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The last glaciers of Greece

by

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with 9 figures and 7 tables

Summary. Four discrete phases of Pleistocene glacial activity are recorded on Mount Smolikas (2,637 m a. s. l.), the highest peak of the Pindus Mountains, Greece: one more than on neighbouring mountains. The most recent glacier advance occurred after the main local glacier maximum of the last cold stage. Palaeoclimatic reconstructions based on modern glacier- and rock glacier-climate relationships suggest that mean annual temperatures during the last phase of glacier activity in the Pindus mountains were 6.3 °C cooler than present day yet *c.* 2.2 °C warmer than the coldest phase of the last cold stage. On the highest slopes of Mount Smolikas, the climate appears to have been close to the threshold between glacier and rock glacier formation with precipitation greater than 2,000 mm yet less than 2,500 mm and mean annual temperatures colder than −2 °C. The last glacial advance in Greece may correlate with global cooling during Heinrich Event 1 between 14,310 ± 200 and 13,960 ± 260 ^{14}C years BP, during which time a series of major floods are recorded in the Boila rockshelter sediment record in the nearby lower Vikos Gorge. However, comparison of glacier equilibrium line altitudes with former glaciers in the Italian Apennines suggests that glacier re-advance occurred during the Mount Aquila Stadial, which has been correlated with climatic deterioration during the Younger Dryas Chronozone.

Zusammenfassung. *Die letzten Gletscher Griechenlands.* – Am Berg Smolikas, dem höchsten Gipfel des Pindus-Gebirges in Griechenland, können vier verschiedene Phasen pleistozäner Gletscheraktivität beobachtet werden: somit eine Phase mehr als in den benachbarten Bergregionen. Der jüngste Gletschervorstoß fand nach dem lokalen Gletschermaximum der letzten Kaltzeit statt. Paläoklimatische Rekonstruktionen, basierend auf modernen Gletscher- und Blockgletscher-Klima-Beziehungen, legen die Vermutung nahe, dass das jährliche Temperaturmittel während der letzten Vergletscherung im Pindus-Gebirge um 6.3 °C unter dem heutigen lag, jedoch 2.2 °C über der kältesten Phase der letzten Kaltzeit. Das Klima der höchsten Abhänge am Berg Smolikas schien nahe der Schwelle zwischen Gletscher- und Blockgletscher zu liegen, mit mehr als 2.000 mm Niederschlag, jedoch weniger als 2.500 mm and Jahresmitteltemperaturen unter −2 °C. Der Gletschervorstoß könnte mit einer globalen Abkühlungsperiode während des Heinrich 1 Ereignisses, zwischen 14.310 ± 200 und 13.960 ± 260 ^{14}C Jahren, korrelieren, in welcher eine Reihe großer Überflutungen der Boila Felshöhlensequenz in der nahegelegenen Vikos-Schlucht stattfand. Ein Vergleich der Seehöhe der Gletschergleichgewichtslinie (Firnlinie) mit früheren Gletschern im italienischen Appenin legt die Vermutung nahe, dass der Wiedervorstoß des Gletschers während des Aquila-Stadials stattfand, welches mit einer Klimaverschlechterung während der jüngeren Dryas-Chronozone in Verbindung gebracht wird.

