Glacier fluctuations in the western Alps during the Neoglacial, as indicated by the Miage morainic amphitheatre (Mont Blanc massif, Italy)

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Holocene glacier variations pre-dating the Little Ice Age are poorly known in the western Alps. Studied for two centuries, the Miage morainic amphitheatre (MMA) is composed of three subconcentric sets of *c*. 25 moraines. Because of its location and of a dominant mode of morainic accretion, the MMA is a well-preserved marker of the glacier dynamics during the Neoglacial. Radiocarbon dates were obtained by digging and coring in inter-morainic depressions of the MMA and through a deep core drilling in a dammed-lake infill (Combal); complementary data for the inner MMA were obtained by lichenometry and dendrochronology. Radiocarbon chronology shows that (i) the MMA not only pre-dates the Little Ice Age (LIA), but was built at least since 5029–4648 cal. yr BP (beginning of the Neoglacial); (ii) outer sets of moraines pre-date 2748–2362 cal. yr BP; (iii) the MMA dammed the Lake Combal from 4.8 to 1.5 cal. kyr BP, while lakes/ponds formed inside the moraines (e.g. from 2147–1928 to 1506–1295 cal. yr BP). The 'Neoglacial model' proposed here considers that the MMA formed during the whole Neoglacial by a succession of glacier advances at 4.8–4.6 cal. ky BP (early Neoglacial), around 2.5 cal. ky BP (end of Göschener I), at AD 600–900 (end of Göschener II) and during the LIA, separated by raising phases of the right-lateral moraine by active dumping because of the Miage debris cover.

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Our knowledge of glacial variations during the present interglacial (Holocene) is an important key to reconstruction of the palaeoclimates of this period, although the transfer function between climate signal and glacier oscillations remains poorly understood. Moraines that form during successive advances at a glacier front and margins are a climate proxy when the following are taken into account: (i) the variability of glacier dynamics at several temporal and spatial scales, due to the size, aspect, slope or supraglacial debris cover of the glacier; (ii) the poor preservation of previous moraines when the glacier expands beyond them (erosion or morainic superposition); (iii) the relative rarity or short span of life of organic elements for radiocarbon dating in (wood, buried soil), on (lichens, trees) or between (peat, charcoal, wood) moraines, while recent dating techniques, such as optically simulated luminescence (Richards 2000; Benn & Owen 2002) or surface exposure dating with cosmogenic radionuclides (Benn & Owen 2002; Ivy-Ochs *et al*. 2004), are not extensively used at present; (iv) the difficulty in recognizing the extension of retreat phases. Thus, data for a region are usually provided by fieldwork on several glaciers (Schneebeli & Röthlisberger 1976; Hormes *et al*. 2001).

Very few data are available for reconstruction of Holocene glacier variations on the SE (Italian) side of the Mont Blanc massif, despite there being 23 glaciers and a *c*. 37.5 km^2 glacierized area. This is due to generally steep and short south-facing glaciers, with few having developed a large morainic complex. Moreover, most glaciers are entirely located well above the present tree line, which in this area is particularly depressed due to local windy conditions, while the large extent reached by the Little Ice Age (LIA) advances (particularly in the first half of the 19th century) obscured a great part of older deposits. Finally, the present glacier retreat has weakly affected debris-covered glaciers (such as Brenva and Miage Glaciers) where the inner slopes of their lateral moraines are still largely hidden by the ice and only sporadic organic remains and buried soils have been retrieved so far (Porter & Orombelli 1982; Deline 1999b). By far the longest, the Glacier du Miage (11–13 km^2) is characterized by a small morainic amphitheatre that constitutes a well-preserved archive for glacier fluctuations because of its peripheral location inside the Miage morainic complex, off active slopes, and the domination of accretion over superposition. From a geomorphological study of the amphitheatre and the palaeolake located upstream, this article reconstructs the main fluctuations of the Glacier du Miage during the second half of the Holocene, when the association of cold stages with frequent

