting repeated slope failure throughout the Cenozoic (Fig. 6.10). We also observed the magnitude of failed sediment increased through time in the area (Fig. 6.10). These mass transport complexes occur in association with other deep-water deposition elements such as channels and sediment waves (Fig. 6.6). Based on our observations presented in previous sections, the MTDs occur primarily within area 2 and described as the mass transport deposit zone (Fig. 6.22a).

Numerous studies have documented several mechanisms that cause slope failure, some of which include cause slope instability includes conversion of Opal A to CT, gas-hydrate destabilization, gas release, earthquake shaking, sea level changes, rapid or increased sedimentation, slope gradient (Davies & Clark 2006; Garziglia *et al.*, 2008; Zhu *et al.*, 2011; Nelson *et al.*, 2011). This product of soft-sediment remobilization or deformation is primarily triggered by difference in pore pressure within the sediment (Frey Martinez *et al.*, 2011).

We investigated some of these mechanisms in our study area and discuss them below. Silica diagenetic transformation of opal A to opal CT has been proposed previously as a trigger for submarine failure in the Faroe-Shetland basin (Davies & Clark 2006). Due to elevated pore pressure during conversion of opal A to CT can result rapid compaction and reduction in sediment shear strength making it susceptible to failure. This however is unlikely in our area, as we do not have any evidence of opal A to opal CT transformation.

Gas hydrates destabilization was also dismissed for slope failure in the study area as bottom simulating reflector was interpreted only locally within SU5, Pliocene-aged to recent sediments in area 1 but MTDs occur more regionally in areas 2 from SU2 – SU5. We also considered the effect of generation, expulsion and migration of hydrocarbons or formation water; however, based on our investigation of the fluid flow processes in the study area, we observed that all the fluid flow products are restricted within area 1 but MTD occur regionally outside these areas were no evidence of thermogenic fluid is observed (Frey Martinez *et al.*, 2011). However, we do not discount the possibility of formation water release from consolidation of sediment (Van Rensbergen *et al.*, 2003).

An alternative and common mechanism for formation of episodic mass transport deposit is sea level change (Nelson *et al.*, 2011). We have no absolute ages for the MTDs in the area to be able to match to sea level rise and fall making it difficult to relate the MTD sheets to sea level rise and fall. However, there was significant global fall in sea level at the onset of the Pliocene (Fig. 2.2).
Fig. 6.22 (a) variance on seabed (b-j) schematic representations of seabed and overburden fluid flow features observed in area 1
This correlates to the period of major increase of MTD development in our study area (Fig. 6.10). Even though, this alone is not sufficient enough to make reasonable conclusions. Thereby we cannot rule out the effect of sea level on episodic MTD formation as we do not have enough information for this. We considered effect of tectonics and earthquake activities. Nigeria Transform Margin falls within the Equatorial conjugate margin characterized by complex wrench and transform faulting. However, transform tectonism was active until Middle to Late Albian time, marked by development of the Late Albian unconformity (Brownfield & Charpentier 2006). This unconformity represents the lower bounding surface of our interval of study, suggesting transform tectonism was no longer active, but continuous extension of the crust resulted increase clastic deposition and thermal subsidence which continued till the Tertiary period in the area (Brownfield & Charpentier 2006).

Net sediment accumulation rate from the Late Albian unconformity to present day seabed was estimated using a simple calculation method adopted from Jordt et al., (2000) (Tab. 6.3) and a representative graph was plotted (Graph. 6.1). TWT values were obtained from thickness maps and a constant velocity of 2 km/s was used. It should be noted that results do not account for compaction, burial or erosion and only based on estimates given the data available.

<table>
<thead>
<tr>
<th>SEISMIC UNITS</th>
<th>SERIES</th>
<th>DURATION (Ma)</th>
<th>THICKNESS (ms) max</th>
<th>VELOCITY (Km/s)</th>
<th>NET ACC. RATE (m/Ma) max</th>
</tr>
</thead>
<tbody>
<tr>
<td>SU1</td>
<td>Late Cretaceous</td>
<td>34.5</td>
<td>800</td>
<td>2</td>
<td>23.2</td>
</tr>
<tr>
<td>SU2</td>
<td>Paleocene-Eocene?</td>
<td>32.1</td>
<td>1100</td>
<td>2</td>
<td>34.3</td>
</tr>
<tr>
<td>SU3</td>
<td>Oligocene?</td>
<td>10.87</td>
<td>700</td>
<td>2</td>
<td>55.2</td>
</tr>
<tr>
<td>SU4</td>
<td>Miocene?</td>
<td>17.7</td>
<td>900</td>
<td>2</td>
<td>39.5</td>
</tr>
<tr>
<td>SU5</td>
<td>Pliocene to date?</td>
<td>5.3</td>
<td>1100</td>
<td>2</td>
<td>150.9</td>
</tr>
</tbody>
</table>

Table 6.3 Estimated net sediment accumulation rates of Cretaceous till present day in NTM

Table 6.3 and graph 6.1 show increased sedimentation through time which corresponds to increase in magnitude of MTDs formed (Fig. 6.10). Decrease in rate of sedimentation between SU3 and SU4 can also be observed from the distribution map of the MTDs. Significant increase from 39.5 m/Ma in SU4 to 150.9 m/Ma in SU5 is also reflected from the MTD map. Based on this, we suggest formation of episodic MTD on the Nigeria Transform Margin was mainly driven rate of sedimentation and increase in magnitude of failed sediment was also controlled by sedimentation.
Chapter 6

Graph 6.1 Graphical representation of estimated net sediment accumulation rate in area. Inset diagram represents spatial distribution of mass transport deposits in the area.

Over steepening of the slope could also be a contributing factor to slope failure in the area. Slope gradient measured is ~ 1° for the present day and this could have enhanced rapid deposition or slope progradation of sediments especially in an area with high sedimentation rate (Zhu et al., 2011).

6.5.2 Controls on fluid flow features and distribution

Interpretation of 3D seismic data from the Nigeria Transform Margin shows evidence of fluid-flow features within SU5 in area 1 (Fig. 6.6, 6.21 & 6.22). Lack of other data such as well data, geochemical data or seepage slick from area makes interpretation based solely on observations made from the seismic data and previous studies. Analysis of these features was carried out using volume and surface attribute extractions to reveal their geometries and spatial distribution along the
margin. A summary table of all the fluid flow products interpreted in the area is shown in figure 6.20. These include: pockmarks, pipes, BSR, furrows seafloor mounds and polygonal faults (Fig. 6.20). They occur both on the present day seabed and below the seabed.

Pockmarks are attributed to upward expulsion of fluids either gas or water from an underlying source, they give indication of the presence of an active petroleum system (Hovland & Judd 1988, Rise et al., 1999; Gay et al., 2007; Judd & Hovland 2007) and are classified as focused fluid flow features alongside with chimneys, pipes and sandstone intrusions (Cartwright 2007; Huuse et al., 2010). Although pockmarks are randomly distributed, they are related to structural highs, deep-seated, regional faults and active and buried deep-water channels (Figs. 6.14-17). These erosional and tectonic structures constitute an important component of the plumbing system in the area (Fig. 6.22). Base on observations and interpretations from the area, we suggest these features have served as migration pathways either through focused zones of weaknesses along the faults or diffused within permeable sediments as in sandstone-rich channels (Ligtenberg 2005; Pilcher & Argent 2007; Gay et al., 2006, 2007). Active petroleum plays exist along the West Africa Transform Margin; which includes the syn-transform Aptian-Albian fields such as Hihon, Fifa, Tano and the younger, post-transform Upper Cretaceous fields such as Aje, Panthere, Belier sourced from Cretaceous shales (Greenhalgh et al., 2011). Most of the regional faults in area 1 are deep-seated and goes down into the Cretaceous interval where source and reservoir rocks within the basin are located (Fig. 6.2b). Pockmarks, pipes, furrows and BSR are related to faults (Figs. 6.22b, c, g-i) while the mound and pockmarks are related to active and buried channels (Figs. 6.22d-f). Seismic quality below the channels is very poor and chaotic, which made it difficult to map regional faults below the channel complexes (Fig. 6.4e). It is therefore assumed that fluids that generated pockmarks above the channels could either have been sourced from within the channels or through faults if present (Figs. 6.22d-f).

### 6.5.3 Fluid type, source and driving mechanism

Lack of geochemical data made it difficult to ascertain the type of fluid expelled during the formation of these seabed and overburden fluid flow features. Most likely fluids are water, gas or oil. In the Lower Congo basin, core samples were taken from pockmarks for geochemical analysis and this confirmed the presence of biogenic gas, thermogenic gas and combination of the two (Gay et al., 2006a). Presence of bright spots with reverse seabed polarity along fault planes and below pipes, and possible free gas below BSR strongly suggests presence of gas in the area (Figs. 6.14 & 6.22b,d & g-i). The Aje field located in OML113 in the northern part of the area is a successful gas field with its reservoirs within the Cretaceous interval (Fig. 6.1b & 6.2c). Recent drilling into Cretaceous sandstones in OPL310 (Ogo discovery) east of Aje field and north of the study area also encountered significant accumulation of oil (http://www.afren.com/operations/nigeria/opl_310/). This supports evidence of active petroleum system in the area.
Based on this, we suggest that fluid type is likely to be either gas or oil. However, we cannot exclude that pore water expelled from reservoirs also contributed to it as a result of differential compaction of coarse-grained sediments and fine-grained mudstones. Regional faults, which are rooted within Cretaceous interval, occur in association with fluid flow phenomena and likely to have facilitated upward migration of fluid from deeper intervals. It is unclear whether the faults are sealing or not but presence of fluid flow features or seal by pass systems in the shallow interval could suggest leakage along faults (Cartwright et al., 2007). We support both biogenic origin of hydrocarbon from shallow interval and thermogenic origin from deeper reservoirs or combination of both for hydrocarbon source. However, this cannot be confirmed without appropriate geochemical analysis (Judd & Hovland 2007).

In the study area, all the fluid flow products occur with the shallow Pliocene to recent section (SU5) (Fig. 6.2b-i). This coincides with timing of hydrocarbon generation and migration in the Cretaceous source rocks within the Dahomey-Benin basin, which started in the Late Miocene and continued till date, although much earlier in other basins along the transform margin (Fig. 6.2b) (Brownfield & Charpentier 2006). Based on this, we suggest timing of fluid flow products formation began after Late Miocene till the present day and fluid flow was triggered as a result of hydrocarbon generation within the basin. This assumption also supports a thermogenic origin for fluids in the area.

### 6.5.4 Implications

Presence of mass transport deposits and fluid-flow features are geological hazards as they result in slope instability and should be investigated before placement of drilling infrastructures (Shipp et al., 2011). MTDs constitute a significant portion of the entire succession and could have impact on sediment pathways and distribution. They can also serve as seals and reservoirs of source rock under the right conditions (Posamentier & Martinsen 2011). Episodic development of MTDs that are related to sea level falls have important implications for hydrocarbon reservoir studies as failed sediments could have been pushed down the slope or basin along with turbidites which are important targets for hydrocarbon exploration (Nelson et al., 2011).

Pockmarks, pipes and BSRs are evidence of active petroleum systems if forms from hydrocarbon but however, their presence also suggests breach in sealing sequence as in sandstone intrusions in the North Sea (Cartwright et al., 2009; Huuse & Cartwright 2007; Olobayo et al., 2015; Chapter 4). Impacts of pockmarks and other seabed fluid flow features on geology, biology and marine environment has been well documented by Judd & Hovland (2007). According to Cauquil and Adamy (OTC 2008), pockmarks and other seabed depressions are considered geoharzards during deep-water exploration and production activities and must be identified and evaluated at the early stages of the project. They went ahead to say that these seabed depressions may affect subsea
installations and must be mapped out carefully before installations of drilling equipment on the seabed (Frey-Martinez et al., 2011).

6.6 CONCLUSIONS

Based on analysis of 3D seismic data available; we divided the post-transform succession into five (5) major seismic units bounded by significant surfaces and major unconformities to investigate depositional and fluid-flow elements along the Nigeria Transform Margin. Conclusions from this study are:

- Presence of depositional, soft-sediment remobilization/deformation and numerous fluid-flow features, which shaped the seafloor topography and overburden succession have been identified on the Nigeria Transform Margin.
- Spatial and temporal occurrence of repeated, large-scale, mass transport deposits along the margin through time is indicative of long-term of slope instability and forms up to 40% of the stratigraphic section within area 2.
- Increased sedimentation has been proposed as major mechanism for repeated mass transport deposit in the area. Slope gradient and sea level change could also have contributed.
- The continental slope is deeply incised in eastern part by well-developed, meandering deep-water channels and gently incised by linear and elongated channels in the centre and western part of the area as revealed from the seabed topography map.
- Occurrence of fluid-flow features such as pockmarks, pipes, furrows, methane-derived carbonate mound and bottom simulating reflection are restricted to area 1. This suggests presence of active petroleum system in the area as well as indication of seal leakage.
- Relationship between pockmarks, pipes, furrows and bottom simulating reflection with regional, deep-seated faults suggests faults could have acted as migration pathways for upward fluid migration from underlying reservoirs.
- Three (3) main fluid sources are suggested; they include pore water, hydrocarbon from biogenic and thermogenic origin. This can only be confirmed with additional data such as geochemical data.
- Hydrocarbon generation and expulsion was proposed as the driving mechanism for formation of fluid flow features in the area.
- First documentation of polygonal faults within the western part of Nigeria margin. These faults have similar dip angles but smaller throw compared to polygonal faults in the North Sea and Faroe-Shetland basins. Fault throws are similar to those interpreted from the Lower Congo basin.
- Results from this study will be useful during exploration and production as mass transport deposits and fluid flow features could form potential geohazards and their distribution should be mapped out and evaluated at the onset of exploration.
ACKNOWLEDGEMENTS

We wish to thank Petroleum Technology Development Fund (PTDF) Nigeria for proving full scholarship that has made this research possible. We want to thank PGS for providing the 3D seismic volume for this project. Appreciation also goes to the reviewers for their constructive comments in the process of reviewing this paper.

REFERENCES


BORSATO, R., GREENHALGH, J., WELLS, S., ROBERSON, R., & FONTES, C. (?) Prospectivity of the Equatorial Conjugate Margins of Africa and South America: PGS presentation.


GOUPTY, N.R (2001). Polygonal fault networks in fine-grained sediments an alternative to the
synthesis mechanism. First break 19, 69-73


PETROLEUM GEO-SERVICES (2006). Techlink, a PGS Geophysical, 6, 2


284
7. DISCUSSION & CONCLUSIONS

This chapter summarizes the major findings and discussion from both study areas (Chapters 3-6). It also includes implications for soft-sediment deformation and fluid flow phenomena on overall basin evolution, hydrocarbon exploration and production. Finally, it highlights key recommendations for future research in the area. Figure 7.1 summarizes the main soft-sediment remobilization and fluid flow features observed in both study areas.