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Résumé. *Les derniers glaciers de la Grèce.* – Quatre phases différentes d'activité glaciaire sont enregistrées sur Smolikas, le plus haut sommet de la chaîne du Pindus, Grèce : une phase supplémentaire par rapport aux montagnes avoisinantes. L'avancée glaciaire la plus récente se produisit après le maximum glaciaire local le plus important de la dernière période froide. Des reconstructions paléo-climatiques basées sur les relations entre le climat moderne et les glaciers – et glaciers rocheux – modernes suggèrent que les températures annuelles moyennes durant la dernière phase d'activité glaciaire dans les montagnes du Pindos étaient plus basses de 6.3 °C par rapport aux températures actuelles, et cependant environ 2.2 °C plus élevées par rapport aux températures durant la phase la plus froide de la dernière période froide. Sur les versants les plus élevés de Smolikas, le climat semble être à la limite entre la formation de glaciers et de glaciers rocheux, avec des précipitations dépassant les 2.000 mm, mais pas plus élevées que 2.500 mm, et des températures annuelles moyennes plus basses que –2 °C. L'avancée glaciaire peut correspondre au refroidissement planétaire durant l'évènement Heinrich 1, situé entre 14.310 et 13.960 ^{14}C année, pendant lequel une série d'inondations importantes est enregistrée dans la séquence de la grotte Boila, située dans la Gorge du Vikos à proximité. Cependant, la comparaison entre l'altitude de la limite des neiges avec des glaciers disparus dans les Apennins italiens suggère qu'une re-avancée glaciaire se produisit pendant le Mont Aquila Stadial, qui correspond à une détérioration climatique durant le Younger Dryas Chronozone.

1 *Introduction*

Evidence of Pleistocene glaciation is widespread in the Pindus Mountains of Greece. On Mount Tymphi (2,497 m a. s. l.) in the northern Pindus, Uranium-series dating has shown that the most extensive glacial phases occurred during the Middle Pleistocene (WOODWARD et al. 2004). The glacial chronostratigraphy for Greece has been recently defined using glacial and periglacial deposits in conjunction with pollen stratigraphy from a continuous 423,000 year-long lacustrine record in the Ioannina basin (HUGHES et al. 2005, TZEDAKIS 1994, TZEDAKIS et al. 2002) (table 1). The earliest and most extensive recorded glaciation occurred during the Skamnellian Stage, which is correlated with the Elsterian Stage of northern Europe, the Mindelian Stage of the Alps and marine isotope stage (MIS) 12. A second glaciation occurred during the Vlasian Stage, which is correlated with the later part of the Saalian Stage of northern Europe, the Rissian Stage of the Alps and MIS 6. The most recent glaciers formed during the Tymphian Stage, which is correlated with the Weichselian of northern Europe, the Würmian of the Alps and MIS 5d-2.

HUGHES et al. (in press) have suggested that glaciers could have formed on several occasions during the Tymphian Stage and they have identified intervals that would have been climatically-favourable for glacier formation in the pollen record at Ioannina. Only minor cirque and small valley glaciers occurred during the Tymphian culminating with the development of periglacial rock glaciers at the most severe arid phase of climate (22–20,000 ^{14}C years BP), just prior to the global last glacial maximum (*c.* 18,000 ^{14}C years BP) (HUGHES et al. 2003). The interval between *c.* 25,000 and 15,000 cal. years BP appears to have been too dry for glacier formation, although a return to conditions favouring glaciation can be identified between *c.* 15,000 and 11,000 cal. years BP. No evidence of later glaciation is represented in the stratigraphical record on Mount Tymphi. However, on Mount Smolikas, the highest peak of the Pindus Mountains and only 10 km to the north, a higher glacial and periglacial strati-

graphical unit exists c. 200 m above the highest cirque floors and moraines of Mount Tymphi (Boenzi et al. 1992). A glacial unit is also present at a similar altitude on Mount Olympus, in northeast Greece, in the north-facing Kazania cirque above 2,200 mm a. s. l. (Messerli 1967, Smith et al. 1997). The glaciers that produced these

Table 1 Chronostratigraphical table showing the relationship between the fragmentary glacial and periglacial sequence in the Pindus Mountains, Greece, and the continuous lacustrine parasequence at Ioannina. § = Names based on Tzedakis et al. (2002) – all other names for the Ioannina sequence are from Tzedakis (1994). * = Interval dates from Tzedakis et al. (2002) – all other dates from orbitally-tuned marine isotope records (Imbrie et al. 1984, Martinson et al. 1987). Modified from Hughes et al. (2005).