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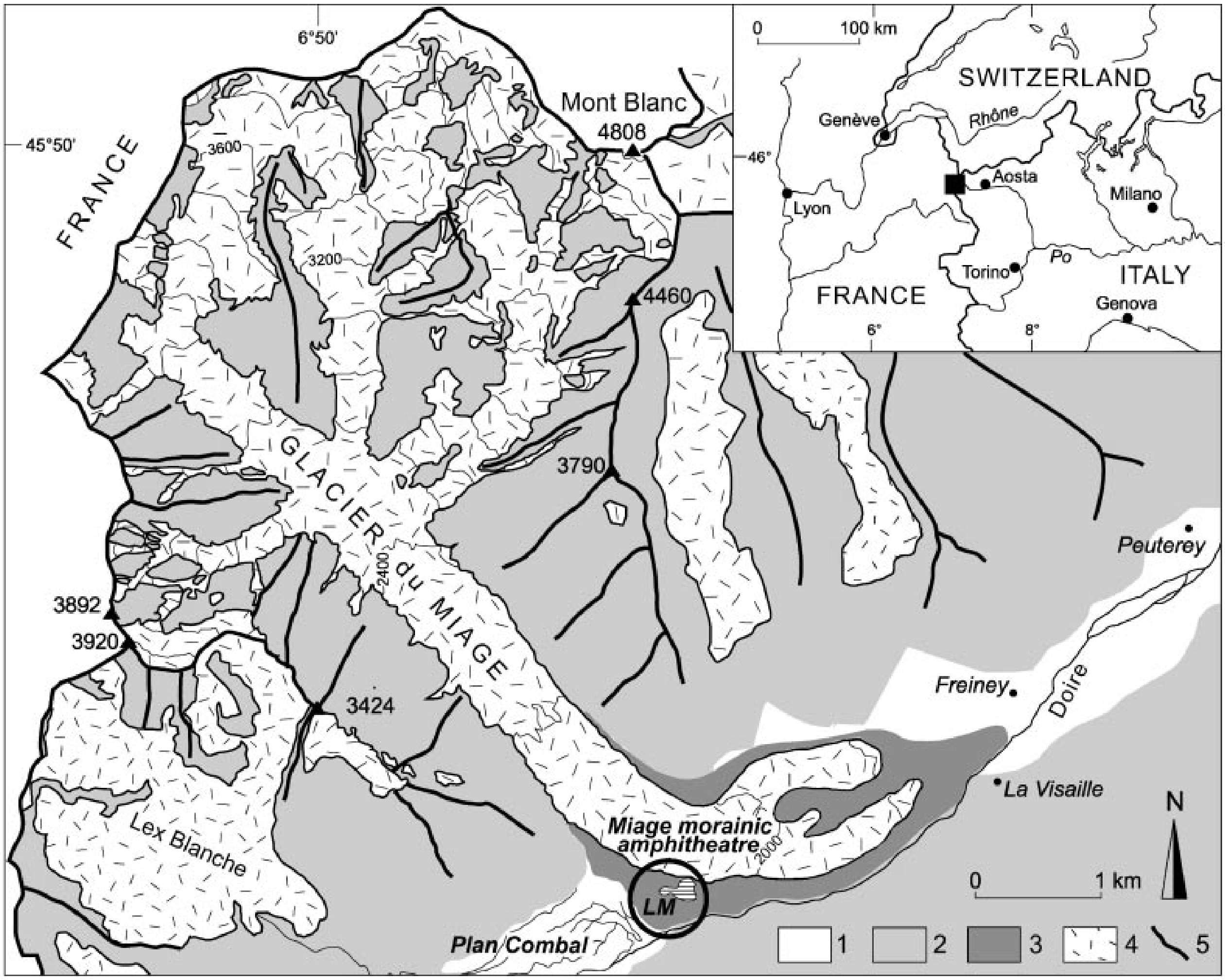

Fig. 1. Location map of Glacier du Miage and the Miage morainic amphitheatre. The main valley drained by the Doire river is Val Veny. 1: Alluvial plains and polygenetic fans; 2: rock slopes; 3: Miage Holocene morainic complex; 4: glacier; 5: crest line (*LM*: ice-contact Lac du Miage). Contour line interval on the Miage is 200 m.

debris cover development at the glacier surface led to the present expansion of the Miage in the trunk valley. For this reconstruction, we discuss previous data in the light of the new dates that we obtained at the MMA and the Combal palaeolake.

Study area

The Miage morainic amphitheatre

The third largest Italian glacier, Glacier du Miage, flows on the SE side of the Mont Blanc massif from Mont Blanc at 4808 m a.s.l. It is a compound valley glacier fed by four steep tributaries; the lower glacier is an 8-km-long, gently sloping tongue, partly entrenched in a deep, straight valley (Fig. 1). A supraglacial debris cover spreads over 4 km^2, from the glacier terminus to *c.* 2500 m a.s.l. at *c.* 6 km upstream. Along with Unteraargletscher in the Bernese Oberland (Switzerland), Miage is the largest debris-covered glacier in the Alps.

The Miage morainic amphitheatre (MMA) is associated with a large right-lateral moraine, where the glacier curves out of the Mont Blanc massif to block the trough of Val Veny (Fig. 1). Composed of about 25 exposed morainic ridges, the MMA constitutes a three-step staircase-like sequence of breach-lobe moraines (*sensu* Benn *et al*. 2003); from the outer to the inner one, the three distinct sets of morainic ridges are labelled A, B and C (Fig. 2). With an area of 200 000 m^2, the MMA rises 100–120 m above its surroundings. In its upper part it contains an ice-contact lake, bounded to the north by a curved ice cliff *c.* 30 m high, from which ice calving is frequent in summer. The area of Lac du Miage (2017 m a.s.l.) was 36 000 m^2 in July 2003 (Diolaiuti *et al*. in press).

Fig. 2. Oblique aerial photography of the Miage morainic amphitheatre (July 1998). The three distinct sets of morainic ridges located in the curved section of the right-lateral moraine (RLM) are labelled A, B and C; in the upper part of the MMA, most recent morainic ridges are immersed in the ice-contact Lac du Miage. The debris-covered Glacier du Miage is in the background.

As suggested by its geometrical relations with right-lateral moraine (RLM), MMA formed by alternating phases of glacier advance through a gap in the large RLM, which built a succession of subconcentric morainic ridges, and raising of the crest of the RLM (Deline 1999a). Intermorainic depressions are partly filled with glaciolacustrine deposits when they are large and with coarse colluvium when narrow. Soil is well developed, except on open work deposits.

The Combal palaeolake

When reaching the Val Veny, the Glacier du Miage bends, deflected by huge lateral moraines (as much as 140 m high for the exposed part), before forming two main divergent moraine-bounded lobes terminating at *c*. 1730 and 1775 m a.s.l.; upvalley, a presently filled moraine-dammed lake (Combal) formed in the trunk valley (Fig. 1). The present alluvial plain, Plan Combal (1953 m a.s.l.), is *c*. 1 km long and 600 m wide; 25% of its 22 km^2 catchment basin is presently covered by glaciers, the larger of which is the Glacier de la Lex Blanche (3.5 km^2).