7.1 PRINCIPAL FINDINGS

Integration of 3D seismic and well data made it possible to investigate two areas; the Northern North Sea (NNS) and the Nigeria Transform Margin (NTM), located within major hydrocarbon prolific basins; the North Sea and the Dahomey-Benin basin (Fig. 1.1). Both study areas have been affected by soft sediment remobilization and fluid flow phenomena on a regional scale through geologic time. The understanding of these geological processes in deep-water settings of the North Sea, Niger Delta and other sedimentary basins has continued to increase, due to improved seismic reflection imaging, from 3D seismic data and synthesis with well data, outcrop and geochemical data (Van Rensbergen et al., 2003; Judd & Hovland 2007; Huuse et al., 2010).

Chapter 3 focused on the review of the stratigraphic framework of the Northern North Sea, divided into 10 major sequences from Early Cretaceous times to present day, based on 3D seismic, 2D lines and well data. Norwegian and Shetland mainlands formed the main sediment sources during the Cenozoic period through series of uplifts that deposited large, sand-rich channels and lobes into the basin centre. Although the area is mudstone dominated, these gravity-driven deposits contribute significantly to the overall lithology, forming thick-sandstone bodies penetrated by well bores. These sand bodies show severe modifications to their original geometries, due to post-depositional remobilization and injection that was prevalent in the area. No major faulting occurred in the post-rift succession, however, series of small-scale, extensional faults were mapped from Cretaceous to Miocene intervals. These faults have polygonal geometry in plan view and interpreted as polygonal faults similar to those observed in other parts of the North Sea (Cartwright 1994). This presents the first study to document polygonal faults propagating more than 2km of stratigraphy. This chapter also examined the well and seismic expression of a silica diagenetic transformation of opal A to opal CT with the present day location within Oligocene unit. This reflection was mapped across the area and represents a diagenetic boundary and not a sequence boundary, as previously interpreted (Martinsen et al., 1999; Jackson 2007).

Chapter 4 provides the first basin-scale documentation of sandstone intrusion complexes, emplaced at different levels during multiple episodes of injection. This forms the main chapter that the research is based on; hence the discussion in the next section will focus on it. The chapter
reviewed sandstone occurrences in the Northern North Sea in the light of recent findings of kilometre-scale sand injectites in adjacent areas of the study area. It examined their seismic expression and well logs calibration and documented their scales, geometries, distributions, relationship with host strata, as well as timing, potential parent bodies and driving mechanisms. This chapter includes interpretation based on mounting evidences and observations to suggest multiple, rather than single emplacement of sandstone intrusions in the area. Parent bodies for these intrusions are sandstones deposited into the basin during series of uplifts along the basin margins.

Chapter 5 provides quantitative analysis of sandstone intrusions, polygonal faults and silica diagenetic boundary in the Northern North Sea. For sandstone intrusions, dip angle, height and width were measured and compared with others from the North Sea. Similar measurements were observed. Older intrusions have different measurements from younger intrusions; this could be due to compaction or mudstone mineralogy. Fault lengths, directions and dip angle of polygonal faults were measured. The chapter examined relationship between dip populations for sandstone intrusions and polygonal faults. Based on this, it was suggested that the faults had no control on intrusion geometry, due to difference between their dip angles. Present day location of the opal A to opal CT boundary was interpreted below Late-Miocene aged intrusions and a possible genetic relationship was suggested.

Chapter 6 presents the first documentation of fluid flow phenomena from the Nigeria Transform Margin. They include paleo-pockmarks, seabed pockmarks, pipes, gas-hydrate bottom simulating reflections, seabed mound and polygonal faults. The chapter revealed details on their distribution, formation and implications on hydrocarbon exploration and production. It is hypothesised that, they were formed during hydrocarbon generation and migration in the basin, which began in the Late Miocene. Their relationship with underlying faults and channels, suggests fluid could have migrated from deeper part of the basin through faults of permeable channel beds, to form the features. Fluid source and type are unknown and can only be confirmed from geochemical analyses done in the area. The chapter also revealed presence of multiple occurrences of mass transport deposits, which constitute significantly to the basin stratigraphy. Slope failure was attributed to increased sedimentation rate through time, slope gradient and probably sea level change. This chapter will be very useful for future studies in the area and exploration activities, both in terms of indications for possible petroleum system and installation of offshore facilities.

Chapters 3-7 examine the soft-sediment remobilization and fluid flow in both areas. These geological phenomena provide important information on sediment type, sediment distribution, fluid type, fluid flow and fluid distribution in the basin. Understanding fluid flow, distribution and storage is crucial to basin analysis, to improve safe, efficient and optimal recovery in hydrocarbon exploration and production (Hurst & Cartwright 2007; Huuse et al., 2010). This can further provide reasonable insight into processes associated with basin evolution (Andresen, 2012).
Chapter 7

SUMMARY OF SANDSTONE REMOBLIZATION AND FLUID FLOW FEATURES IN THE STUDY AREAS

NORTHERN NORTH SEA

- Remobilized Channel
- Sand Injectites
- Silica Diagenetic Front
- Polygonal Faults

SANDSTONE REMOBLIZATION AND FLUID FLOW FEATURES INTERPRETED FROM BOTH BASINS

- Elongated Pockmarks

NIGERIA TRANSFORM MARGIN

- Pockmarks and Pipes
- Bottom Simulating Reflection
- Seafloor Mound
- Polygonal Faults

Elongated Pockmarks

Fig. 7.1 Summary diagram with seismic examples of sandstone remobilization and fluid flow features interpreted from both basins
7.2 DISCUSSION

7.2.1 Northern North Sea

The main focus of study in the Northern North Sea was on the sandstone intrusion complexes, manifested as high-amplitude, discordant or concordant anomalies, similar to those observed in other parts of the North Sea, Faroe-Shetland Basin, Barent Sea and Lower Congo Basin (Tab. 7.1) (Huuse & Mickelson; Shoulders et al., 2007; Cartwright et al., 2007; Saponova et al., 2012; Monnier et al., 2014).

7.2.1.1 Origin of amplitude anomalies in the Northern North Sea

Three main types of anomalies are observed from the Northern North Sea (NNS). They include high-amplitude, discordant, high amplitude concordant and mound anomalies (Chapter 4). Interpretation of the origin of discordant amplitude anomalies are mainly based on, but not limited to the following observations in seismic data: V, U or W-shaped in cross section, discordant with host mudstones, high-amplitude reflection, circular to oval geometry in plan view, 3D conical geometries, emplaced within low-permeability strata (usually mudstones), isolated nature and jack up of overburden strata (Huuse & Mickelson 2004). If penetrated by well bore, the amplitude anomaly should calibrate to sandstone lithology. For mound anomalies, they have steep dip angle, flat base, onlaps onto the mound, circular to oval geometry in plan view (Huuse et al., 2004; Andresen et al., 2009). Figure 7.2 shows schematic diagrams and key seismic examples illustrating some of the diagnostic criteria listed above for interpretation of remobilized and injected sands. Their discordant and high-amplitude nature, in most cases indicates they are different from the host strata and formed after deposition of the surrounding unit, which they are emplaced in.

The saucer-shaped anomalies have a concordant base with the discordant margins, dykes or wings attached on both sides (Huuse et al., 2004; Andresen et al., 2009; Cartwright et al. 2008). The more conical anomalies do not have significant concordant part at its base, indicating little or no horizontal propagation before dyke formation; however, it is uniquely characterized by a downward directed apex (Cartwright et al. 2008). Both the conical and saucer-shaped of anomalies typically are associated with doming or forced folding of the overburden; and this generally indicates intrusion or injection origin (Figs. 4.15 & 4.18) (Huuse et al., 2004; Shoulders et al., 2007; Szarawarska et al., 2010). This folding over anomalies could also be generated by differential compaction above depositional sandstone body (Dmitrieva et al., 2012), but typically for anomalies created by post-depositional processes, onlap of overlying sediment is often observed above the folding (Shoulders et al., 2007). A summary table of the geometrical characteristics of sandstone injectites, observed from the study area, is presented in table 7.2.
Table 7.1 Summary of geometric characteristics of intrusions measured in the area and other published examples from the North Viking Graben, Outer Moray Firth and Faroe-Shetland Basin

<table>
<thead>
<tr>
<th>UNIT/AGE</th>
<th>DIP ANGLE (degrees)</th>
<th>HEIGHT (metres)</th>
<th>UPPER WIDTH (metres)</th>
<th>LOCATION/ AUTHORS</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>MIN</td>
<td>MAX</td>
<td>MEAN</td>
<td>MIN</td>
</tr>
<tr>
<td>CSS0 (Cretaceous)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>1</td>
<td>20</td>
<td>7</td>
<td>7</td>
</tr>
<tr>
<td>CSS1 (Paleocene)</td>
<td>17</td>
<td>32</td>
<td>25</td>
<td>90</td>
</tr>
<tr>
<td>CSS2 (Eocene)</td>
<td>15</td>
<td>38</td>
<td>25</td>
<td>120</td>
</tr>
<tr>
<td>CSS4 (Oligocene)</td>
<td>12</td>
<td>35</td>
<td>20</td>
<td>60</td>
</tr>
<tr>
<td>Lower to mid-Eocene</td>
<td>25</td>
<td>40</td>
<td>-</td>
<td>50</td>
</tr>
<tr>
<td>Lower Eocene</td>
<td>5</td>
<td>25</td>
<td>-</td>
<td>100</td>
</tr>
<tr>
<td>Eocene to Oligocene</td>
<td>7</td>
<td>33</td>
<td>22</td>
<td>90</td>
</tr>
<tr>
<td>Mid-Late Miocene</td>
<td>5.5</td>
<td>22</td>
<td>24</td>
<td>-</td>
</tr>
<tr>
<td>Mid-Late Miocene</td>
<td>-</td>
<td>-</td>
<td>63</td>
<td>-</td>
</tr>
<tr>
<td>Mid-Late Miocene</td>
<td>-</td>
<td>-</td>
<td>40</td>
<td>-</td>
</tr>
<tr>
<td>Eocene to Oligocene</td>
<td>6</td>
<td>57</td>
<td>26 (+/- 2)</td>
<td>250</td>
</tr>
</tbody>
</table>

7.2.1.2 Possible interpretations of amplitude anomalies in the Northern North Sea

Several geological processes in the subsurface can cause formation of conical or saucer-shaped high-amplitude, discordant anomalies, similar to those observed in the study area. Some of them include: igneous intrusions, incised valleys, fault planes, pockmarks, seismic artefacts and sand injectites.
Fig. 7.2 Three (3) models suggested for the occurrence of sandstone in the North Sea basin with seismic examples from this study in the Northern North Sea (partly modified from Huuse et al. 2009; AAPG).
**Channels or incised valleys** - The conical V, U or W-shaped geometry in cross section is typical expression of channels or incised valleys; however, when observed in plan view, they are often circular to oval in shape and not representative of channels or incised valley systems (Fig. 4.14).

**Igneous intrusions** – Igneous intrusions often have high-amplitude reflection in seismic and form similar cross section, plan view and 3D geometry, as anomalies interpreted in the study area (Hansen *et al.* 2005; Shoulders & Cartwright 2004; Polteau *et al.*, 2008). Very close relationship in mechanics and geometries between igneous intrusions and discordant anomalies have been invoked by these workers. However, there are no records of igneous rocks in the area and calibrations of anomalies to sandstones make an igneous origin unlikely (Figs. 4.14c & 4.16b).

**Polygonal fault planes** – This unique class of fault often occurs with discordant anomalies observed in the area (Huuse & Mickelson). They are characterized by polygonal-shape in plan view and sometimes crosscut stratigraphy in cross section. However, we reject a polygonal-shape in plan view, as anomalies described in the area form conical or saucer-shaped geometries in cross section, which is unlikely for polygonal faults and also anomalies do not form polygonal geometries in plan view, instead they are characterized by circular or oval-shape (Fig. 4.14d).

**Pockmarks** – Pockmarks are fluid escape features and are generally formed within fine-grained sediments, like anomalies observed in the study area. Pockmarks form depressions in cross sections and majority of them are characterised by circular to oval geometry in plan view (Judd & Hovland 2007). Similar features were interpreted as pockmarks in the Outer Moray Firth (Cole *et al.* 2000); however in this study, the thickness of anomalies, which corresponds to the sand thickness, is almost uniform throughout its entire body, unlike pockmarks, which increases towards the centre (Huuse & Mickelson 2004). Also uplift or jack up of overburden, which is usually observed above anomalies in the study area is not common to pockmarks, making a pockmark origin unlikely (Figs. 4.15 & 4.18) (Monnier *et al.*, 2014).

**Seismic artefacts** – Similar V-shaped anomalies in seismic cross sections were originally interpreted as artefacts from diffraction (Løseth *et al.*, 2003). However, seismic artefacts are unlikely to terminate at nearly same stratigraphic level as we observe here and anomalies in the Northern North Sea are too organised to be artefacts (Fig. 4.14) (Huuse & Mickelson 2004). Also calibration to sandstone lithology suggests anomalies, as related to sedimentary bodies, rather than artefacts. Pull-up effects are typically observed beneath the conical-shaped anomalies; this relationship often exists when velocity within the feature of interest is higher than surrounding sediments, suggesting a geological feature, rather than an artefact (Løseth *et al.*, 2003; Andresen *et al.*, 2009). Lithologies that create such features include salt, carbonate, sand and magmatic materials. We have no knowledge of salt or thick carbonates around the area that could have remobilized into the intervals in question. Though anomalies show evidence of carbonate cementation in boreholes, but not often is the entire lithologies composed of carbonate (Hurst *et al.*, 2003; Huuse *et al*. 2004; Jonk et al., 2003. 2004).
7.2.1.3 Lithology of amplitude anomalies and interpretation as remobilized and injected sand

The sedimentary successions in the study area consist mainly of smectite-rich and siliceous-rich mudstones; characterized by low-amplitude, parallel and transparent reflections, high-gamma ray in seismic and well logs, respectively (Chapters 3-5). These intervals of mudstone form the host strata form the high-amplitude anomalies, creating sharp contrast between the seismic reflection of the anomalies and the background mudstones, due to difference in acoustic impedance contrast.

Wells do not penetrate all the amplitude anomalies interpreted from the area, therefore lithological interpretation will be based on anomalies intersected by boreholes, as presented in chapter 4 already. Lithologies of those anomalies not penetrated by wells were determined indirectly from seismic observations, similar seismic expressions and geometries with those penetrated by wells and other parts of the North Sea. However, this should be properly investigated, as several other geologic features have similar seismic expression and geometries.

Lithologies often associated with injections or give rise to high-amplitude anomaly in seismic include: salt, carbonate, tuff, chalk igneous rocks and sand (Loseth et al., 2003; Hudec & Jackson 2004; Hansen et al., 2005; Wild & Briedis 2010; Andresen & Clausen 2014). We have no knowledge of salt, carbonate, chalk and igneous materials in the area that could have created the anomalies observed. Tuffaceous mudstones exist within the Balder Formation, in the Late Paleocene to Early Eocene, however; we have no previous knowledge, where conical, discordant anomalies have been calibrated to tuff and this location of the tuffaceous mudstones does not explain the deeper anomalies (Huuse & Mickelson 2004). Salt and carbonate often create much higher acoustic impedance contrast with surrounding mudstones (Andresen & Clausen 2014).