Age (x 1,000 years)	MIS	Ioannina (IN 249/ 284)	Para-stratotype boundary (IN 249)	Pindus Chrono-stratigraphy	Local Stratotype
11.5 -	1	Holocene	17.25 m		
66 - 11.5 *	2			**Tymphian Stage**	Tsouka Rossa Member 39°58'45"N, 20°50'40"E, 2025 m a.s.l.
	3				
	4				
83 -66*	5a	Interstadial 2§			
88.5 - 83*	5b	*Stadial 2*§			
104 - 88.5*	5c	Interstadial 1§			
111 - 104.5*	5d	*Stadial 1*§	45.88 m		
127 - 111*	5e	Metsovon	59.00 m		
190 - 126.6*	6		76.00 m	**Vlasian Stage**	Vourtapa Member 39°55'50"N, 20°51'10"E, 1650 m a.s.l.
250 -190	7a-e	IN-26 Zitsa IN-23a		?	
300 250	8				
340 - 300	9a-e	Katara IN-17 Pamvotis			
350 - 340	10				
430 - 350	11	Dodoni I / II	162.75 m		
480 - 430	12		184.00 m	**Skamnellian Stage**	Kato Radza Member 39°54'08"N, 20°50'40"E, 984 m a.s.l.

deposits on Smolikas and Olympus represent the last glaciers of Greece and they formed some time after the local glacial maximum of the Tymphian Stage.

This paper presents the evidence for glaciation and periglacial activity on Mount Smolikas with particular focus on glaciers that formed moraines in the highest cirques, which post date the local glacial maximum of the Tymphian Stage. The palaeoclimatic implications of these glaciers are discussed and, in combination with other records, used to examine the possible timing of this last phase of glacier activity in Greece.

2 *Study area*

Mount Smolikas is located in the northern Pindus Mountains of Greece, in Epirus, only 10 km from the Greece-Albania border (fig. 1). The mountain is formed in ultrabasic and basic ophiolitic rocks which include lithologies such as serpentinite, dunite and harzburgites (IGME 1987). Jurassic limestones and schists are also present, and both are found mainly at the overthrust nappe of the ophiolitic complex.