Previous studies

The MMA: a long-standing object of glacio-geomorphologic study

Used as a fortification before the end of the 17th century (Arnod 1968), the MMA had interested scientists since the 19th century because of its singularity and structure. Various Miage chronologies were established. Whereas Forbes (1843) mapped only four 'ancient moraines', Baretti (1880) distinguished nine ridges assumed to mark two glacier advances over the lake. Sacco (1917) considered that the Miage advanced out of the Mont Blanc massif at the beginning of the 16th century and built the MMA (17 ridges) until the 17th century. Kinzl (1932) supported this view, but Capello (1952) regarded the MMA basement as part of a frontal moraine built during a Miage Lateglacial advance ('post-Daun'). Mayr (1969) could not agree with either Sacco, because of a well-developed palaeosoil under the 17th century military settlements, or Capello, by considering the MMA basement younger than the Holocene Climatic Optimum ('Hypsithermal').

Recent geomorphological studies at the MMA

Up until the end of the 1970s, no radiometric dates supported the interpretations, although Porter (1981) pointed out that moraines dating to at least the mid-15th century were present. Aeschlimann (1983) obtained radiocarbon dates of four pieces of wood in buried soils at 0.50–0.80 m depth in the silty sediments between the A_{6W} and B_{3W} moraines (Fig. 3; Table 1: sites 1 and 2). The oldest dated layer (760–574 cal. yr BP, i.e. AD 1190–1376) located >40 m above the Plan Combal surface indicates that the MMA mainly pre-dates the LIA. To date the

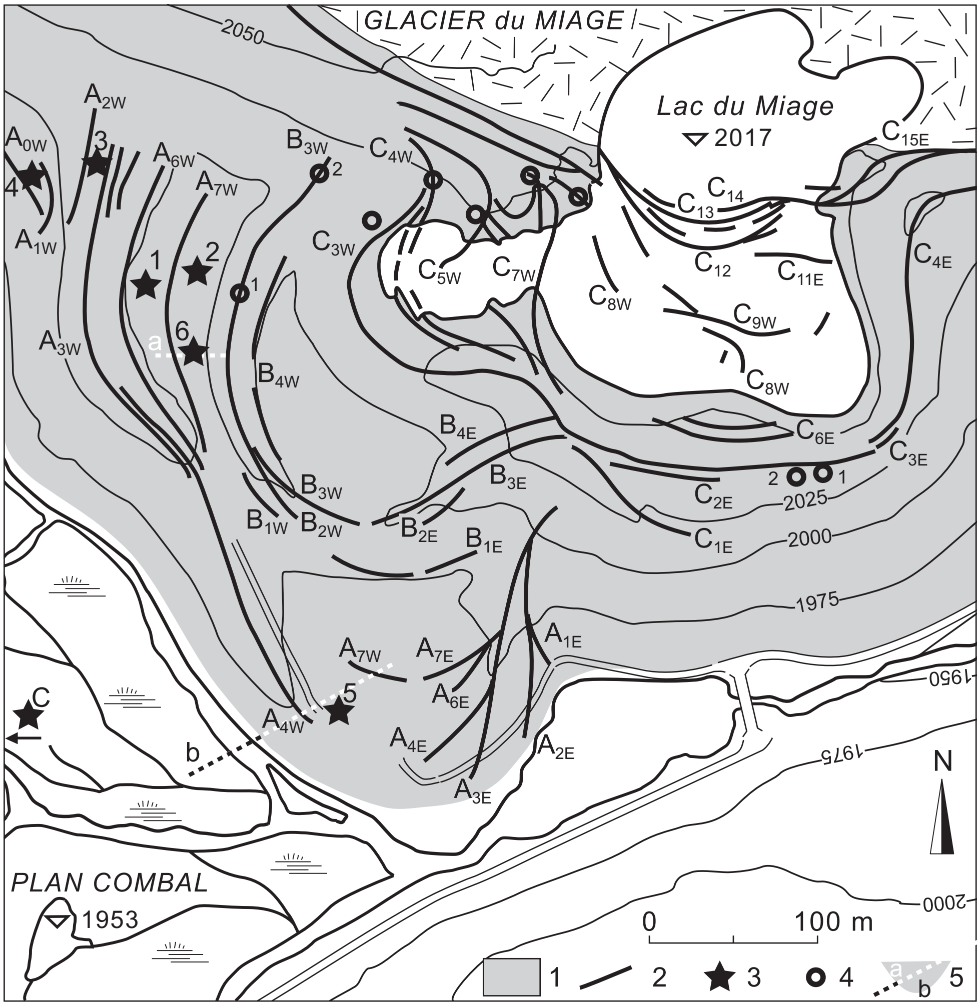

Fig. 3. Geomorphologic sketch of the Miage morainic amphitheatre. At least 25 moraines can be identified, forming one of the richest sets of Holocene moraines in the Alps. 1: Till (MMA and RLM); 2: moraine crest; 3: radiocarbon date site; 4: site of dendrochronological date on living Larch (*Larix*); 5: cross section (a: Fig. 5; b: Fig. 4).

formation and development of the MMA, we have been conducting a systematic prospecting programme since 1996. Dates of charcoals found in two excavations in the NW outer area of the MMA (Fig. 3; Table 1: sites 3 and 4) were in good agreement with Aeschlimann's dates on the inner sites: 1713–1530 cal. yr BP between A_{3W} and A_{2W}, and 2326–1711 and 2748–1934 cal. yr BP between A_{1W} and A_{0W} (Deline 1999a; Orombelli & Deline 2002). This coherent set of dates indicates that the MMA is at least *c*. 2000 cal. yr old and pre-dates the LIA.

This first MMA chronology was invalidated by the dates obtained with a 1999 core drilling in the small plain located in the MMA south area, just inside the A_{4W} moraine (Figs 3, 4). Coherent (except one) dates of six pieces of wood deposited at different levels in a 5-m-deep lacustrine/paludal laminated deposit are between 1506–1295 and 2147–1928 cal. yr BP (Table 1: site 5). Since A_{4W} is older than this deposit but younger than moraines A_{0W}–A_{3W}, two of the NW outer area charcoal dates (Table 1: sites 3 and 4) are too young: charcoals have penetrated into the moraines after their deposition, through open work structure, and give only minimum ages for the concerned moraines (Orombelli & Deline 2002). To clarify the chronology of the MMA sequence and development, we recently conducted new investigations.