Direct well calibration confirms that amplitude anomalies observed in the Northern North Sea coincide with sandstone units in boreholes (Figs. 4.14c & 4.16b). For anomalies not intersected by wells, lithology determination was based on seismic expression and similar geometries, as those intersected by wells and those observed in other parts of the North Sea (Lonergan et al., 2002; Huuse et al. 2004; 2007; Jackson & Somme 2011).

Anomalies observed in the study area are similar to conical and saucer-shaped sandstone intrusions, sand injectites and remobilized sandstones in the North Sea and other sedimentary basins (Molyneux et al., 2002; Huuse & Mickelson 2004; Huuse et al. 2004; Shoulders et al., 2007; Cartwright et al., 2007; Saponova et al., 2012; Monnier et al., 2014). Therefore based on the mounting evidences provided above and similarities with known examples from other basins, we interpret these discordant, conical and saucer-shaped anomalies as sandstone intrusions and remobilized sandstones.

With respect to whether intrusions are interpreted as remobilized depositional sandstones and partially or wholly injected sands, has been discussed by previous workers (Figs. 7.2b & c) (Duranti
<table>
<thead>
<tr>
<th>Intruded interval</th>
<th>Acoustic Impedance</th>
<th>Dip Angle</th>
<th>Dimensions (m)</th>
<th>Cross section/3D Geometry</th>
<th>Plan View Geometry</th>
<th>Overburden</th>
<th>Lithology</th>
<th>Timing</th>
<th>Injected/Remobilized</th>
</tr>
</thead>
<tbody>
<tr>
<td>CSS0 (Upper Cretaceous)</td>
<td>High-amplitude</td>
<td>1-20 (7°)</td>
<td>W: 150 - 1740 m; H: 7-90 m</td>
<td>Bedding</td>
<td>Channelized</td>
<td>Jack up, differential compaction</td>
<td>Sandstone confirmed from well</td>
<td>Upper cretaceous</td>
<td>Remobilized channels, extruded</td>
</tr>
<tr>
<td>CSS1 (Paleocene to Early Eocene)</td>
<td>High-amplitude, low-amplitude</td>
<td>17-32 (25°)</td>
<td>W: 440-1290m; H: 90-210 m</td>
<td>Same as CSS0, V-shaped geometries, mound</td>
<td>Isolated, oval-circular</td>
<td>Jack up, differential compaction</td>
<td>Sandstone confirmed from well</td>
<td>Middle Paleocene</td>
<td>Channels, extruded</td>
</tr>
<tr>
<td>CSS2 (Early Eocene to Oligocene)</td>
<td>High-amplitude</td>
<td>14-37 (24°)</td>
<td>W: 490-1830m; H: 120-215m</td>
<td>V, U, W and saucer-shaped geometries</td>
<td>Isolated, circular</td>
<td>Jack up, sediment onlaps</td>
<td>Sandstone confirmed from well</td>
<td>Mid-Late Eocene</td>
<td>Injected, remobilized</td>
</tr>
<tr>
<td>CSS3</td>
<td>High-amplitude</td>
<td>12-35 (20°)</td>
<td>W: 500 – 1940m; H: 90-215m</td>
<td>V, U, W, saucers, ziz-zag, complex geometries</td>
<td>Isolated, oval, circular</td>
<td>Jack up, sediment onlaps</td>
<td>Sandstone confirmed from well</td>
<td>Mid-Late Miocene</td>
<td>Injected, remobilized</td>
</tr>
<tr>
<td>CSS4 (Oligocene to Miocene)</td>
<td>High-amplitude, low-amplitude</td>
<td>NA</td>
<td>Extensive Mounded geometries</td>
<td>Circular, culmination</td>
<td>Sediment onlaps</td>
<td>Sandstone confirmed from well</td>
<td>Mid-Miocene to Ear Pliocene</td>
<td>Extruded</td>
<td></td>
</tr>
<tr>
<td>CSS5</td>
<td>High-amplitude, low-amplitude</td>
<td>NA</td>
<td>Extensive Mounded geometries</td>
<td>Circular-elongated mounds</td>
<td>Sediment onlaps</td>
<td>Sandstone confirmed from well</td>
<td>Early Pliocene</td>
<td>Extruded</td>
<td></td>
</tr>
<tr>
<td>CSS6</td>
<td>High-amplitude, low-amplitude</td>
<td>NA</td>
<td>Extensive Mounded geometries</td>
<td>Circular-culmination</td>
<td>Sediment onlaps</td>
<td>Sandstone confirmed from well</td>
<td>Early Pliocene</td>
<td>Extruded</td>
<td></td>
</tr>
</tbody>
</table>

**Tab. 7.2** Summary of geometrical characteristics of sandstone injectites observed in the Cenozoic Northern North Sea basin
& Hurst 2004; Szarawarska et al., 2010; Jackson et al., 2011; Hurst et al., 2011; Huuse et al., 2009; 2012; Andresen & Clausen 2014). The latter often implies dominant injection where all the sands have been injected from the parent body, which is often not attached to the injected body (Fig. 7.2c), while the former represents a depositional body that has been modified by process of sand injection, such that the parent body is still attached to the injected part and often forms the concordant or basal sill. We apply the same approach for distinguishing between dominantly injected and remobilized depositional sandstone in this study and based on this, we suggest that the area is majorly composed of initially deposited sandstone bodies that were later remobilized or injected into surrounding mudstone strata. In addition to this, we classify the conical discordant, high-amplitude anomalies as mostly injected and the saucer-shaped anomalies as remobilized depositional sandstones with exception of few examples were the basal concordant sill has been uplifted, suggesting full injection as in figure 4.19 (Figs. 7.2) (Huuse et al., 2009; Szarawarska et al., 2010; Andresen & Clausen 2014).

### 7.2.1.4 Parent sand body and feeder systems

Identifying the actual source or parent sand body for sandstone intrusions complexes is one of the key uncertainties and challenges in the study of sand injectites (Cartwright 2010; Morton et al., 2014). The presence of remobilized sand, sand injectites or sand extrudite indicates the existence of a parent sand body, either directly attached to, or detached away from it (Hurst et al., 2003; Shoulder et al., 2007). An injectite can be located either very close to the parent body forming wings at the side or top of the body (Huuse et al., 2007, Dmitrieva et al., 2012) or located either at some distance (100’s of metres) away from it (Shoulders et al., 2007; Vigorito et al., 2008; Andresen et al., 2009, 2014). Therefore, sand can be injected upwards, downwards or laterally (Jolly & Lonergan 2002; Vigorito et al., 2008; Svendsen et al., 2010; Kazerouni et al., 2011; Andresen & Clausen 2014).

The source sediment or parent body must be uncemented and sealed within the host rock such that when excessive pressure is generated, fracture gradient is exceeded and seal fails, so that the sands can inject into surrounding host rocks (Lonergan et al., 2000; Hurst et al., 2011). For sands to flow they must be uncemented or unconsolidated, substantial fluid must be present in the system (hydrocarbon or water or both) and fluid migration in the subsurface must be strong enough to entrain the sands, when the fluid velocity is exceeded (Huuse et al., 2010). The effective stress, which is the difference between overburden stress/load and fluid pressure within the parent sandstone body, must be zero (Lonergan et al., 2000; Jolly & Lonergan 2002; Hurst et al., 2011).

Sandstones were deposited into the basin in form of channels and low-stand fan bodies during the Late Cretaceous and Cenozoic periods, providing evidence of depositional sandstone bodies in the area (Fig. 7.3). Distribution and thickness of these sandstones vary across the basin, both laterally and vertically. Evidence of gravity flow processes were observed from core data, analysed from
the Late Cretaceous depositional system (Jackson et al., 2008). Well 35/6-2S intersected the wing along one of the smaller depositional systems on the Maløy slope and coincides with sandstone lithology (Jackson & Somme 2011).

Identifying the exact source of parent sand for a sandstone intrusion complex is difficult without heavy mineral analysis on both the injected sand and the potential parent body. Recent studies in the Eocene succession of the North Sea on two potential parent bodies and sand injectite in the Maule Field sand was carried out by Morton et al., (2014). The two parent bodies initially proposed were the Brimmond channel system and underlying Forties Sandstone Member; ages of the depositional systems are Eocene and Paleocene, respectively. Heavy mineral and garnet geochemical analysis of the Maule injectite, however, revealed similar characteristics with the Eocene-aged depositional Brimmond sandstones (Morton et al., 2014). Heavy minerals analyses have also helped to distinguish between in-situ depositional or remobilized bodies and injected bodies, based on different sorting patterns (Kazerouni et al., 2011). In the absence of such information and detailed analysis in the study area, our interpretation of parent body for injectites was based on closeness to depositional sandstone bodies.

Potential parent bodies for intrusions, studied from each interval, have been discussed in chapter 4. Figure 7.3 shows that the distribution maps for depositional sandstones do not always match the distribution of intrusions in the area, however, there is evidence of potential source sand, either at the same stratigraphic level, where intrusions have been mapped, or below the intrusions, suggesting either of these depositional sandstone bodies may have sourced injectites in the area (Jolly & Lonergan 2002; Shoulders et al., 2007). As mentioned earlier, majority of the saucer-shaped intrusions, interpreted from the study area, are likely to have been part of originally deposited sand bodies related to sediment gravity flows that were later remobilized and injected creating complex geometries (Figs. 4.8 & 4.11) (Jackson et al., 2008; Dmitrieva et al., 2012; Huuse et al., 2012). In such a case, the remobilized or injected parts i.e. the wings are attached to the basal concordant part which represents the parent body and considered to be in situ remobilization, not whole injection (Fig. 7.2b) (Szawarska et al., 2010). Majority of those interpreted within the CSS0 (Late Cretaceous) and CSS1 (Middle Paleocene) belong to this category (Figs. 4.8 & 4.11).

In the Eocene, two large, sand-rich depositional fans, sourced deposited from the eastern part of the basin, were mapped (Figs. 3.11, 4.16a & 4.17a). They are grouped under the Frigg Sandstone Member and particularly important based on their location below Oligocene-emplaced intrusions anomalies and relationship to some of the Eocene-emplaced intrusions (Figs. 4.16a & 4.17). Amplitude reflections within the fan bodies are distorted and could suggest evidence of remobilization (Fig. 4.16a). Below some of the intrusions in the Oligocene interval are high-amplitude, concordant reflections at the base (Figs. 4.18 e-g), which are possible depositional sand units and may have form part of the parent bodies. Large, sand-rich fan systems were also deposited into the basin from the Shetland platform during early to mid-Oligocene (Figs. 3.13, 4.10d, g & 7.3)
Alternative sand sources from deeper part of the basin were also suggested in the area based on interpretations made by Wild & Briedis (2010) for the Balder mounds on Utsira high. They suggested sands could have been entrained by underlying fluid from pre-Cretaceous and injected into the Paleocene unit. We considered this possibility in our study area; however, Cretaceous sandstones are only restricted to the north-eastern part and not very extensive in the Northern North Sea making a Cretaceous parent body unlikely for shallower intrusions interpreted (Fig. 7.3).

As mentioned earlier, constraining the source of an intrusion complex is very challenging and our study area has been proven more challenging, due to the multiple locations of intrusions at different intervals.

Apart from the potential feeder dykes below extrudites emplaced in the mid-Paleocene and mid-Late Miocene times, no other type of feeder systems has been observed from the area (Figs. 4.12 & 4.19). Feeder dykes were observed directly below Oligocene injectites in the eastern North Sea (Andresen & Clausen 2014), we have not identified similar structures in the study area. Other types of feeder systems in seismic include vertically focused, blow-out or fluidization pipes, observed offshore Nigeria (Fig. 1.3b) and southern Utah (Fig. 2.9); such features were not observed from our

Fig. 7.3 Simplified sand distribution maps re-drawn from previous and present study, showing depositional (yellow outlines) and post-depositional sandstone (red outlines) facies. Main sediment sources are the Shetlands and western Norway.
area. This could be because of seismic imaging problems due to high velocities below them, nature of inclined margins of intrusions and poor processing or interference with polygonal faults (Løseth et al., 2003; Huuse & Mickelson 2004). The pipes are attributed to upward migration or expulsion of fluid. Sand injectites are generally considered as feeder systems, as they act as foci for fluid migration and individual injectites can feed each other, thereby facilitating hydraulic connectivity in the sub-surface (Huuse et al., 2003; Braccini et al., 2007; Shoulders et al., 2007; Hurst et al., 2011).

7.2.1.5 Timing of emplacement and implications (Single vs. Multiple episodes)

In addition to calibration of age, quality and resolution of seismic data; constraining the timing depends on the nature of the injectite complex, i.e. whether it comprises well developed extrudites and whether these were preserved in the stratigraphic record, acoustic impedance contrasts (between sands and shales), the nature of subsequent sedimentation (pelagic or turbidites) and finally, assumptions based on current understanding of the injection process (whether wing tips reach seafloor or not). The extensive literature on sandstone intrusions have estimated timing, based on three (3) main criteria, each with their own assumptions and uncertainties (Cartwright 2010). However, these methods of dating of intrusion emplacement still remain the best techniques so far and are presented in the illustrations below (Fig. 7.4).

(1) Presence of an extrudite, vented on the paleo-seafloor – Identifying an extrudite above sand injectites is very important, as it defines the position of seabed at the time of intrusion and extrusion (Fig. 7.4a) (Huuse et al., 2004; Hurst et al., 2006; Vigori to et al., 2008; Cartwright 2008). The surface, which an extrudite is emplaced on, or the seabed at the time of formation, pre-dates the extrudite and sediments that onlap onto an extrudite clearly post-dates it; suggesting emplacement is between the age of the seabed and the onlapping sediments. However, identifying extrudites in the subsurface is difficult, due to low level of preservation, mainly because of erosion or strong bottom currents (Hurst et al., 2006).

(2) Termination of wings at a common datum – A stratigraphic datum, at which intrusions terminate, may have represented a paleo-seabed at the time of emplacement (Fig. 7.4c) (Huuse et al., 2004). Ability to map and date the datum can provide estimation into timing of emplacement of intrusions. Cartwright (2010) noted that the true upper tips of injectites might not always be clearly imaged, due to seismic resolution limit, but recent experimental analysis confirmed that the upper tips of sand injectites represent the free surface at the time of emplacement (Bureau et al., in press). The experiment showed the upper tips of the injectites always come to the free surface.