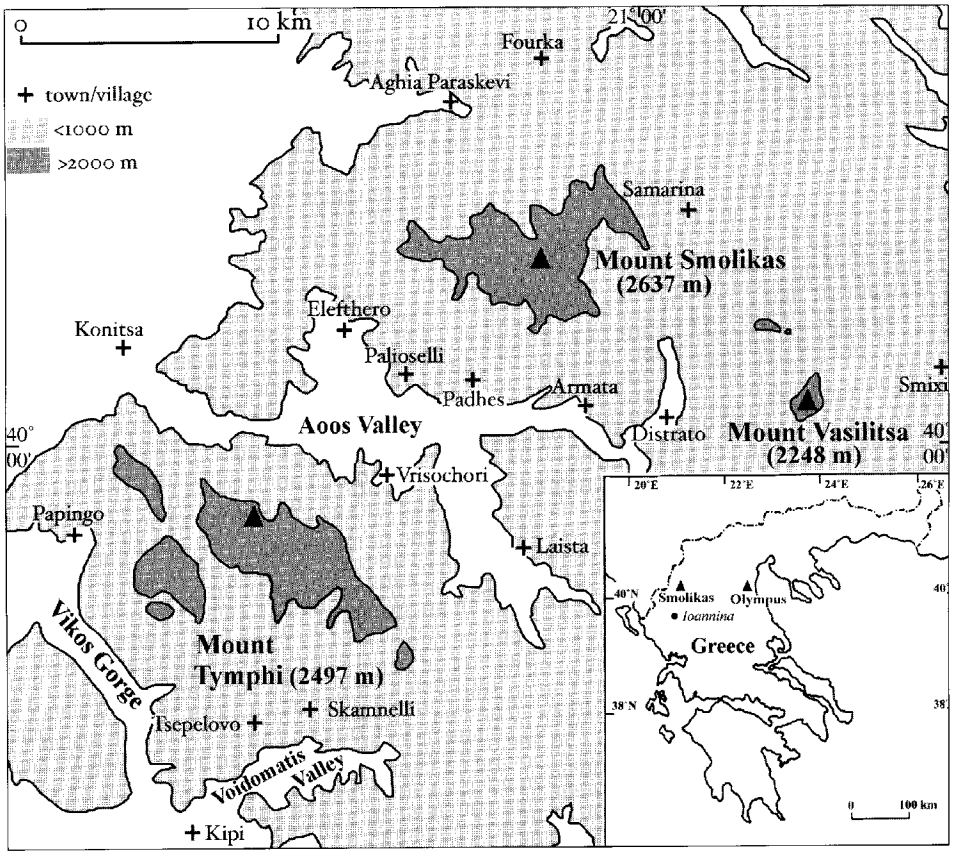

Fig. 1. Location map.

Fig. 2.
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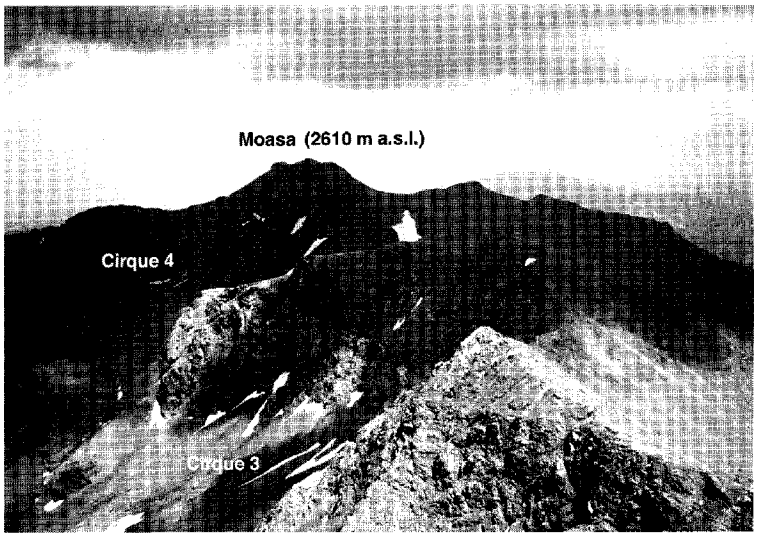

Fig. 2. The main ridge of Mount Smolikas, looking east from the summit (2637 m a. s. l.) (Photograph by P. D. HUGHES, June 2001).

The highest recorded mean annual precipitation on Mount Smolikas is 1,391 mm at the village of Fourka (1,350 m a. s. l.) in the northern foothills (fig. 1) (FOTIADI et al. 1999). However, precipitation in the highest central areas is likely to be considerably higher, although no records exist. On the highest slopes of the Pindus Mountains above 2,000 m a. s. l., FURLAN (1977) estimated that mean temperatures of −5 and 15 °C occur during winter and summer months respectively. During the winter, snow falls are very heavy with drifts of several metres thickness persisting through the spring until early summer in the northern cirques (fig. 2). Both climate and geology contribute to the characteristic vegetation cover of black and Balkan pine (*Pinus nigra* and *Pinus heldreichii*), although the highest slopes above 2,000 m a. s. l. are characterised by open alpine terrain.

3 *Geomorphological evidence*

Glacial and periglacial features were mapped on to 1:25,000 base maps in the field between 2001 and 2004. All the evidence for glaciation occurs on the northern and eastern slopes of Mount Smolikas (figs. 3, 7, 8). In the Vadulakkos valley, four discrete suites of moraines can be recognised (fig. 3). The lowest deposits are characterised by thick (> 30 m) accumulations of diamicton deposits extending down to nearly 1,000 m a. s. l. [Aghia Paraskevi Member] (fig. 4). Higher up-valley, similar deposits form clear ridges on each side of the valley between *c.* 1,100 and 1,350 m a. s. l. [Vadulakkos Member]. Detailed sedimentological analyses have shown that the diamictons of both the Aghia Paraskevi and Vadulakkos Members are characterised by striated, matrix-supported clasts with strong clast fabric oriented in the up-valley direction, grading upwards into clast-supported boulder horizons (fig. 4). HUGHES (2004) in-