Methods

To supplement previous data, two complementary approaches were used. Fieldwork at the subsurface of the MMA provided more data about the recent stages, while core drilling in the Combal sediments deposited

Table 1. Radiocarbon dates from the Miage morainic amphitheatre (sites 1–6) and the Combal palaeolake sediments (site C).

Site no. (depth, m)	Material	Laboratory no.	$\delta^{13}C$ VPDB (‰)	Uncalibrated age (1σ years BP)	Calibrated age (2σ, years) (BP)	(AD/BC)	Source
1 (−0.70)	Wood	UZ-397		295 ± 55	496–5	AD 1454–1945	Aeschlimann (1983)
1 (−0.80)	Wood	UZ-396		760 ± 50	760–574	AD 1190–1376	Aeschlimann (1983)
2 (−0.50)	Wood	UZ-335		465 ± 55	618–337	AD 1332–1613	Aeschlimann (1983)
2 (−0.80)	Wood	UZ-334		690 ± 60	727–549	AD 1223–1401	Aeschlimann (1983)
3 (−0.90)	Charcoals	ARC-1521	−25.00	1720 ± 40	1713–1530	AD 237–420	Deline (1999a)
4 (−0.55)	Charcoals	GX-24380	−24.60	2025 ± 115	2326–1711	376 BC–AD 239	Orombelli & Deline (2002)
4 (−1.00)	Charcoals	GX-26209	−25.00	2300 ± 150	2748–1934	798 BC–AD 16	Orombelli & Deline (2002)
5 (−1.45)	Wood	GX-26203	−24.60	1720 ± 110	1882–1354	AD 180–428	Orombelli & Deline (2002)
5 (−3.10)	Wood	GX-26204*	−26.60	1480 ± 40	1506–1295	AD 444–655	Orombelli & Deline (2002)
5 (−3.70)	Wood	GX-26205	−25.30	1710 ± 130	1922–1314	AD 28–636	Orombelli & Deline (2002)
5 (−4.10)	Wood	GX-26206	−23.80	1820 ± 70	1920–1560	AD 30–390	Orombelli & Deline (2002)
5 (−4.70)	Wood	GX-26207	−25.30	1960 ± 60	2041–1738	91 BC–AD 212	Orombelli & Deline (2002)
5 (−5.10)	Wood	GX-26208*	−26.50	2070 ± 40	2147–1928	198 BC–AD 22	Orombelli & Deline (2002)
6 (−4.25)	Grass	LY-10664	−26.37	2515 ± 45	2748–2362	798–412 BC	This article
C (−6.48)	Peat	LY-10421	−27.89	1340 ± 55	1332–1172	AD 618–778	This article
C (−47.42)	Peat	LY-1905 OxA*	−28.48	4240 ± 45	4866–4648	2916–2698 BC	This article
C (−57.16)	Peat	LY-10248	−26.50	4265 ± 75	5029–4575	3079–2625 BC	This article

*AMS radiocarbon date.

in a palaeolake mainly dammed by the MMA makes it possible to date its base.

At the MMA, four 1.80 to 4.50-m-deep core drillings through the inter A_{7W}–B_{3W} clay to sand sediments (Fig. 5) were performed with a Russian corer on caterpillar (APAGEO 22CV) in 2000. As topography limits the use of heavy core drills, a handy Swedish corer was also used to investigate inter-A_{7W}–B_{3W} sediments, but no result was obtained because of the high compaction of the silts and clays. Dendrochronological coring on living larches (*Larix decidua*) and lichenometry on *Rhizocarpon* were also used. However, (i) old trees are absent; (ii) the time interval between stabilization of the moraines and establishment of *Larix* seedlings on the stabilized moraines is poorly known; (iii) *Larix* and *Rhizocarpon* span of life limit dendrochronology and lichenometry to recent phases of the MMA development. These methods were therefore used to obtain a minimum age only for the MMA innermost area, which is the most