(3) Dating of onlapped sediments – Forced folds or jack up, created above injectites, are often onlapped by latter sediments, suggesting there was a positive topography on the seabed before the overlying deposition. Dating the sediments that onlap on to the forced folds indirectly helps to
estimate the time of injectite formation (Shoulders & Cartwright 2004; Shoulders et al., 2007; Cartwright 2010) (Fig. 7.4c). Onlap requires gravity flow deposits, so pure pelagic sediments will make recognition difficult. Also, if the injectite is attached to an in-situ depositional sand, then one might expect an implosion at top of the in-situ sand due to sand withdrawal (as observed above the Oligocene sands creating the Utsira topography).

The main challenge with this method of dating is most often the onlaps are not well preserved, due to erosion or in the case of intense polygonal faulting above the interval, thereby disrupting the stratigraphy.

![Fig. 7.4 Criteria used in estimating timing of emplacement of sandstone intrusions](image)

In chapter 4, we presented evidences from each unit, where injectites have been emplaced and using similar approach from those illustrated in figure 7.4. Based on this, we propose at least five (5) major episodes of emplacement: Late Cretaceous, Middle Paleocene, Middle to Late Eocene, Middle Miocene and Mid-Late Miocene to Early Pliocene. In that case, intrusions from levels 1 to 5 would have been emplaced at different times through the stratigraphy (Fig. 7.5b)

On the contrary, in the Faroe-Shetland basin, a single event was proposed for sandstone intrusions emplacement, which is Middle to Late Miocene (Shoulders et al., 2007; Cartwright 2010). Although 3D mapping in the area revealed intrusions distributed in multi-storey array and likely to be interconnected over large part of the area, it was concluded that the deeper intrusions only fed the shallower ones in a single event. Establishing a clear injection stratigraphy in the FSB is however hampered by a very extensive polygonal fault network which makes it difficult to establish any paleo-seafloor surfaces prior to the Intra Neogene Unconformity.

Another important factor to consider, in association with a single or multiple emplacements of intrusions, is the location of the parent bodies. Cartwright (2010) pointed out that for multiple emplacements, an explanation would need to be provided as to why the parent body was able to build-up to or close to lithostatic pressure, deflate and re-pressure during each episode; considering some of the pore fluid and sand would have been lost at each time. However, with the
multiple parent scenario, each parent sand body for each level of intrusion behaves independently and once remobilization and injection have occurred, the sands do not have to be re-pressured for subsequent remobilization (Fig. 7.5b). Based on the evidences and discussions presented above and in chapter 4, it is believed that the parent bodies feeding the intrusions and extrusions in the study area are located at multiple intervals, similar to the San Joaquin basin, where the intrusions and extrusions were sourced from different parent bodies during multiple episodes (Figs. 4.10 & 7.5b) (Vettel & Cartwright 2009).

Some of the events are synchronous with other parts of the North Sea. For example, in the South Viking Graben, two events are interpreted in the Early Eocene and Middle Eocene, based on presence of extrusion and termination of conical intrusions at the unconformity, respectively (Huuse et al., 2004). Middle-to-Late Eocene timing was also proposed for conical intrusions in the Tampen Spur area, west of the Eocene-emplaced case study (Huuse & Mickelson 2004). Rodriguez et al., (2009) also identified onlaps on forced folds, above underlying sandstone intrusions, aged mid-Miocene in the Tampen Spur area. Above the Siri Canyon in the Norwegian-Danish basin, an extrudite was interpreted on the mid-Miocene unconformity (Andresen et al., 2009). The implication of this based, on the examples above and from independent observations made in this study is that the Middle to Late Eocene and Middle Miocene times probably represented periods of regional sandstone intrusion and extrusion, and related fluid flow in the North Sea.

7.2.1.6 Relationship between intrusions and polygonal faults

Small extensional faults observed from Cretaceous to Miocene are interpreted as polygonal faults, based on their distinct polygonal nature in plan view (Cartwright 1994). The faults are pervasive throughout the study area in, at least, two distinct tiers (Chapters 3-5). Tier 1 or lower tier is bounded above and below by the top Paleocene and lower Cretaceous horizons, respectively, while tier 2 or upper tier is bounded above and below by the Middle Miocene and top Paleocene horizons, respectively (Figs. 4.6 & 7.1). Fault dip angles are similar to those measured in other sedimentary basins (Chapter 5).

Extensive studies of sandstone intrusions show that often occur within polygonally faulted mudstones area. Their occurrences with sand injectites extend beyond the study area and they are observed in several other basins (Fig. 4.1c). Previous studies have inferred that the faults exert major control on the geometry of sand injectites, based on their close physical relationship (Lonergan & Cartwright 1999; Lonergan et al., 2000; Gras & Cartwright 2002; Molyneux et al., 2002). In the Central North Sea, the Middle Eocene Alba reservoir shows evidence of modification from subsurface remobilization and injection and was attributed to polygonal faults, which had major control on their formation (Lonergan & Cartwright 1999; Lonergan et al., 2000; Gras & Cartwright 2002; Molyneux et al., 2002). However, more recent studies have shown that the faults
Fig. 7.5 Single Vs Multiple emplacement. (a) scenario a is single emplacement proposed in the Faroe-Shetland Basin (Shoulders et al., 2007) and (b) scenario b illustrates multiple emplacement proposed in this study (Northern North Sea). Single
do not exert control on the geometry or formation of the sandstone intrusions, as previously thought (Huuse et al., 2004; Huuse & Mickelson 2004; Shoulders et al., 2007; Cartwright et al., 2007). This is supported by the difference in dip angles between them and the fact that sandstone intrusions still form in the absence of polygonal faults.

Dip angle population between intrusions and polygonal faults is presented below (Graph 7.1). Dip measurements taken for both intrusions and polygonal faults from our study area show that the dip angles of the discordant wings of the intrusions are much lower than the polygonal fault dips inline with previous observations (Shoulders et al., 2007; Cartwright et al., 2007). This lack of relationship suggests that they are not directly related and the geometry of intrusions is not directly controlled by polygonal faults. The genesis of polygonal faults is beyond the scope of this study and has been documented extensively in literature (Cartwright, 2011).

**Graph 7.1** Dip angle measurements for polygonal faults and sandstone intrusions. Note that polygonal faults have higher dip angles than sandstone intrusions.
7.2.1.7  **Relationship between intrusions and underlying Mesozoic faults and structural highs**

Sandstone intrusions and normal faults in the south-western Barent Sea reveal similar NNE-SSW orientation. This suggested the faults had control on their distribution and likely served as pathways for deeper fluids into parent sand bodies in the Eocene (Safronova et al., 2012). Similar relationship was observed in Faroe-Shetland Basin, such that sandstone intrusions and underlying basement faults have same NE-SW trend (Shoulders et al., 2007). The North Sea basin was tectonically active in the Mesozoic time, with series of normal faults and grabens, which formed during the rifting (Fig. 4.5) (Ahmadi et al., 2003). Major Jurassic Fields in the Northern North Sea are associated with horst, grabens and structural highs, created as a result of the rifting (Fig. 4.9) (Ahmadi et al., 2004).

Map of the base Cretaceous unconformity reveals the structural elements by highlighting structurally high areas from low areas (Fig. 4.9). The map also reveals relay fault zones, fault linkage systems and graben step overs linked to underlying faulting and rifting (Fossen et al., 2010). The faults and structural highs have NNE-SSW orientation across the basin, which locally coincides with distribution of some of the injectites in the area (Fig. 4.9). For example, the mid-Late Eocene injectites occur along the crest and above underlying structural high (Fig. 4.14). This relationship was also observed from the mid-Paleocene intrusions.

This spatial relationship suggests the Mesozoic faults may have influenced distribution of sandstone intrusions locally in the Northern North Sea, similar to the SW Barents Sea and Faroe-Shetland Basin. Faults are likely to act as pathways for fluids from these underlying reservoirs, as fluid may preferentially flow along fault planes (Ligtenberg 2005; Cartwright et al., 2007).

7.2.1.8  **Factors facilitating large-scale remobilization, injection and extrusion in the Northern North Sea**

Despite decades of studies of sandstone intrusions, the exact mechanisms driving and triggering large-scale remobilization and injection sand bodies are still poorly understood (Jolly & Lonergan 2002). The general conceptual understanding is that excessive pressure is required to facilitate their emplacement (Jolly & Lonergan 2002). A sandstone dyke is an example of a natural hydraulic fracture, which propagates and is subsequently filled with sand (Cosgrove 1995; Jolly & Lonergan 2002). In summary, it involves three main steps;

\[
\text{Overpressure build-up} \quad = \quad \text{Seal failure} \quad = \quad \text{Fluidization}
\]

It is possible that no single factor facilitated the large-scale remobilization, injection and extrusion of sand in the Northern North Sea. For such basin-scale remobilization the following conditions must be in place:
Chapter 7

- The parent body must be extensive and unconsolidated during remobilization (Lonergan et al., 2000). Extensive parent bodies are available in the area and likely to have been unconsolidated during injection.

- The parent body must be sealed within fine-grained sediment, such that excess overpressure can be generated within the system (Graph 2.1). Overpressure can be generated by several mechanisms, such as disequilibrium compaction, high tectonic stresses, lateral pressure transfer, hydrocarbon generation/migration and silica diagenetic transformation (Obermeier 1996; Huuse et al., 2010).

- The sealing unit must be breached so that the sand can fluidize, remobilize or inject into surrounding hydraulically fractured, low-permeability sediments (Lonergan et al., 2000; Jolly & Lonergan 2002; Hurst et al., 2011).

- Addition of significant volume of fluids (e.g. gas) from deeper part of the basin is probably required to aid injection (Lonergan et al., 2000; Duranti & Hurst 2004).

Overpressure is generated, when the pore fluid pressure with a sealed system is greater than hydrostatic pressure at a given depth (Maltman 1994; Obermeier 1996; Swarbrick & Osborne 1998). The state, at which overpressure is generated and seal fails, is known as liquefaction; and fluidization is the ability of fluid to lift cohesionless sediments (Obermeier 1996; Duranti & Hurst 2004). During liquefaction, the fracture gradient is exceeded and sands fluidize into propagating fractures when the effective stress within the sediment is reduced to zero (Jolly & Lonergan 2002; Hurst et al., 2011).

**Priming & triggering mechanisms**

Driving mechanisms for sandstone intrusions are often classified under primers and triggers, with the former being the processes that facilitate overpressure generation and the latter includes the mechanisms that triggers the actual injection (Huuse et al., 2010). Some of the priming mechanism, invoked by previous workers to drive sandstone remobilization and injection, include: disequilibrium compaction resulting in rapid burial of sand bodies and inability of pore fluids to escape normally (Osborne & Swarbrick 1997; Jackson et al., 2010; Leseth et al., 2013), hydrocarbon generation, lateral pressure transfer and fluid buoyancy (Yardley & Swarbrick 2000; Reilly & Flemings 2010; Andresen et al., 2009; Monnier et al., 2014), migration of basinal fluids (Jolly & Lonergan 2002; Molyneux et al., 2002; Safronova et al., 2012), silica diagenesis (Davies et al., 2006; Huuse et al., 2010) and tectonic stresses (Cartwright 2010), whereas triggering mechanisms include: (Jolly & Lonergan 2002; Cartwright 2010), seismic waves from large magnitude earthquakes (Molyneux et al., 2002; Huuse & Mickelson 2004), bolide impact (Cartwright 2010), propagation of polygonal faults into overpressured sandstone bodies (Molyneux et al., 2002) and buoyancy effects of hydrocarbons (Jonk 2010; Monnier et al., 2014). We investigated some of these mechanisms in the study area.
Disequilibrium compaction resulting in rapid burial of sand bodies and inability of pore fluids to escape normally is a very common overpressure generation mechanism (Osborne & Swarbrick 1997; Jackson et al., 2008). This mechanism is efficient when the seal integrity is very good and sedimentation rates are as high as or greater than 600 m/Ma (Durant & Hurst 2004; Osborne & Swarbrick 1997). Sedimentation rates, estimated in the study area from CSS0 to CSS9, are within the range of 24.10 and 415.63 m/Ma, for maximum rates observed in the CSS2 (Eocene) and CSS7 (Pliocene) units, respectively (Tab. 3.3 & Graph 3.1) (compaction not taken into account). If units are decompacted, only the rate during Pliocene (CSS7) would be close to or greater than the 600 m/Ma. Based on these low values, with the exception of the Pliocene, we do not think disequilibrium compaction sedimentation rate in the area was high enough to generate enough overpressure in the area. However, the rates in the Pliocene may have contributed at that time.

Another process that generates excess pressure is high tectonic stresses. Areas with applied tectonic stresses, such as strike-slip basins, fold and thrust belts have very high differential and applied stresses that can create excess pressure (Lonergan et al., 2000). The North Sea is characterized by series of rift structures with the last phase of rifting between Late Jurassic to Early Cretaceous time (Ziegler 1990). By Late Cretaceous times, the North Sea was no longer actively rifting and the post-rift phase was characterized by thermal subsidence (Lonergan et al., 2000). The oldest intrusions in the Northern North Sea are observed in the Late Cretaceous interval, by then the area was no longer tectonically active (Lonergan et al., 2000). The lack of active faulting in the area also suggests there were no large earthquakes with magnitudes greater than 5 in the area (Lonergan et al., 2000); making tectonic stresses an unlikely mechanism for overpressure generation.

Addition of fluid, such as hydrocarbon, is another common mechanism, often sited in literature to generate overpressure in parent bodies of injectites (Lonergan et al., 2000; Molyneux et al., 2002; Jolly & Lonergan 2002; Duranti & Hurst 2004; Andresen et al., 2009; Wild & Brieditis 2010; Monnier et al., 2014; Andresen & Clausen 2014). This process is also thought to be very effective in remobilizing large volumes of unconsolidated sand and facilitate injection. Introduction of hydrocarbon, especially gas can generate high pore-fluid pressure in sealed sands, due to buoyancy (Jolly & Lonergan 2002; Duranti & Hurst 2004; Hurst et al., 2011). This is a very attractive mechanism for overpressure build up in the study area; first, because of the presence of underlying Late Jurassic Kimmeridge Clay Source rock (age equivalent of Draupne Formation in the Norwegian Margin) and basin modelling studies shows hydrocarbon generation in the North Sea, started since the Late Cretaceous (Fig. 4.2b) (Kubala et al., 2003; Schlakker et al., 2002). This is coeval with the timing of emplacement for the Late Cretaceous intrusions in the study area (Fig. 4.8). Second, the location of some of the intrusions in the area above structural highs and Mesozoic faults, which houses most of the underlying reservoirs, suggests some kind of relationship between them (Figs. 4.9, & 4.14). However, not all intrusions are present on structural highs and faults, as they are also observed within the structurally low areas, absent above some structural highs, such as the Troll fault blocks and located above areas, not underlain by
hydrocarbon fields (Fig. 4.9). Therefore, it is possible that this generation and migration of hydrocarbon constituted an important role in both generation of overpressure and subsequently formation of intrusions; this mechanism alone, however, might not be sufficient enough in the study area, due to partial correlation between underlying structures and mapped injectites.