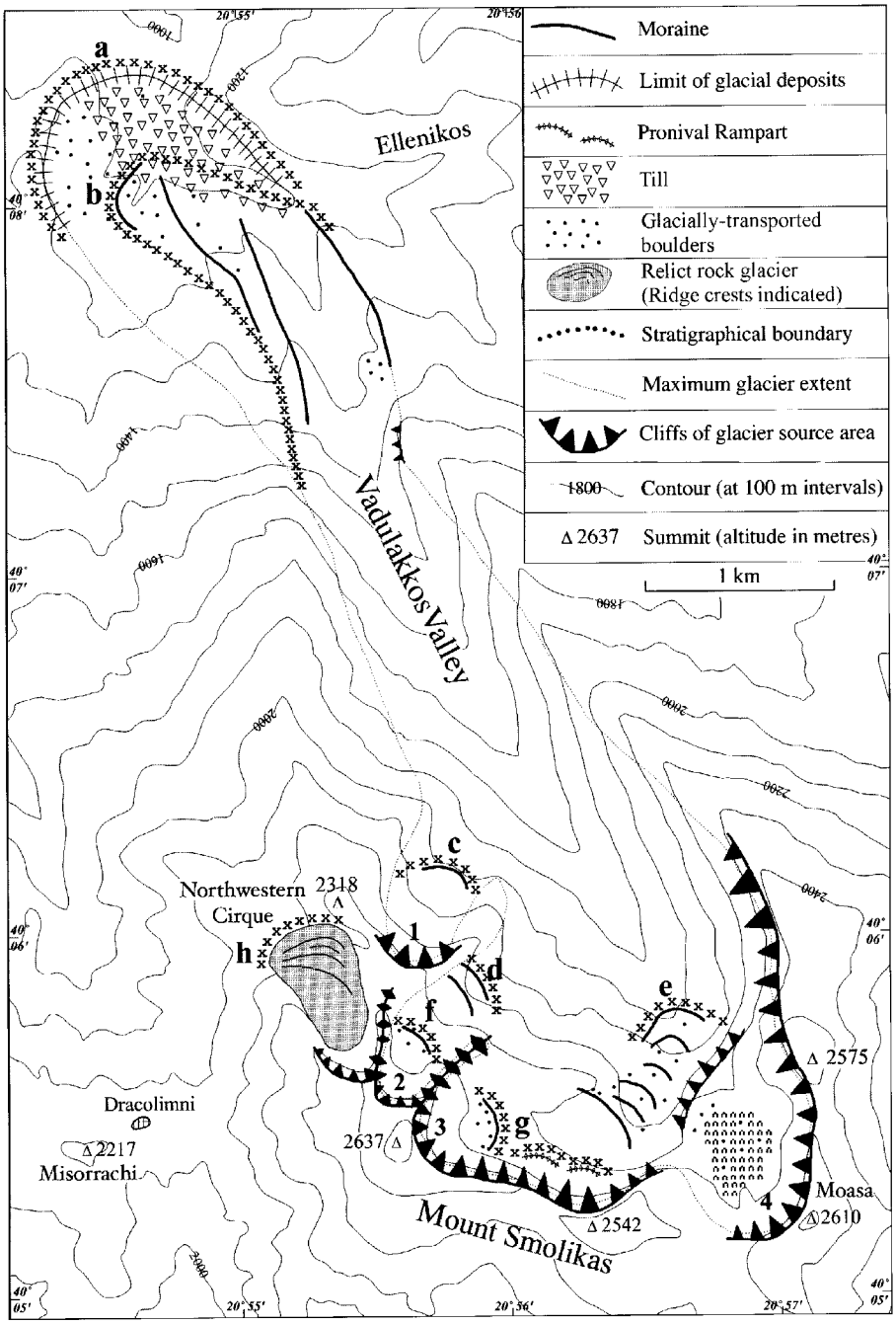

Fig. 3. Glacial geomorphological map of the central and northern Mount Smolikas area. a: Aghia Paraskevi Member, b: Vadulakkos Member, c: Cirque 1 Member, d: Cirque 2 Member, e: Cirque 3/4 Member, f: Smolikas N. Member, g: Smolikas N.E. Member, h: N.W. Cirque Member. Cirques draining into the Vadulakkos Valley are numbered 1 to 4.