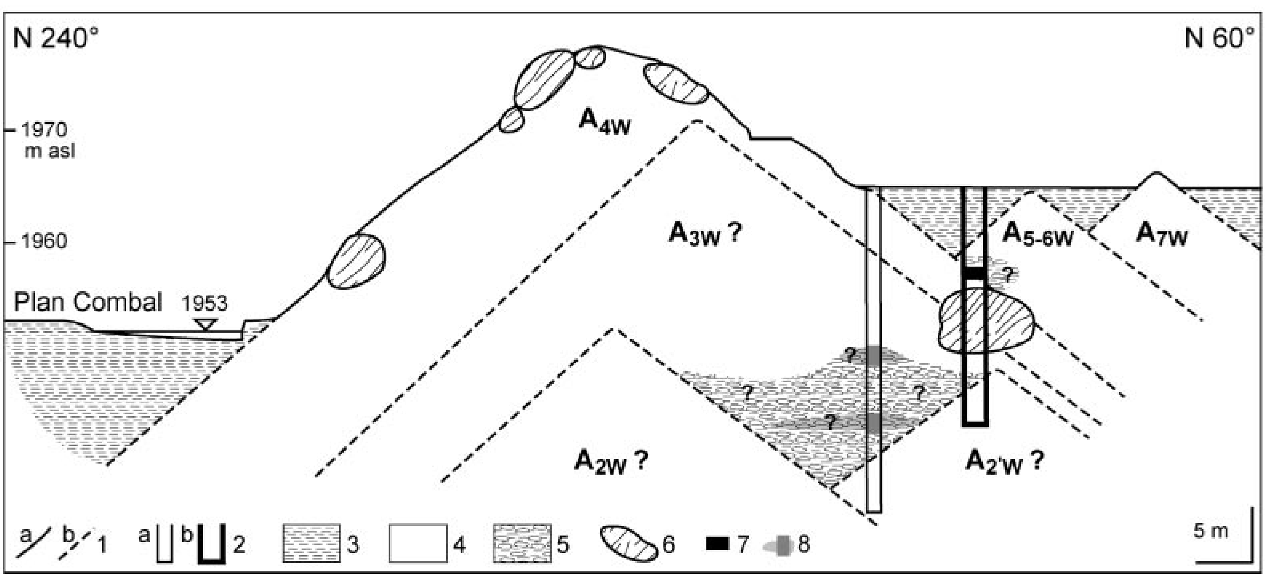

Fig. 4. Cross section of the southern area of the Miage morainic amphitheatre. 1: Moraine profile (a: exposed; b: supposed); 2: core drilling (a: 29.20 m in 1997; b: 21 m in 1999); 3: lacustrine/paludal deposit; 4: till; 5: glaciofluvial deposit; 6: gneissic megablock; 7: buried soil (?); 8: peat traces (possible levels?). Radiocarbon dates of the 1999 core drilling are located between −1.45 and −5.10 m.

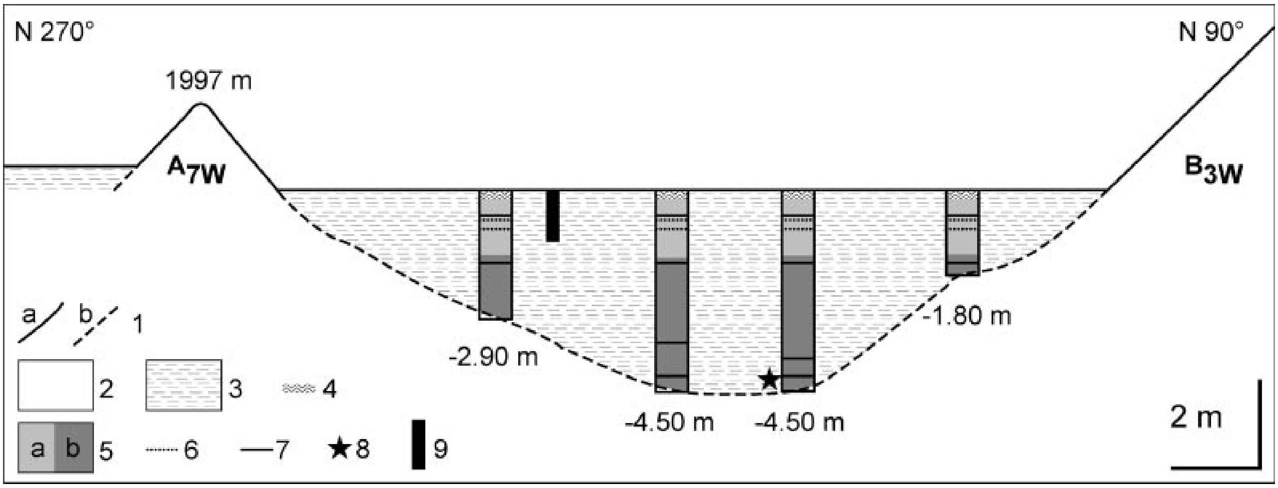

Fig. 5. Cross section of the inter A_{7W}–B_{3W} sediments, Miage morainic amphitheatre. Depth of the four 2000 cores is indicated. 1: moraine profile (a: exposed; b: supposed); 2: till; 3: fine sediments; 4: soil; 5: clays (a: yellow; b: grey); 6: sand layer; 7: buried soil; 8: radiocarbon date (Table 2: site no. 6); 9: Aeschlimann (1983) core drilling.

recent one. This fieldwork at the MMA was supplemented by the study of historical documents, especially photographs from the end of the 19th century.

At Combal palaeolake, geophysical (electrical and seismic) surveys were performed in 1997 and 1999. In September 2000, a core drilling (Ø 101 mm) was carried out in the distal area of the palaeolake. At a site located 200 m upstream from the MMA, where geophysical studies suggest that the infill is at its maximal thickness (140 m), a 78-m-long core was obtained with a hydraulic rotary core drill (Fig. 6). Radiocarbon dating, sedimentological, palynological and magnetic susceptibility measurements were performed in 2001 and 2002.

Results and interpretation

The 2000 inter-A_{7W}–B_{3W} core drillings (Fig. 5) show much deeper infill sediments than suggested by