Earthquakes have been proposed to trigger remobilization and injection of unconsolidated sand by a process known as shear-induced liquefaction or dynamic liquefaction. These studies reveal that earthquake events may create shearing motion within the rock, which leads to grain crushing, causing significant increase in fluid pressure, weakening in overburden rocks and causing injection (Obermier 1989; Cartwright 2010). However, this is known to occur at very shallow depth (within few metres of the surface) and produces centimetres to few metres structures (Obermier 1996; Cartwright 2010). Jolly & Lonergan (2002) also noted that at greater depth, it is difficult to liquefy sediments by dynamic liquefaction, due to increase in overburden stress with depth. The scale of intrusion, depth of intrusion and magnitude of earthquake should be considered, when invoking seismically-induced liquefaction as a potential driving mechanism for intrusions (Jolly & Lonergan 2002). In the study area, the scale of intrusions is in hundreds and thousands of magnitudes larger than those formed by seismically-induced liquefaction. Depths of intrusion in the area are assumed to be within the range of 400 – 600 m, therefore too deep for dynamic liquefaction, based on the above. And lastly, no known record of earthquakes with magnitudes greater than 5 is known in the area (Huuse & Mickelson 2004). Based on the above, we do not favour earthquakes as a possible triggering mechanism in the area.

Bolide impact, which created the Silver Pit crater in the Southern North Sea and Ries impact in Germany during the mid to late Eocene and mid to late Miocene, respectively, has also been suggested in literature as potential triggers for sandstone intrusions (Cartwright 2010). Although the timing of these events coincides with timing of emplacement of some of the intrusions in the area, they occurred at great distances away from the study area and their impact is not likely to have reached the Northern North Sea making this process unlikely.

Another mechanism proposed in literature to cause overpressure increase in the subsurface is the process of silica diagenetic transformation, which is the conversion of biogenic silica, opal A into to a more stable, crystalline silica opal CT (Davies et al., 2006). The conversion, which often occurs at shallow burial (first 0.5 - 1 km), causes collapse of the pore framework, drastic porosity loss and rapid pore fluid expulsion, which facilitates generation of overpressure within the unit. The mechanism was first proposed by Davies et al., (2006), as both primer and potential trigger for generation of sandstone intrusions and have also been suggested as the overpressure generation mechanism responsible for other soft-sediment remobilization products, such as pockmark formation, polygonal faults and slope failures (Davies & Clark 2006; Cartwright 2011). This study embraces the process of diagenetic transformation as a potential mechanism for large-scale intrusions formation in the area and will be discussed much further.
For the scale of remobilization and injection, observed in the study area, a continuous or re-occurring driving mechanism will be more efficient.

The appeal to this mechanism is based on the following:

- **Timing** – as presented in chapter 4 and under section 7.2.1.5, sandstone intrusions in the Northern North Sea were emplaced during multiple episodes: Late Cretaceous, Mid-Paleocene, Mid-Late Eocene, Mid-Late Miocene and Early Pliocene. The proposed timing is based on three main criteria; termination at a stratigraphic datum, onlaps on forced fold or jack up and presence of an extrudite.

- **Evidence of intervals rich in opal A silica and transformation to opal CT.** Results from scanning electron microscopy (SEM) and x-ray diffraction (XRD) analysis by Rundberg (1991), reveal opal A to opal CT transformation took place within Paleocene, Eocene and Oligocene intervals (Fig. 5.13).

- **Presence of sandstone intrusions within siliceous-rich intervals, where transformation has taken place; and occurrence of Oligocene-emplaced intrusions immediately above the position of the diagenetic boundary (observations from seismic and well logs) (Figs. 4.16 & 4.18)**

- **Presence of potential parent sand body within opal rich interval.** Potential parent bodies for intrusions are located within silica bearing intervals in the area.

- **Average depths at time of injection are between 300 – 600 m in the area (for intrusions with wing height of ~ 200 m to 400ms TWT, assuming an interval velocity of 2km/s, decline in porosity of 60-40% (Tada 1991); and diagenesis usually occurs within the first 0.5 - 1 km (Davies et al., 2006). This suggests that silica diagenesis transformation (water expulsion from siliceous sediments) would probably have occurred at similar depths at the time of intrusion formation**

- **Nature of the host rock – the parent body must be sealed within an effective seal host rock.** As presented earlier, a laterally extensive polygonal fault system is developed in Cretaceous to Miocene aged sediments spanning more than 2km in thickness in the study area (Fig. 4.6). The sediments are mudstone dominated with high content of smectite and other clay minerals (Rundberg 1991; chapter 5). Previous studies have shown relationship between polygonal faults and diagenesis, resulting in physical and chemical changes in the rock properties, e.g. drastic reduction in porosity at the transformation boundary; concluding diagenesis causes shear fracturing in fine-grained sediments, such as mudstones (Cartwright 2011).

- **Lastly, the co-existence of opal-rich rock and sandstone intrusions is very compelling in the North Sea, Faroe-Shetland Basin, Sakhalin Island, More Basin and San Joaquin Basin (Fig. 4.1c)(Davies et al., 2006; Thompson et al., 2007).**
Prior to the Cretaceous, series of horsts and grabens and other structural elements were formed, as a result of the rifting (Fig. 7.6a, time0). This interval houses the Late Jurassic Kimmeridge Clay Source Rock (equivalent of Draupne Formation in the area) and extensive shallow marine sandstones, which constitutes the main reservoirs in the North Sea (Evans et al., 2003). Late Cretaceous fan and channels were deposited into the basin at time 1 (Fig. 7.6). Mudstone dewatering probably started in the mid-Late Cretaceous and these mudstones are rich in smectite (Thyberg et al., 2010).

For sands to remobilize, they must be unconsolidated and sealed so that overpressure is generated (Lonergan et al., 2000). Based on the timing of intrusion emplacement, fluidization began in the Late Cretaceous which corresponds to timing of hydrocarbon generation from North Sea basin modelling (Kubala et al., 2003; Schlakker et al., 2002). Fluid from hydrocarbon leakage and pore water, expelled during diagenetically-driven processes at this time, would have facilitated fluidization of sands at time 2 (Fig. 7.6a). Clastic deposition continued throughout the Tertiary with deposition of large, sand-rich fans and channels (Evans et al., 2003). Clay mineral analysis shows mudstones of the Paleogene are very rich in silica and smectite; and with increased burial, they are transformed and significant volume of pore water is produced (Rundberg 1991; Davies et al., 2006; Marcussen et al., 2009). All the pore water produced during diagenetic transformation will try to get out of the host rock and if it intersects an unconsolidated sand body, the sand may be entrained, when fluidization velocity is exceeded and remobilization is initiated (times 3 – 5) (Huuse et al., 2010). This process would have been repeated in the basin, to aid multiple emplacements of sandstone intrusions, as the sealed sands would have subsided through the transformation zones (Fig. 7.6a). Fluidization would also have been supported by any additional influx from deeper part of the basin, either as hydrocarbon, or water (Lonergan et al., 2000; Jolly & Lonergan 2002; Wild & Briedis 2010).

In most cases, only the present-day location of the opal A to opal CT diagenetic boundary is observed in seismic or outcrop and represented as a high-amplitude reflection in seismic, corresponding to a downward increase in bulk density and seismic velocity (Davies et al., 2006; Davies & Cartwright 2002). Most smectite to illite conversion are based on experiments, petrophysical analysis and well log response (Rundberg 1991; Marcussen et al., 2009). The present-day location of the opal A to opal CT diagenetic boundary is directly below the Oligocene-emplaced intrusions (Figs. 4.16, 4.18). The boundary is conformable to the near-base Miocene and mid-Miocene reflections, indicating the time, at which the transformation ceased and the diagentic front became fossilized (Davies and Cartwright 2002; Neagu et al., 2010). This coincides with last period of significant sandstone intrusion and extrusion in the area (Fig. 7.6a, time 5). The last episode of intrusion in the area was during the Early Pliocene and transformation ceased at about mid-Miocene times (Fig. 7.6a, time 6). It could be assumed that it was a gradual process, strong enough to still generate water to aid fluidization in the Early Pliocene. However, there is no evidence for this. Presently, we have no explanation for this, however, we mentioned earlier that estimation of rate of sedimentation was much higher during the Pliocene, (415.63 m/Ma,
compaction unaccounted for) (Tab. 3.3 & Graph 3.1) compared to other times in the area. This could have facilitated overpressure development within the unit (Fig. 7.6a, time 6).

Based on the above, we propose the main fluid sources could have driven large-scale remobilization and injection in the Northern North Sea; they are: Intraformational fluid sources, such as diagenesis of the host rock, compaction and extraformational fluid sources, such as hydrocarbon or/and water from deeper parts of the basin (Fig. 6b). For such scale of remobilization, a basinal event might be needed to trigger it, such as regional events like earth quakes and bolide impacts (Obermier 1989; Cartwright 2010; Huuse et al., 2010). However, these two processes seem unlikely in the area as discussed above. The fluid budget might be sufficient in the area to facilitate fluidization and subsequent remobilization and injection without an external trigger. Experimental analysis reveals that introduction of water into the sealed system below the parent body, creates hydrofractures to the surface, which sands can migrate through till they get to the free surface (Bureau et al., in press).
Fig. 7.6 (a&amp;b) Schematic diagrams illustrating proposed model of formation of sandstone intrusions in the Northern North Sea
7.2.2 Nigeria Transform Margin

The interpretations presented in chapter 5 suggest that the Nigeria Transform margin is severely affected by processes of soft-sediment deformation recorded as mass transport deposits and fluid flow phenomena. Interpretation was based solely on seismic data in the absence of well data in the area.

This study presents the first documentation of mass transport deposits and fluid flow phenomena on the Nigeria Transform margin. The area was divided into 2 for ease of description based on distribution of mass transport deposits and fluid flow phenomena. All present-day seabed and overburden fluid flow phenomena interpreted are located in area 1 within the fluid flow zone while mass transport deposits dominate area 2 within the mass transport deposit zone (Fig. 7.9). Findings from the Nigeria Transform Margin are presented in a paper format in chapter 6. The paper discusses in details all the observations and interpretations.

7.2.2.1 Mass Transport Deposits (MTDs)

Series of buried and active mass transport deposits (MTDs) were mapped throughout the Cenozoic interval in the Nigeria Transform Margin (NTM) (Fig. 7.8). They range from few hundreds to tens of kilometres and constitutes up to 20% of the entire stratigraphic section. We adopt the general terminologies used by Bull et al., (2009) to define these MTD’s; these include headwall scarps, lateral margins, deformed blocks, pressure ridges, ramps and outrunner blocks (Fig. 7.7) (Shipp et al., 2011 & references there in). Internally, MTDs are characterized by very low-amplitude, chaotic and discontinuous reflections (Fig. 6.9) (Posamentier & Kola, 2003; Posamentier & Martinsen, 2011); occasionally reflections could exhibit high-amplitude character as in sand-prone, submarine MTDs (Meckel, 2011). Their multiple occurrences signify repeated slope failure in the basin (Morscadelli & Wood, 2008; Bull et al., 2009; Shipp et al., 2011). MTDs are recognised from the Early Paleocene interval to the present-day seabed (Fig. 7.8). Vertical and lateral distribution of the mass transport deposits from the margin also revealed that the magnitude of failed sediment increased through time (Fig. 7.8a). Each component has been discussed in detail in chapter 6.

Kinematic indicators provide information on the direction of failed sediment and we interpreted an overall flow direction from northeast to southeast (Figs. 6.8 & 6.9). Deformed blocks as high as 350 ms TWT and ~ 2 km in length are observed (Fig. 6.9a). Smaller blocks were also interpreted on the present-day seabed (Fig. 7.7). They are similar in height to rafted blocks observed in Hinlopen Slide on the northern Svalbard Margin in the Artic Ocean which are 450 m high and more than 5 km wide (Vanneste et al., 2006). Ramps cuts downward or upward on the basal shear surface and often as deep as 150 ms TWT, with lateral extent from 3 Km to 20 Km (Fig. 6.9e) (Frey Martinez et al., 2005). These components of MTD create instability in the sub-surface and care must be taken especially during drilling and installations of infrastructures.
**Fig. 7.7** Summary diagram of key components of the mass transport deposits along the Nigeria Transform Margin
7.2.2.2 Mechanism for slope failure

Mass transport deposits are recognised at a variety of scales ranging from small-scale as in cores, medium-scale in outcrop and to regional seismic scales such as the Storegga slide offshore Norway (Bull et al., 2009; Shipp et al., 2011; Dykstra et al., 2014). Regardless of the scale at which they occur, MTDs are direct response to slope instability in sedimentary basins (Posamentier & Martinsen 2011).

Seismic data revealed numerous buried and active MTDs mapped on the margin and occurred repeatedly through time. In addition to the repeated occurrence, magnitude of failed sediment also increased with time from the oldest to the youngest (Fig. 7.8). As MTDs constitutes important components of deep-water sediments, it is important to what internal or external factors that could have resulted in such large-scale and repeated slope failure along the margin (Frey Martinez et al., 2011). Active exploration has only just began on the Nigeria Transform Margin, it is therefore important to know what processes have occurred in the area and their implications on exploration and production as slope failures modifies the architecture of the slope.

Mechanism that trigger slope failure have been investigated for decades and widely accepted to initiate when the downslope-oriented shear stress exceeds the shear strength of the sediments along the slope (Frey Martinez et al., 2011). In order word, slope failure is a result of increase in the shear stress or decrease in the shear strength of the sediments or both (Davies & Clark 2006). Numerous studies have documented several mechanisms that could result in slope failures and these are often associated with difference in pore pressure within the sediment (Shipp et al., 2011).

Some of these mechanisms include: conversion of opal A to opal CT, gas-hydrate destabilization, gas release, earthquake shaking, sea level changes, rapid or increased sedimentation, slope gradient (Davies & Clark 2006; Garziglia et al., 2008; Zhu et al., 2011; Nelson et al., 2011). According to Davies & Clark (2006), generation of overpressure within the sediments may prime the sediments in right conditions rendering them susceptible for failure but an external mechanism such as an earthquake may be required to act as a trigger. Slope failure could be primed or triggered by one of the above mechanism or a combination of several mechanisms. They can also occur once or repeatedly as observed on the Nigeria Transform margin.

Conversion of opal A to opal CT - Silica diagenetic transformation of opal A to opal CT has been proposed previously as a primer and trigger for submarine failure in the Faroe-Shetland basin (Davies & Clark 2006). Conversion of opal A – CT transformation is a thermochemical dehydration reaction that results in rapid compaction of sediments. This causes an increase in pore pressure, which leads to abrupt reduction in the sediment strength, making it susceptible to failure (Davies & Clark 2006). This however is unlikely in the area, as we do not observe any evidence that opal A to opal CT transformation occurred in the area.