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Fig. 4. A thick sequence of diamicton deposits cut by the Aghia Paraskevi to Fourka road. The sequence is *c.* 30 m thick and forms the Aghia Paraskevi and Vadulakkos Members and the deposits are interpreted as tills formed by valley glaciers originating in the northern cirques of Mount Smolikas.

terpreted these deposits as composite moraines formed by ice-thrusting in front of former extensive valley glaciers that emanated from the northern cirques of Mount Smolikas on at least two separate occasions.

The next suite of moraines occurs *c.* 6 km further up-valley at the entrance to the highest cirques which are scalloped into the northern slopes of Mount Smolikas and feed into the Vadulakkos valley (fig. 3). Four separate sets of moraines, at *c.* 2000–2,150 m a. s. l., bound the entrance to four cirques, numbered here from west to east [Cirque 1, Cirque 2, Cirque 3/4 Members].

Hummocky moraines and perched boulders are present in the highest parts of Cirque 4 at *c.* 2,350 m a. s. l. However, no clear terminal moraine is evident and the lower entry to this cirque is bounded by steep cliffs. It is probable that these deposits formed upon retreat and melt-out of the former glacier that deposited terminal moraines beneath the cliffs at the cirque entrance and the deposits are considered contiguous with the Cirque 3/4 Member.

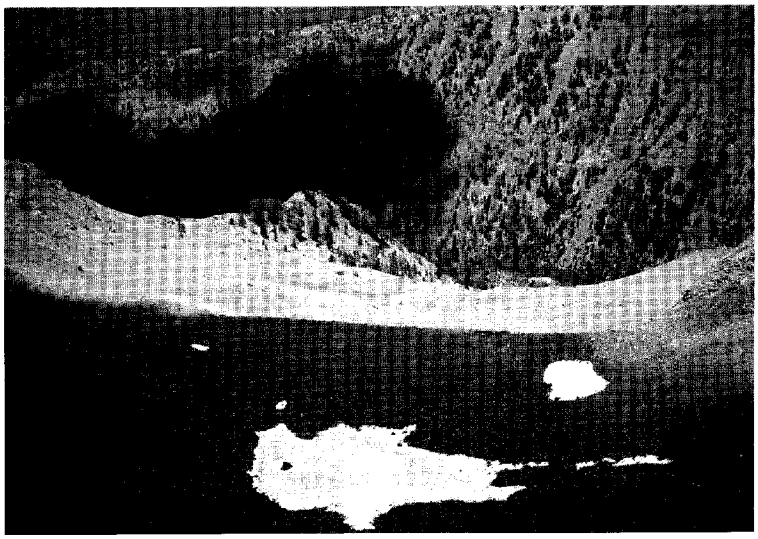

Fig. 5. The moraines (in shade) of the Smolikas North Member in Cirque 2 viewed from near Mount Smolikas summit. These represent some of the highest glacial deposits of the area (Photograph by P. D. HUGHES, June 2001).

Table 2 The morpho-lithostratigraphical sequence of glacial and periglacial units on Mount Smolikas.

Unit	N. Smolikas Formation	Konkutino Formation	Samarina Formation	N. W. Cirque Formation
4	Smolikas N. E. Member			
	Smolikas N. Member			
3	Cirque 1 Member	Galanos Limni Member		
	Cirque 2 Member	Moasa Member		
	Cirque 3/4 Member			
2	Vadulakkos Member	North Limni Member		
1	Aghia Paraskevi Member	Bogdoni Member Konkutino Member	Samarina Member	N. W. Cirque Member