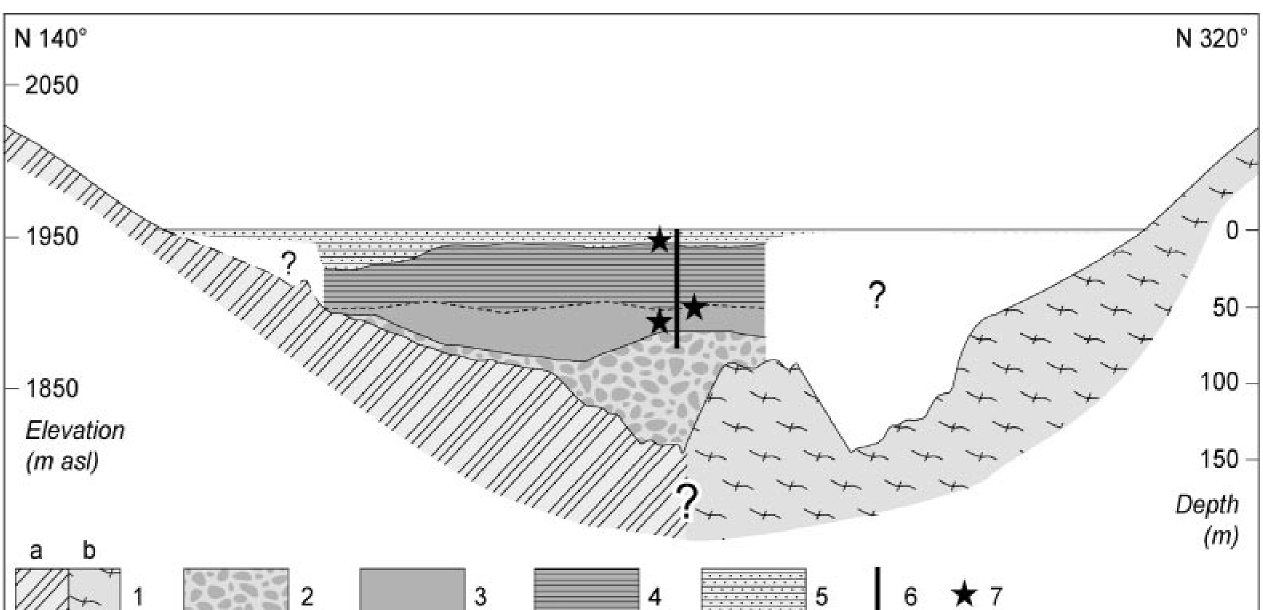

Fig. 6. Cross section of Combal palaeolake sediments obtained through core drilling and geophysical surveys. 1: bedrock (a: meta-sediments; b: gneiss and micaschists); 2: till; 3: glaciofluvial sediments; 4: glaciolacustrine sediments; 5: alluvial and glaciofluvial sediments; 6: 78-m-long core drilling; 7: radiocarbon date (Table 2: site no. C).

Table 2. Dendrochronological data for the inner/upper area of the Miage morainic amphitheatre (all measurements in 1996, except *: 2000).

Location	Tree diameter[a] (cm)	No. of counted tree rings	No. of missing tree rings (estimated)		Total no. of tree rings	Moraine minimal age[b] (AD)
			from core	from base		
B_{3W} n°1	72	160	40	30	230	1710–1730
B_{3W} n°2	62	131	20	20	171	1770–1790
C_{3W}	70	160	40	30	230	1710–1730
C_{3E} n°1		185	0	15	200*	1745–1765
C_{4W}	67	150	20	20	190	1750–1770
C_{3E} n°2		162	8	20	190*	1755–1775
C_{5W}	79	135	5	20	160	1780–1800
C_{6W}	55	94	5	20	119	1820–1840
C_{8W}	29	94	8	20	122	1820–1840

[a]Bark included and at 1.30 m above the ground.
[b]With a *Larix* duration of seedling establishment on stabilized moraines of 35–55 years.

Aeschlimann (1983) and no other morainic ridges between A_{7W} and B_{3W} (Fig. 5). A 4.25-m-deep buried soil gives a date of 2748–2362 cal. yr BP (Table 1: site 6), which is the present oldest date for the MMA. This confirms that in the NW outer area charcoals are younger than the enclosing moraines, while A_{4W} moraine is older than this age.

The smallest diameter of the two *Rhizocarpon* largest thalli on C_{3W} moraine was 90 mm in 1996, which corresponds to an age of *c.* 330 yr when extrapolated from the local growth curve established by Orombelli & Porter (1983), i.e. a minimum age of AD 1670 for stabilization of the C_{3W} moraine. Dendrochronology on oldest living *Larix* on this moraine shows *c.* 230 tree rings in 1996, i.e. a minimum age of AD 1710 (Table 2); taking into account the germination time, this fits well with the lichenometrical dating.

At the Combal palaeolake coring site, the stratigraphy of the infill consists of 4 units (Fig. 6), the chronology of which is given by 9 radiocarbon dates. From bottom to top, the 4 units are (Fig. 7):

- Unit 1 (*c.* 140–71 m) is a *c.* 70-m-thick coarse unit with an electric resistivity of 200–300 Ωm. In the upper transition layer (78 to 71 m), which was directly recognized by the drilling, the gneiss and micaschist diamicton shows a rough fining-up of boulders (up to 0.5 m thick), small cobbles (7–10 cm long) and angular pebbles. Most of Unit 1 is likely a till, possibly of Lateglacial age.
- Unit 2 (71–47.5 m) is a *c.* 25-m-thick glaciofluvial layer, where fine to coarse sands and gravels and small pebbles dominate. Four 20 to 50-cm-thick clay and silt bands show short lacustrine stages, with two peat levels at 57.2 and 53.5 m. As shown by the dating of the lower peat level, Unit 2 deposition has started shortly before 5029–4575 cal. yr BP (Table 1: site C).
- Unit 3 (47.5–8.5 m) is a *c.* 40-m-thick glaciolacustrine layer. Laminated silts and clays dominate, with two thick sandy layers that contain a few beds of small (<1 cm) gravels. Four thin woody and peat levels are present. Dating of two peat levels, at the Unit 3 bottom and in Unit 4 (Table 1: site C), shows that Unit 3 deposition took place during *c.* 3 millennia, starting at 4866–4648 cal. yr BP and ending before 1332–1172 cal. yr BP. The age/depth model (Fig. 8) indicates that the sedimentation rate was highly variable during the glaciolacustrine period: very strong (21 mm yr^{-1}) during the first period of Combal palaeolake (*c.* 4.7 to *c.* 4.0 cal. kyr), weaker (5.5 mm yr^{-1}) during its second period (*c.* 3.9 to *c.* 2.0 cal. kyr), and very strong again (23 mm yr^{-1}) during the last period of the palaeolake (*c.* 2.0 to *c.* 1.4 cal. kyr). This high variability of the sedimentation rate expresses variations of both palaeolake level and catchment basin morphodynamics.
- Unit 4 (8.5–0 m) is a thick alluvial deposit dominated by gravel and small pebbles. One thin clay and peat bed suggests short local lacustrine conditions around 1332–1172 cal. yr BP.