Gas hydrates destabilization – We mapped a continuous reflection characterized by negative polarity located at about 300 ms below the present-day seabed (Fig. 6.18). The reflection tracks the
seabed but often has a cross cutting relationship with surrounding stratigraphic reflections. Based on the observations, we interpreted this reflection as a gas-hydrate bottom simulating reflector. Gas hydrates destabilization has been proposed as a potential mechanism for slope failure. Although, this is an attractive mechanism in the area, but interpretation shows the bottom simulating reflector, which is a likely indicator of presence of gas hydrates are restricted to the eastern part of the study area (Gay et al., 2010) (Fig. 6.18). Distribution map of MTD shows they occur in the western and central part of the basin and occur within SU2 and SU5, which is deeper than the unit the BSR was mapped (Fig. 7.9). Based on this, we ruled out the possibility of gas hydrate destabilization as the mechanism for slope failure on the NTM.

**Effect of migration of fluid** – Fluid could be either formation water or hydrocarbon. Hydrocarbon generation, expulsion and migration are a well-known process that causes increase in pore pressure (Duranti & Hurst 2002; Jolly & Lonergan 2002). From our interpretation, we clearly demonstrated fluid flow in the area by the presence pockmarks, pipes and possible shallow gas accumulations in the first 400 ms TWT (Fig. 6.14 – 6.16). However, these fluid flow phenomena are restricted to area 1 (eastern part of the area) but MTD occur regionally in area 2 (western and central) were no evidence of thermogenic fluid has been observed (Fig. 7.9). We do not discount the possibility of formation water release from consolidation or compaction of sediment (Van Rensbergen et al., 2003).

**Sea level rise and fall** – Sea level rise and fall is a common mechanism for formation of episodic mass transport deposit (Nelson et al., 2011). We have no absolute ages for the MTDs in the area to be able to match to sea level rise and fall making it difficult to relate the MTD sheets to sea level rise and fall. However, there was significant global fall in sea level at the onset of the Pliocene (Fig. 2.2). This correlates to the period of major increase of MTD development in the study area (Fig. 6.10). Even though this alone is not sufficient enough to make reasonable conclusions, we cannot rule out the effect of sea level on episodic MTD formation.

**Earthquake** - We considered effect of tectonics and earthquake activities as a possible mechanism that triggered slope failure. Nigeria Transform Margin falls within the Equatorial conjugate margin characterized by complex wrench and transform faulting. However, transform tectonism was active until Middle to Late Albian time, marked by development of the Late Albian unconformity (Brownfield & Charpentier 2006). This unconformity represents the lower bounding surface of the interval of study, suggesting transform tectonism was no longer active, but continuous extension of the crust resulted increase clastic deposition and thermal subsidence which continued till the Tertiary period in the area (Brownfield & Charpentier 2006). We have no evidence of major earthquakes in the area during the Tertiary period, therefore we rule out earthquakes as a possible trigger for slope failure on the Nigeria Transform Margin.

**Net sediment accumulation rate** - An estimated net sediment accumulation rate from the Late Albian unconformity to present day seabed was carried out using a simple calculation method adopted from Jordt et al., (2000) (Tab. 6.3) and a representative graph was plotted (Graph 7.2).
TWT values were obtained from thickness maps and a constant velocity of 2 km/s was used. This does not account for compaction, burial or erosion and only estimates based on available data.

Based on the estimates of the net sediment accumulation rate (Graph 7.2), we observed a continuous increase in sedimentation through time and this corresponds to increase in magnitude of failed sediments (Fig. 7.8). Rate of sedimentation increases consistently from SU1 to SU3 and a decrease was recorded between SU3 and SU4. This decrease coincides with reduction of MTD as shown from the distribution map (Fig. 7.8). The significant increase in rate of sedimentation from 39.5 m/Ma in SU4 to 150.9 m/Ma in SU5 is also reflected from the MTD distribution map. Based on this, we favour increased sedimentation through time as the main driving mechanism for formation of episodic or repeated MTD and increase in magnitude of failed sediment through time on the Nigeria Transform Margin was mainly driven by rate of sedimentation. Over steepening of the slope could also be a contributing factor to slope failure in the area. Slope gradient measured is ~ 1° for the present day and this could have enhanced rapid deposition or slope progradation of sediments especially in an area with high sedimentation rate (Zhu et al., 2011). The main uncertainty here is the lack of well control and ages of surfaces bounding the MTDs were obtained from PGS interpretation traced from nearby Aje discovery (Appendix 1.2 & 1.3).

7.2.2.3 Seabed fluid flow phenomena

Two-way-time and attribute maps of the seabed reveal several depressions of varies sizes and a single mound on the present-day seabed of the Nigeria Transform Margin (Figs. 6.6 & 6.8). They have been interpreted as pockmarks and mound (Chapter 6) (Figs. 7.1 & 7.9).

Pockmarks - Pockmarks are expressed as circular depressions on the present-day seafloor. They vary from 10 - 15 ms in depth and 150 - 200 ms in diameter. The circular simple geometry of pockmarks can be altered through merging of individual pockmarks, carbonate precipitation and bottom current erosion to produce more diverse range of geometries such as elongated, bulls-eye, composite and complex (Andresen et al., 2008). All the pockmarks are interpreted in area 1 and randomly distributed above structural high, shallow and deep-seated faults, bottom simulating reflectors; and active and buried channels (Figs. 7.6d, f, g, i & j). They occur pockmarks either along the hanging wall of the faults (Fig. 6.15d) or directly above fault planes (Fig. 6.15e) as in fault-hanging wall and fault-strike pockmarks respectively similar to those observed in other parts of the West African margin (Pilcher & Argent, 2007). Presence of pockmarks along faults is likely indication of fluid leakage through the fault (Ligtenberg, 2005). Pockmark and fault relation is well documented from the Lower Congo Basin; the faults create curved depression on the sea floor and served as pathways for fluid migration (Gay et al., 2007).

Pockmarks represent evidence of fluid expulsion (pore water or hydrocarbon) on the present-day seabed or paleo-seabed (Judd & Hovland 2007). Constraining timing of expulsion provides information on timing of fluid flow within the basin.
Graph 7.2 Graphical representation of estimated sediment accumulation rate for the studied intervals in the Nigeria Transform Margin. Note increase in sedimentation rate through time, which corresponds to increase in mass transport deposits within the seismic units.

Fig. 7.8 Evolution and distribution of MTDs along the Nigerian Transform Margin during the Cenozoic. Coloured patches represent single MTD drawn from its basal surface in petrel. Deformation increases with time. Note that outline of seabed MTDs are not included.
Chapter 6

**Seafloor mound** - A single mound of up to 30 ms high and 500 m wide was interpreted on the seafloor. Below the mound is a high amplitude positive reflection followed by a negative reflection and a 300 ms TWT long vertical column; characterised by distorted amplitudes and vertically stacked pull-up reflections. In time slice, the feature forms a circular geometry and is located about 5km close to the main channel complex. Gay et al., (2007) described a similar feature on the seabed from Lower Congo Basin and core analysis suggested carbonate-rich sediments with cold-water corals interbedded with hemipelagic muds. A single mound was also described on the mid-Miocene unconformity in the Norwegian-Danish basin and Northern North Sea; they were interpreted as sand extrudite (Andresen et al., 2009; chapter 4).

The origin of the mound was investigated as several known geological features create mounded geometry such as carbonate mound or reef, shale diapirs, salt diapirs, sand extrudite or sand volcanoes e.t.c. (Stewart 1999). The vertical column below the mound is rooted within high-amplitude, semi-continuous to discontinuous reflection packages interpreted as sandstone-rich channel (Fig. 6.19b & c). No well or core information is available in the area to ascertain the lithology within the mound. A salt origin is discarded, as there is no evidence of halokensis in the area. Mound volcanoes have been described from the Niger-Delta basin but location of mound above a possible sandstone-rich channel makes a mound lithology unlikely (Graue 2000). Two possible origins proposed for this mound include: (i) sand mound formed from sand extruded from the buried channel supposing channel is sand-rich (ii) methane-derived carbonate mound formed as a result of upward movement of fluid from underlying channel (Fig. 7.6e). However, due to the very high velocity calculated within the mound (~3.3 km/s), a sandstone origin is also unlikely. Lithologies known to produce such high seismic velocities are often carbonates (Anselmetti & Eberli, 2012). Based on the very high velocity of 3.3 km/s estimated within the mound, it is likely to be of carbonate origin rather than siliciclastic. We therefore propose a methane-derived carbonate mound origin formed from fluid sourced from underlying channel sands through the vertical column (Fig. 16d & e) (Cauquil & Adamy 2008, OTC).

7.2.2.4 Overburden fluid flow phenomena

Overburden fluid flow phenomena include all other fluid flow phenomena that occur below the seabed and are interpreted from area 1 and have been discussed in details in chapter 6 (Fig. 7.9). Those interpreted on the Nigeria Transform Margin include: paleo-pockmarks, stacked pockmarks, pipes, direct hydrocarbon indicators (DHLs), furrows and bottom-simulating reflections (BSRs) (Fig. 7.9). They occur in the first 400 ms TWT below the seabed. Polygonal faults are also classified under overburden fluid flow phenomena.
Fig. 7.9 (a) variance extraction on the seabed (b) schematic representations of distribution of MTDs through the entire stratigraphy (c-j) schematic representations of fluid flow features in area 1. Note how all the fluid flow features are concentrated in area 1 and MTDs are in area 2.
**Stacked and paleo-pockmarks** - The stacked pockmarks interpreted in the area often occur below the seabed and do not show any depressions on the present-day seabed (Fig. 7.9h). Individual depression and width varies between 10 – 35 ms and 270 – 480 m from shoulder to shoulder respectively (Fig. 6.15b). The stacked depressions are associated with the hanging wall of the faults and the high-amplitude, soft-kick reflections (possible gas accumulation) terminate against the fault plane (Fig. 6.15a & d). Stacked pockmarks have been interpreted from the Lower Congo Basin and other sedimentary basins and indicative of repeated fluid expulsion within the sedimentary column (Cartwright et al., 2007; Andresen & Húse 2008; Frey-Martínez et al., 2011).

**Pipes and direct hydrocarbon indicators** - Pipes are characterised by vertical columns varying from 50 to 80 m in diameter and up to 400 ms TWT in vertical extent. They often terminate upward into pockmarks and located above structural highs within polygonally faulted shallow interval. These pipes are evidence of upward and focused fluid flow through the sedimentary column (Løseth et al. 2009). High-amplitude anomalies with reverse seabed polarity observed randomly below the pipes or along fault planes are interpreted as direct hydrocarbon indicators formed from possible gas accumulation (Fig. 7.9d). The pipes interpreted on the Nigeria Transform Margin are linked to possible gas accumulations within shallow reservoirs and faulted-structural highs (Figs. 6.14 & 7.9). Relationship between pockmarks, pipes and sandstone reservoir was identified in the deep-water Niger Delta (Fig. 6.1b) (Løseth et al., 2001; 2011). Løseth et al., (2011) suggested that crater-like depressions on the seabed below vertical pipes formed from gas expulsion from underlying hydrocarbon-charged reservoir unit. We propose similar formation mechanism in the the study area (Fig. 7.10).

**Gas- hydrate bottom simulating reflections (BSRs)** - BSR is characterised by a negative polarity reflection that is parallel to the seabed and occur at about 300 ms TWT below the seabed reflection. It is often continuous and cross cuts surrounding strata. Below the BSR are high-amplitude, anomalies interpreted as free gas (Fig. 7.9 j). BSRs indicate the likely presence of gas hydrate (Shipley et al., 1979). Distribution of BSR in on the Nigeria Transform Margin coincides with underlying faults in the eastern part of the area (Fig. 6. 18e). Extent of the BSR mapped in the area suggests extent of gas hydrates present within the unit. Previous studies have shown that not all BSRs are related to gas hydrates. Drilling through some BSR showed no evidence of gas hydrates and gas hydrates have also been penetrated in the shallow subsurface without any evidence of BSR (Hovland, 2005). However, the presence of possible free gas below the mapped BSR in the study area is indicative of a gas-hydrate BSR.

Presence of gas hydrates and BSR have been thought to impede upward flow of fluid through the gas hydrate stability zone but continuous identification of fluid flow phenomena such as pockmarks, pipes, gas hydrate pingoes above BSRs suggests otherwise (Cummingham & Lindolm 2000; Hovland 2005; Gay et al., 2006a; Ostanin et al., 2012; Serie et al., 2012). Interpretation of pockmarks on the present day seabed above BSR also supports this (Fig. 6.18e & d). The interval above BSR is faulted by small extensional faults and these faults could have permitted migration of gas through the sedimentary column to the seabed as pockmarks (Fig. 6.18c & d).
**Polygonal faults** - This is the first documentation of polygonal faults along offshore Nigeria. The faults are characterised as small, extensional faults best imaged in cross section in the shallow interval up to 400 ms below the seabed and form polygonal geometry in plain view (Fig. 6.20). Fault throws measured are less than 12 m (between 3 – 11 m, 6 m average) and dip angle range of 41 – 50° (46° average) assuming a velocity of using 2000 m/s (Tab. 6.2). Fault dip angle is similar to those in the North Sea and Faroe-Shetland Basins but the throws are relatively smaller (Tab. 7.2). Extensive literatures on polygonal faults have attributed their formation to dewatering of fine-grained sediments particularly mudstones during early burial (Cartwright 1994; Lonergan & Cartwright, 1999; Lonergan et al., 1998; Goulty 2001; Stuevold et al., 2003). Presence of polygonal faults within Pliocene to Holocene sediments suggests they are still fairly recent and could explain why they have very small throws compared to those documented in the North Sea and Faroe-Shetland basins formed within much older sediments and terminate at the mid-Miocene and Intra-Oligocene unconformities respectively (Lonergan et al., 1998; Shoulders et al., 2007; Chapter 5).

### 7.2.2.5 Major controls and distribution of fluid flow phenomena on the Nigeria Transform Margin

Interpretation of 3D seismic data from the Nigeria Transform Margin revealing mounting evidence of fluid flow phenomena within the first 400 ms TWT in area 1 (SU5). They include seabed and paleo-pockmarks, pipes, carbonate mound, possible gas accumulations, gas-hydrate bottom simulating reflections (Fig. 7.9). Interpretation was based only on seismic data available and can be improved with additional data such as well data, geochemical data or seepage slicks.

Pockmarks are attributed to upward expulsion of fluids either gas or water from an underlying source, they give indication of the presence of an active petroleum system (Hovland & Judd 1988, Rise et al., 1999; Gay et al., 2007; Judd & Hovland 2007) and are classified as focused fluid flow features alongside with chimneys, pipes and sandstone intrusions (Cartwright 2007; Huuse et al., 2010). Although pockmarks interpreted are randomly distributed, they are related to structural highs, deep-seated, regional faults and active and buried deep-water channels (Figs. 6.14-17). These erosional and tectonic structures constitute an important component of the plumbing system in the area (Fig. 7.9). Base on observations and interpretations from the area, we suggest these features have served as migration pathways either through focused zones of weaknesses along the faults or diffused within permeable sediments as in sandstone-rich channels (Ligtenberg 2005; Pilcher & Argent 2007; Gay et al., 2006, 2007).

We propose that the fluid flow phenomena on the eastern part (area 1) of the Nigeria Transform margin is directly related to underlying features such as faults and channels (Fig. 7.9).