Thus, the present radiocarbon chronology indicates that the MMA not only pre-dates the LIA but has formed at least since 5029–4648 cal. yr BP, at the beginning of the Neoglacial (i.e. the second half of the Holocene, characterized by a clear cooling). It also shows that A and B sets of moraines pre-date 2748–2362 cal. yr BP, the A set being older than the B set. Finally, it demonstrates that the MMA dammed Lake Combal for at least 3 cal. kyr.; during this period, small lakes and ponds formed in the MMA, which led to lacustrine/paludal sedimentation, e.g. from 2147–1928 to 1506–1295 cal. yr BP.

Reconstruction of glacier advances and discussion

The MMA radiocarbon chronology associated with the analysis of spatial and stratigraphical relations in the

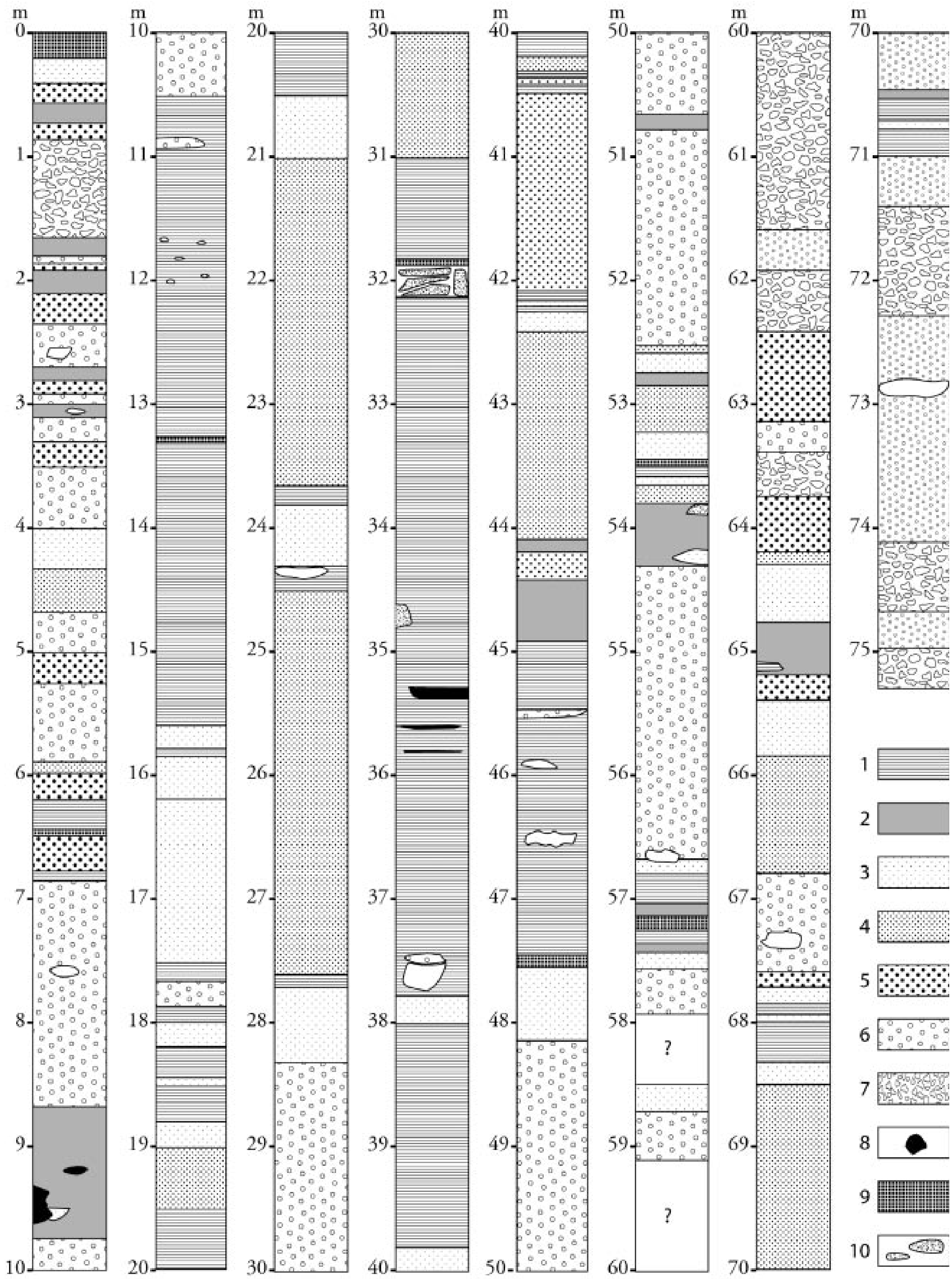

Fig. 7. Stratigraphy of the core in the Combal palaeolake infill. 1: clays; 2: silts; 3: fine sands; 4: coarse sands; 5: gravels; 6: subrounded pebbles; 7: subangular pebbles; 8: black clays; 9: peat; 10: wood.

MMA suggests the following reconstruction of Neoglacial fluctuations of the Glacier du Miage (Fig. 9):

1. Before *c.* 5.0 cal. kyr BP, the Glacier du Miage started to advance in its deep and straight valley.
2. *c.* 4.8 cal. kyr BP (Fig. 9A), the front of the Miage has reached the large trough of Val Veny (Fig. 1). In the Combal area, a glaciofluvial layer was deposited on Lateglacial tills fed from the upstream glacierized catchment basin.