Active petroleum plays exist along the West Africa Transform Margin; which includes the syn-transform Aptian-Albian fields such as Hihon, Fifa, Tano and the younger, post-transform Upper
Cretaceous Fields such as Aje, Panthere, Belier sourced from Cretaceous shales (Greenhalgh et al., 2011). Most of the regional faults in area 1 are deep-seated and goes down into the Cretaceous interval where source and reservoir rocks within the basin are located (Fig. 6.2b). Majority of the pockmarks, pipes, furrows and BSR are related to faults (Figs. 6.22b, c, g-i) while the mound and other pockmarks are related to active and buried channels (Figs. 6.22d-f & 7.9). Seismic quality below the channels is very poor and chaotic, which does not image the faults well (Fig. 6.4e). It is therefore assumed that fluids that generated pockmarks above the channels could either have been sourced from within the channels or through faults below them (Figs. 6.22d-f).

7.2.2.6 Potential fluid type and source

Lack of geochemical data or slick information made it difficult to ascertain the type of fluid expelled during the formation of the fluid flow phenomena interpreted on the Nigeria Transform Margin. Availability of these data improves confidence of interpretation and to confirm the actual fluid that migrated and created these features (Gay et al., 2006; Judd & Hovland 2007; Andresen 2012).

The most common fluid in the sub-surface is formation water (Van Rensbergen 2003) but hydrocarbon (gas or oil) also exists especially in hydrocarbon prolific basins. The occurrence of polygonal faults could be an indication of mudstone dewatering by mechanical or chemical compaction during early burial of sediments (Cartwright 1994; Lonergan & Cartwright, 1999; Andresen 2012). Polygonal faults occur with fluid flow phenomena and provide evidence of significant pore water release in the area. However, distribution of polygonal faults does not match distribution of fluid flow features. In the Lower Congo basin, core samples taken from seabed pockmarks for geochemical analysis confirmed the presence of both biogenic and thermogenic gas (Gay et al., 2006a). Bright spots with reverse seabed polarity representing possible gas accumulations along fault planes and below pipes and possible free gas observed below the bottom simulating reflection could suggest presence of gas on the margin (Figs. 6.14 & 6.22b,d & g-i). The Aje Field, is located in OML113 in the northern part of the area is a successful gas field with its reservoirs and source rock in the Cretaceous interval (Fig. 6.1b & 6.2c). Recent drilling into Cretaceous sandstones in OPL310 (Ogo discovery) east of Aje Field and north of the study area also encountered significant accumulation of oil (http://www.afren.com/operations/nigeria/opl_310/). This provides evidence of working petroleum system on the Nigeria Transform Margin; thereby fluid source could be likely hydrocarbon. However, without sufficient data to confirm the fluid type, we propose that the fluid flow phenomena on the Nigeria Transform Margin could have formed from either of three sources or combination of two or all three of them: formation water, gas or oil.

The fluid flow phenomena represented by pockmarks and pipes could be composed of either thermogenic origin from deeper parts of the study area or biogenic origin in shallow subsurface (Fig. 7.10) (Judd & Hovland 2007). Presence of possible gas accumulations and presence of gas-hydrate BSR supports a shallow, biogenic methane generation from microbial activities of organic
matter origin and the link between some of the features with underlying faults and presence of active petroleum system in the area suggests a thermogenic origin (Judd & Hovland 2007; Andresen 2012). This can only be confirmed by additional data from geochemical analyses in the area. It is also possible that fluid sources are composed of both thermogenic and biogenic origin as confirmed by geochemical analysis on subsurface samples in Lower Congo Basin (Gay et al., 2006a).

7.2.2.7 **Origin of fluid flow and driving mechanism**

In the study area, all the fluid flow phenomena were interpreted within the first 400ms TWT in the shallow section, which is probably Pliocene to recent in age (SU5) (Fig. 6.22b-i). The timing of hydrocarbon generation and expulsion in the Dahomey-Benin basin began in the Late Miocene and continues till present-day (Fig. 7.10 & chapter 6) (MacGregor, 2003). This occurrence of fluid flow phenomena began right after hydrocarbon generation and expulsion (Fig. 2.2).

Hydrocarbon generation and migration have been widely proposed as a driving mechanism for pore pressure increase and formation of fluid flow phenomena such as sand injectites, pockmarks, pipes e.t.c. (Løseth et al., 2001, 2011; Jolly & Loneragan 2002; Hurst & Duranti 2002; Andresen et al., 2009; Monnier et al., 2014). This suggests that generation and migration of hydrocarbon facilitated increase in pore pressure within the reservoir (either shallow or deep), which exceeds the fracture gradient of the seal and fractures the rock. Upward migration of fluids through the succession creates series of pipes and pockmarks on the paleo and present day seabed (Løseth et al., 2001, 2011).

7.3 **IMPLICATIONS FOR HYDROCARBON EXPLORATION AND PRODUCTION**

All soft-sediment remobilization products and fluid flow features interpreted from both basins contribute greatly into understanding sediment distribution, fluid flow history and basin evolution in general. Sandstone intrusions, sandstone extrusions, pockmarks, pipes and polygonal faults are all recognised as seal bypass systems and their implications should not be overlooked (Cartwright et al., 2007).

Most hydrocarbon products in siliciclastic environments are stored in depositional elements such as channels and fans. The North Sea is one of the most prolific basins in the world and has been greatly explored for more than five decades. Exploration in the Northern North Seas centred on the Jurassic reservoirs sourced by the world-class Draupne mudstones (age equivalent of Late Kimmeridge Formation in the UK sector). However, in the last few years, there has been increased
interest in the Cenozoic section with two major successes from the Paleocene section (34/10-8-A) and Pleistocene (35/2-1). Several other wells drilled have penetrated brine-filled sandstones in the Tertiary interval and since plugged and abandoned. High-amplitude, discordant and concordant anomalies interpreted as sandstone injectites were recently drilled in the Paleocene interval around the Troll area, although confirmed presence of sandstone with excellent reservoir, the well did not encounter commercial hydrocarbon accumulation (Tullow, press release).

The Cenozoic interval of the Northern North Sea is severely affected by post-depositional remobilization, injection and extrusion of sandstone through hundreds of metres of shale-dominated strata from Late Cretaceous to Early Pliocene interval. This wholesale injection and extrusion through multiple stratigraphic units signifies breach in the sealing mudstone on a basin scale (Cartwright et al., 2007). In other parts of the North Sea basin such as the South Viking Graben and Outer Moray Firth, intrusions constitute significant reservoirs and migration pathways for hydrocarbon such as Alba, Balder, Gryphon, Leadon Fields (Fig. 1.2) (Lonergan et al., 2000; Hurst & Cartwright, 2007; Huuse et al., 2010). However, they appear to have compromised seal integrity in the Northern North Sea due to their multiple occurrence and possible cross-stratal connectivity through the Cenozoic mudstones. Sandstone units in the study area have been greatly modified by intrusion processes resulting in discordant margins either along sandstone bodies or as isolated conical of saucer-shaped intrusions (Chapter 4). Because they primarily have good porosities and permeabilities, sandstone intrusions have potential to form long-lived conduits for fluid migration before they become cemented (Hurst et al., 2003; Huuse et al., 2010).

It is therefore important to incorporate these unconventional sandstone occurrences into existing framework to know to what extent they have modified the overall stratigraphy and for accurate reservoir models. It is anticipated that lessons learned in the study area and the North Sea can be readily applied to other, less mature hydrocarbon basins in regions such as the Atlantic margins of Norway, United Kingdom and West Africa.

The Nigeria Transform Margin on the other hand, is a new frontier for petroleum exploration based on recent discoveries of significant accumulations in surrounding basins in Ghana, Benin and Nigeria. Exploration is centred on the Cretaceous interval where deep-water fans have proven to contain significant hydrocarbons (Brownfield & Charpentier, 2006). Presence of seabed and overburden fluid flow phenomena such as pockmarks, pipes, direct hydrocarbon indicators, furrows and bottom simulating reflections in the shallow, Pliocene to Recent interval suggest active petroleum system in the eastern part of the study area (area 1) (Chapter 6). This could also suggest leakage in the sealing capacity of the overburden rock. Pockmarks distributed along and above fault planes; active and buried channels suggest some sort of leakage through these tectonic or erosional structures.

Repeated occurrence of mass transport deposit along the Nigeria Transform Margin suggests continuous slope failure; this should be greatly considered during installation of drilling equipment as they constitute geohazards both on the seafloor and in the subsurface (Shipp et al., 2011).
Other fluid flow products such as pockmarks, seabed mound and BSR also constitute potential geohazards. Modelling of reservoir affected by sub-surface remobilization and extrusions must account for them as although they can improve aquifer drive; they can also result in early water break through (Huuse & Cartwright, 2007) and unexpected encounter during drilling can result to mud losses.

7.4 FURTHER WORK AND RECOMMENDATIONS

Integration of seismic and well data (where available) enabled us to identify and document depositional, remobilized and fluid flow features from two major sedimentary basins in the world; the Northern North Sea and along the Nigeria Transform Margin. However, observations and analysis were often limited by lack of specific data types that could have provided more robust interpretation from both areas. For future work in the area we recommend the following:

- For the Northern North Sea study, better seismic data with better resolution will improve quality of interpretation. Bin spacing for seismic used for the project is 50 by 50 metres. Seismic volume of smaller bin spacing will definitely improve identification and mapping of intrusions present in the area. Based on this, we believe that intrusions that are below seismic resolution were not imaged, therefore more intrusions are likely to be present in the area.
- Access to well logs, core and other useful well information from recently drilled wells in the Paleogene interval of the Northern North Sea will enable direct calibrations to some of the high-amplitude, anomalies interpreted as possible intrusions in the area.
- Heavy mineral analysis or similar analysis can help match sandstone intrusion complexes to their parent bodies as recently confirmed from the Central North Sea (Morton et al., 2014). This could also provide insight into source of fluid that remobilized the sandstone intrusions. Analysis should be carried out both on potential parent bodies in from Tertiary sand bodies and from Jurassic sandstones.
- Three-dimensional (3) petroleum system modelling for detailed information on hydrocarbon generation, expulsion, migration and diagenesis accumulation across the area as the current study obtained this information from 1 and 2D modelling from previous work. Results of spatial distribution of intrusions and mapped surfaces can be incorporated into the 3D model.
- Mapping of sandstone intrusions and extrusions show stratigraphic overlap between intrusions of different episodes in the area. Detailed reservoir modelling using computer-based methods to understand actual connectivity between individual sandstone intrusions across the whole area will be very useful for future exploration as this should identify where sandstone intrusions have formed thief sands.
- Detailed analysis on Cretaceous and Cenozoic mudstones could also prove useful in understanding the rheology of mudstones. Although this has been attempted previously by
different workers, taking samples from wells that penetrated intrusions and through silica diagenetic boundary might provide new findings into their relationship

- We have proposed the transformation of opal A to CT as the driving mechanism both for generation of overpressure and fluid supply for intrusions, laboratory experiment on this might prove useful to actually be able to quantify the volume of water expelled during the conversion as fluid budget required for such large scale remobilization and injection is worth looking at experimentally. But this remains the best model so far based on the study
- Future study from the Nigeria Transform Margin will definitely benefit from well data for direct calibration to constrain age of surfaces and units as well as for lithology delineation
- Surface and overburden geochemical data from the Nigeria Transform Margin will provide information on the fluid source and fluid type associated with fluid flow features in the area. This will help reduce uncertainties from interpretation based solely on seismic data
- The area will be a good site to study repeated MTDs in detail and results applied to regional studies. Quantitative analysis can be useful for building mechanical models
- Based on location and distribution of fluid flow features in area 1 (eastern part), any drilling in the area should be within that area as occurrence of fluid flow features represent likely presence of active petroleum system. However, care must be taken as they also signify breach in sealing capacity of the rock (Appendix 7.1 shows location of proposed IODP site)

Over all, it is recommended that there is need to re-appraisal sandstone occurrences especially within deep-water settings from basins in order to know the extent at which they have been affected by soft-sediment remobilization, injection or re-distribution and fluid flow phenomena as this could have significant implication on reservoirs, seals, traps and migration within the basin.

### 7.5 CONCLUSIONS

The thesis documents for the first time basin-scale sandstone remobilization and injection at multiple intervals emplaced during five (5) episodes within the Northern North Sea and fluid flow phenomena on the Nigeria Transform Margin. Both studies cover part of the Cretaceous and the entire Cenozoic successions, and show evidence of repeated soft-sediment deformation, remobilization and fluid two within the two major sedimentary basins: the North Sea and the Dahomey-Benin basin. The Northern North Sea is associated with large-scale sandstone intrusions/extrusions, while mass transport deposits dominate the Cenozoic stratigraphy along the Nigeria Transform Margin. Both study areas have undergone complex tectonic histories in the Late Jurassic to Early Cretaceous times and basin evolution is often linked to tectonics, sea-level changes and climatic factors; however, the study has shown that soft-sediment remobilization and fluid flow constitute a very significant part of the basins history.
The main episodes of emplacement in the study area Late Cretaceous, Middle Paleocene, Middle to Late Eocene, Middle to Late Miocene and Early Pliocene; and this reflects multiple fluid flow periods within the basin (Huuse et al., 2010). Some of these are synchronous with other parts of the North Sea and could suggest periods of regional fluid flow across the basin. They occur in sizes that are comparable to published examples from other parts of the North Sea and Faroe-Shetland basin. On the Nigeria Transform Margin, episodic mass transport deposits and fluid flow phenomena which include pockmarks, pipes, bottom simulating reflections, and possible methane-derived carbonate mound. Polygonal faults have also not been documented before from offshore Nigeria and these faults have dip angles comparable with those in the North Sea basin, Faroe-Shetland basin and More basin.

Emplacement of sandstone intrusions in the Northern North Sea has been linked to fluidization by diagenetically-released water (opal A to opal CT and smectite to illite transformations) and influx of pore water and hydrocarbon from deeper part of basin. Multiple emplacements of intrusions would suggest that the process re-occurred through time. Constraining the actual parent body of an intrusion is very challenging without heavy mineral analyses (Morton et al., 2014); however potential depositional parent bodies are present in the area and have been mapped based on the closeness to intrusions. Intrusions are mostly emplaced within polygonally faulted intervals form Cretaceous to Miocene but the faults do not seem to exert control on its geometry or distribution based on difference in dip populations as previously thought.

Episodic occurrence of MTDs along the Nigeria Transform Margin is attributed, mainly to increase in rate of sedimentation through time. Although effect of other factors such as slope gradient and possible sea-level change cannot be overlooked. Increase in magnitude of failed sediments corresponds to net sediment accumulation rate estimated in the area. However, uncertainties occur in age delineation of horizons, which form bounding surfaces for the failed sediments.

Soft-sediment remobilization such as sandstone intrusions and extrusions, mass transport deposits and fluid flow phenomena such as pockmarks, pipes; have major implications on sediment distribution and fluid flow within the basin. Some of these include; modifications to reservoir geometries, reservoir properties, reservoir distributions, reservoir connectivities and change in sediment pathways. Cross cutting nature of sandstone intrusions can greatly enhance permeability between reservoirs as observed in some of the hydrocarbon fields in the South Viking Graben and Outer Moray Firth in the North Sea; however they can compromise the sealing capacity of the host rocks (Cartwright et al., 2008). Therefore there is need to incorporate them into reservoir models at the early stage of exploration and production (Hurst & Cartwright 2007).

Presence of successive large-scale mass transport deposits and fluid flow phenomena have implications for hydrocarbon exploration and production, as they constitute potential geohazards and must be properly evaluated prior to drilling. Fluid flow phenomena indicate a leaking petroleum system. This study is therefore important as it provides evidence and distribution of these features on the Nigeria Transform Margin useful for future exploration in the area.
REFERENCES


BORSATO, R., GREENHALGH, J., WELLS, S., ROBERSON, R., & FONTES, C. (?). Prospectivity of the Equatorial Conjugate Margins of Africa and South America: PGS presentation


BUREAU, D., MOURGUES, R., CARTWRIGHT, J., & HUUSE, M (in press).Large-scale sandstone intrusion emplacement and geometry


MILLER, K.G., KOMINZ, M.A., BROWNING, J.V., WRIGHT, J.D., MOUNTAIN, G.S., KATZ, M.E.,

from a submarine lobe fringe during hydrocarbon migration and salt diapirism: a seismic example

pressures and formation waters. In: The Millenium Atlas: Petroleum Geology of the Central and
Northern North Sea (Ed. by D. Evans, C. Graham, A. Armour & P. Bathurst). Geological Society
London, London, 279-287

NEAGU, R.C., CARTWRIGHT, J., DAVIES, R., & JENSEN, L. (2010). Fossilisation of a silica
diagenesis reaction front on the mid-Norwegian margin. Marine and Petroleum Geology 27, 2141-
2155

NELSON, C.H., ESCUTIA, C., DAMUTH., J.E., & TWICHELL (Jr), D.C. (2011). Interplay of mass-
transport and turbidite-system deposits in different active tectonic and passive continental margin
(eds). Mass transport deposits in deep-water settings. SEPM Special Publication 96, 39-66


in Earth Sciences 120, 103-108

flow and diagenesis. MSc taught project

OLOBAYO, O., HUUSE, M. & JACKSON, C. A. L. (2012). Basin scale sand injection and extrusion in
the mid/late Miocene of the Northern North Sea: a result of basin scale silica diagenesis? Extended
abstract, 74th EAGE 2012 Conference and Exhibition incorporating SPE EUROPE 2012

PETROLEUM GEO-SERVICES (2006). Techlink, a PGS Geophysical, 6, 2

POSAMENTIER, H. W & KOLLA, V. (2003). Seismic geomorphology and stratigraphy of depositional
elements in deep-water settings. Journal of Sedimentary Research, 73, 3, 367 – 388

POSAMENTIER, H. W & MARTINSEN, O.J (2011). The character and genesis of submarine mass-

RUNDBERG, Y. & SMALLEY, P.C. (1989) High-resolution dating of Cenozoic sediments from the
northern North Sea using 87Sr/86Sr stratigraphy. AAPG Bulletin, 73, 298–308.


RUNDBERG, Y. & EIDVIN, T. (2005). Controls on depositional history and architecture of the
Oligocene-Miocene succession, northern North Sea Basin. Norwegian Petroleum Society, Special
Publication, 12, 207–239.

SAFRONOVA, P.A., ANDREASSEN, A., LABERG, J.S., & VORREN, T.O. Development and post-
depositional deformation of a Middle Eocene deep-water sandy depositional system in the

SCHLAKKER, A, CSIZMEG, J., POGÁCSÁS., G, AND HORTI, A. (2012). Burial, thermal and
maturation history in the Northern Viking Graben (North Sea). AAPG 2011 International


Appendix 1.1 Global distribution of sandstone intrusions, silica diagenetic boundaries and polygonal faults (partly modified from Huuse et al., 2010;
Appendix 1.2 Seismic line through Aje discovery. Horizons used in the study area where traced from this seismic line. No well available or well tops for the project.

Appendix 1.3 Geoseismic representation of appendix 1.2 form Aje discovery.
Appendix 4.1 Seismic section across Paleocene intrusions in the study area. Well correlation panels shown in next page.
Appendix 4.2 Well log correlation and RMS attribute map of remobilized sandstones in the Paleocene for Fig. 4.10 (Chapter 4)
Appendix 5.2 Estimated temperature gradients for opal A to opal CT boundary using a constant seabed temperature (Rundberg 1991). The transition occurred between 22 and 44° as shown in temperature @ boundary column. Similar to those estimated from previous studies in the Faroe-Shetland and mid-Norwegian ridge. Rundberg estimated 27 and 40° for wells 31/2-5 and 30/3-3 in the area. Methodology adopted from Neagu et al., 2009. Geothermal gradient: Difference in temperature/borehole depth. Temperature at boundary: Depth to boundary*temperature difference/borehole depth + seabed temperature.
Appendix 5.2 Estimated temperature gradients for opal A to opal CT boundary using a constant seabed temperature (Rundberg 1991) against depth
Appendix 5.3 Composition of clay minerals from wells taken from Cenozoic interval in the NNS (compiled from Marcussen et al., 2009)

Appendix 7.1 International Ocean Drilling Program (IODP) location for proposed drilling of Cretaceous and Paleogene succession in along the Nigeria Transform Margin (NTM-01). Study area in represented by the rectangle
Complexity of Sandstone Bodies in the Northern North Sea and Their Implications on Hydrocarbon Prospectivity

O. Olobayo* (The University of Manchester), M. Huuse (The University of Manchester) & C.A.L. Jackson (Imperial College London)

SUMMARY

Millions of barrels of hydrocarbon are produced daily from sandstone reservoir intervals in deep-water settings from petroliferous basins such as the North Sea, Niger Delta etc. These sandstones are commonly believed to have been deposited by gravity-flow processes inform of large, deep-water channel-lobe systems and low-stand fans; however, detailed investigation reveals unusual geometries that are difficult to unravel by normal depositional processes. It is believed that, the sandstones have been subject to sub-surface remobilization and injection that significantly modified their geometries. Early Tertiary sandstones in the South Viking Graben, Outer Moray Firth and East Shetland Platform in the North Sea (Alba, Balder, Chestnut, Kraken, Mariner, Volund etc) show evidence of such modifications from seismic, wireline logs and core data (Lonergan et al. 2000). Products of these post-depositional processes are recognized from the Cretaceous to Pliocene intervals in the study area. They include remobilized sands, sand injectites and sand extrudites embedded in mud-rich successions. Evidences show the Cenozoic Northern North Sea underwent basin-scale remobilization and injection in a scale that has not been previous documented in the North Sea or any other basin in the world. We observe an exclusive stratigraphic overlay of these unconventional sandstones and if the sands are connected, could have impacted hydrocarbon prospectivity in the basin. Therefore, there is need to incorporate them into the current Cenozoic stratigraphic framework and geologic models at the early stages of exploration; to ascertain to what degree they may have influenced fluid flow in the basin. We propose a multiple phase emplacement through the interval.
Introduction

The Cenozoic succession of the Northern North Sea basin is severely affected by sub-surface sediment remobilization, injection and extrusion of sands. These post-depositional processes result in modifications of original reservoir geometry and properties, sandstone distribution and in some cases form significant trap with potentially large hydrocarbon volumes (Lonergan et al., 2000; Hurst & Cartwright 2007; Huuse et al., 2010). The North Sea basin houses the best examples of these unconventional sandstones in the world and they have been intensely studied at different scales within the basin. Sandstone intrusions and extrusions, as they are broadly known, were initially thought to be insignificant and completely overlooked during exploration until recent break-through in the last two decades in Paleocene-Eocene aged reservoirs of the North Sea (Alba, Balder, Catcher, Chestnut, Gryphon, Mariner, Volund etc.), were they are known to have significant impact on hydrocarbon production. Prior to this discovery, all sandstones were interpreted to be depositional in origin in form of low-stand fans and channel-lobe systems, however, integration of improved 3D seismic, well logs, core and outcrop data have revealed evidences that some of these sand bodies were either remobilized, injected or extruded (Fig. 1).

Figure 1 Three (3) models for sandstone origin in the North Sea basin (Huuse et al. AAPG 2009)

The study area is located in the northernmost part of the North Sea basin between latitude 60 – 62°N and longitude 1 – 5°E (Fig. 2a). The aim of this study was to re-evaluate the distribution and origin of sandstones within the Tertiary interval in the light of recent findings of kilometer-scale sand injectites; that have been discovered in the adjacent parts of the North Sea and investigate their implications on petroleum systems development.

Figure 2 (a) Structural map of the North Sea with study area (red outline). Green boxes - fields with remobilization; yellow stars – previous studies (b) stratigraphic column of studied interval
Method

Our study covers an area of 29,000 km$^2$ in the Northern North Sea and encompasses sediments from late Cretaceous to present day (Fig. 2a & 2b). We utilized a high-resolution 3D MegaSurvey, 2D seismic lines and wireline logs to carry out regional mapping across the area. Well data information such as formation tops, completion logs and some core data were also available. Integrating these data, we defined 10 units bounded by time-significant surfaces to review and build-on the present tectono-stratigraphic framework in the area. Time-structure, time-thickness and attributes maps were also generated to define depocentres, sediment provenances, sandstone distribution in the area.

Seismic and Well Observations

The Cenozoic succession is well preserved in Northern North Sea with thickness reaching up to ~2200 meters (Fig. 3). Series of uplifts along the margins deposited clastic sediments into the basin from the Shetland Platform and Norwegian Landmasses (Rundberg 1991; Ahmadi et al., 2003). The interval is mudstone-dominated but well data confirms presence of varying thicknesses of sandstone units believed to have been deposited during the uplifts. Detailed investigation reveals unusual geometries in some of these sandstones that cannot be unravelled by normal depositional processes. They appear to have been modified by post-depositional processes that resulted in their present and complex geometries (Lonergan et al., 2000).

Our interpretation is based on mounting evidences observed from study. They include: (1) presence of high-amplitude, discordant anomalies embedded in low-amplitude strata (2) occurrence of discordant anomalies in close association with deep-water depositional systems (3) calibration of some of the anomalies to thick sandstone intervals (4) thin sands cross-cutting mudstone strata in core (5) complexity of original geometry of in-situ sandstone bodies (6) unusual location of isolated sand bodies in the stratigraphy (7) difficulties in defining top surface of a depositional sand body (8) abrupt vertical and lateral termination of sand bodies (9) very steep-angled mounds with on laps on the upper surface (10) jack-up of overburden above high-amplitude discordant facies. Some of these are also observed in the well-exposed Panoche-Tumey Injectite complex in California (Hurst et al., 2011). A very unique observation in our study is the multiple occurrences of these anomalies suggesting a basin-scale remobilization and injection; the first-ever to be documented in similar studies (Fig. 3).

Figure 3 NW – SE seismic and geoseismic section showing multiple occurrences of depositional and post-depositional sands in the Northern North Sea.
Interpretation

Similar features have been intensely documented in Early Tertiary sandstone reservoirs in the South Viking Graben and Outer Moray Firth; adjacent to our study area (Fig. 2a). They are interpreted as products of sub-surface remobilization, injection or extrusion of sands (Fig. 1) depending on their present geometry (Huuse et al., 2010). Based on this and the evidences presented above, we propose that several sandbodies in the Northern North Sea have undergone post-depositional remobilization, injection and extrusion and should be clearly distinguished from depositional low-stand fans or channel-lobe system deposits. This interpretation should be extended to other basins in regions such deep-water Niger Delta, Gulf of Mexico, Barents Sea, Angola and even less mature hydrocarbon basins; as there is need to incorporate them in geologic and basin models at the early stages of exploration.

Figure 4 seismic section through the Eocene – present day seabed in Quadrant 35, Northern North Sea showing a saucer-shaped intrusion believed to have been sourced from the Eocene slope fan. Also shows a sand extrudite on the MMU. Inset is a 3D image of the saucer-shaped intrusion.

Relationship with underlying structures and mechanisms

Based on our findings, we observe a multiple occurrence of sandstone intrusion and extrusion complexes, cross-cutting through thick, low-permeable, mud-rich sequences from Cretaceous to Pliocene (Figs. 3 & 4). We propose a multiple phase emplacement in the area; this stems from the presence of on laps above individual examples and extrudite (Fig. 4) at more than one stratigraphic level. Spatial distribution of these features within each Cenozoic succession was overlain on a TWT - structure map of the base Cretaceous unconformity to investigate any relationship with underlying Mesozoic structural elements (Fig. 5).

The map shows a common NE-SW trend between the sandstone intrusion/extrusion complexes and the underlying faults. They are mostly distributed above fault planes and structural highs although much younger ones occur within the Viking Graben (Fig. 5). We speculate a genetic relationship in terms of causative mechanism between these structures; through upward fluid movement from underlying hydrocarbon kitchens and silica diagenetic process. We also observe a stratigraphic overlap between the sandstones across the area. Because sandstone intrusions are known to enhance connectivity between isolated units, if they are connected in our case, are likely to pose major risk to prospectivity.
Implications of basin-scale remobilization and injection in the Northern North Sea

Sandstone intrusions and extrusions are becoming an important component of a reservoir and petroleum system as a whole; mainly due to their positive and negative implications on the system. In the South Viking Graben and Outer Moray Firth (green boxes in Fig.1); many of the reservoirs are associated with injectites and constitute a significant aspect of the system either as stand-alone traps based on their excellent properties, improving hydraulic communication between isolated sandbodies or adding to hydrocarbon volume (Braccini et al. 2008). However, their presence is indicative of a breach in the sealing capacity of the host-rock mudstones (Cartwright et al. 2007). In this study area, although we recognize similar sandstone intrusions and extrusions as those observed in other parts of the North Sea, there has only been one successful discovery (35/10-A-8) in the Paleocene sandstone interval till date; other sandstones penetrated by wellbores have been water-wet. We therefore infer that, the effect of basin-scale remobilization and injection of sandbodies through host-rock mudstones could have impacted prospectivity negatively in the Tertiary succession of the Northern North Sea.

Figure 5 overlay of distribution of sandstone intrusions/extrusions on base Cretaceous Unconformity.

Conclusions

Detailed re-examination of sandstones in the Northern North Sea sheds light into the influence of post-depositional remobilization and injection. They should be incorporated into the current Cenozoic framework to understand how much influence they have on sandstone reservoirs and to know what degree this would have on future hydrocarbon exploration and production in the area.

Acknowledgements

The main author is grateful to PTDF (PhD sponsorship), PGS (NNS MegaSurvey, 3D seismic data), TGS-NOPEC (NSR 2D lines), NPD website (well information), and Schlumberger (Petrel software).

References (some)