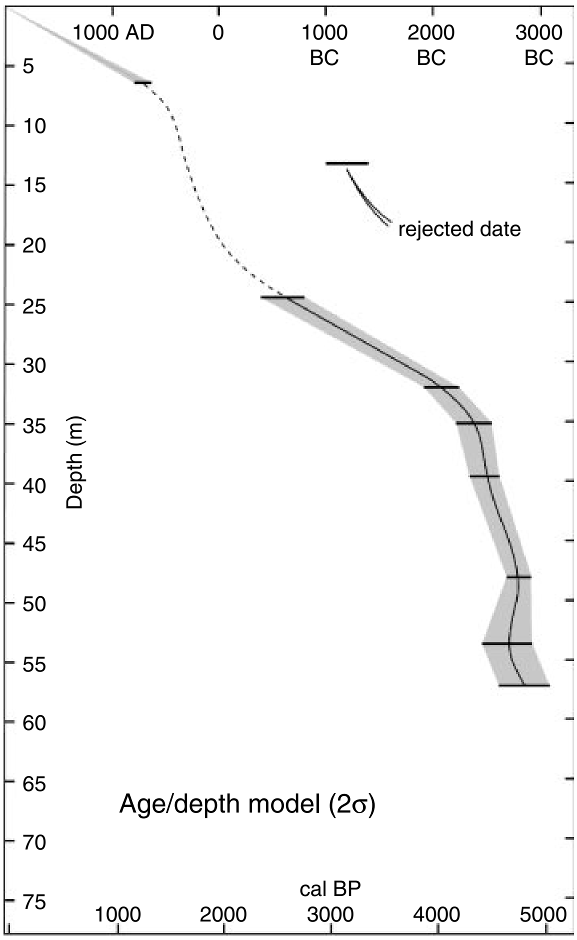

Fig. 8. Age/depth model of the sedimentation in the Combal palaeolake (rejected date: probably resedimented material).

3. At *c*. 4.7 cal. kyr BP (Fig. 9B), the southern part of the terminal moraine became the MMA basement with the start of the 1st overflow stage ($A_{1–2}$ moraines), which dammed Val Veny. Deposition of glaciolacustrine sediments commenced in the young Combal lake.
4. At *c*. 4.7 and *c*. 2.5 cal. kyr BP (Fig. 9C), most of the time the glacier was behind the RLM, the height of which was increased by >20 m by morainic superposition. During the early part of this period, several overflows (A_3 to A_7 moraines) and retreats of ice lobe occurred in the MMA. This is suggested by two elements: (i) beyond the 5-m-deep lacustrine/paludal deposit, the 1999 core drilling in the southern area of the MMA reached three layers 1, 1.50 and 13.50 m thick: diamicton (till), glaciofluvial deposit and till with very large boulders (Orombelli & Deline 2002); at 7.50 m depth, a palaeosoil likely developed on the A_{4W} inner slope before glaciofluvial sediments and $A_{5–6W}$ moraines were deposited (Fig. 4); (ii) in a nearby core drilling performed in 1997 (Fig. 4), peat traces were found at 14–16 m and 20–22 m depth in a *c*. 10-m-thick sandy to gravelly deposit (F. Gregori, unpublished report). These peat layers suggest the development of ponds that were not in contact with the ice, and at least two paludal stages when the ice lobe which built the A moraine set retreated (Fig. 9C). A_{4W} moraine has likely buried older A_{3W} and A_{2W} moraines by superposition; A_{3W} moraine is preserved upstream because A_{4W} moraine was built by morainic accretion in this area (Fig. 3), while the existence of A_{2W} and an additional moraine could explain the glaciofluvial deposit with peat traces in the 1997 core (Fig. 4). Taking these assumptions into account, the inner part of the A_{4W} moraine is much older than 2147–1928 cal. yr BP.
5. At *c*. 2.5 cal. kyr BP (Fig. 9D), the 2nd overflow stage which built B_1 to B_3 moraines took place, as proved by the date of the interA_{7W}–B_{3W} buried soil obtained by the 2000 core drilling. Although B_4 moraine cannot be directly associated with this date, B_4 likely formed during this stage. As suggested by just a few ridges, limited extent and small volume of the B moraine set, the 2nd overflow stage probably lasted for a short time compared with the 1st one.
6. Between *c*. 2.5 and *c*. 1.4 cal. kyr BP (Fig. 9E) the 2nd RLM build-up stage occurred, with a *c*. 10–20-m-thick morainic superposition. A lake was present behind the B moraines, possibly an ice-contact lake during short ice lobe advances. This upper lake worked as a buffer between the glacier and a shallow lake located in the southern area of the MMA, which lasted 400 to 900 years, between 2147–1928 and 1506–1295 cal. yr BP. The MMA was at least partly forested, as suggested by 11 layers with wood pieces found in the 1999 core drilling.
7. The 3rd overflow stage (Fig. 9F). Up to now, no radiocarbon date is available for the inter B-C moraine depression. A minimum age of C_{3W} moraine is given by lichenometry (AD 1670) and dendrochronology (AD 1710) indicating that C_1–C_5 moraines could have formed during the LIA. However, B_{3E} and B_{4E} moraines climb up the C outer side for 35 m (Fig. 3). This spatial relation between C and B moraine sets indicates that the inner/basal part of C is older than the B moraine set. Two elements question the LIA age of C_1–C_5 moraines: (i) if so, no overflow stage would have occurred at the MMA between *c*. 2.5 cal. yr BP and the LIA, whereas one neoglacial cold stage, the Göschener II (AD 350–900), is recognized in the central and eastern Swiss Alps during this period (Maisch *et al*. 1998; Hormes *et al*. 2001); (ii) the diversified floor of the present lake, gentle and shallow (<7 m) in the western basin but very rough and deep (up to >30 m) in the larger eastern

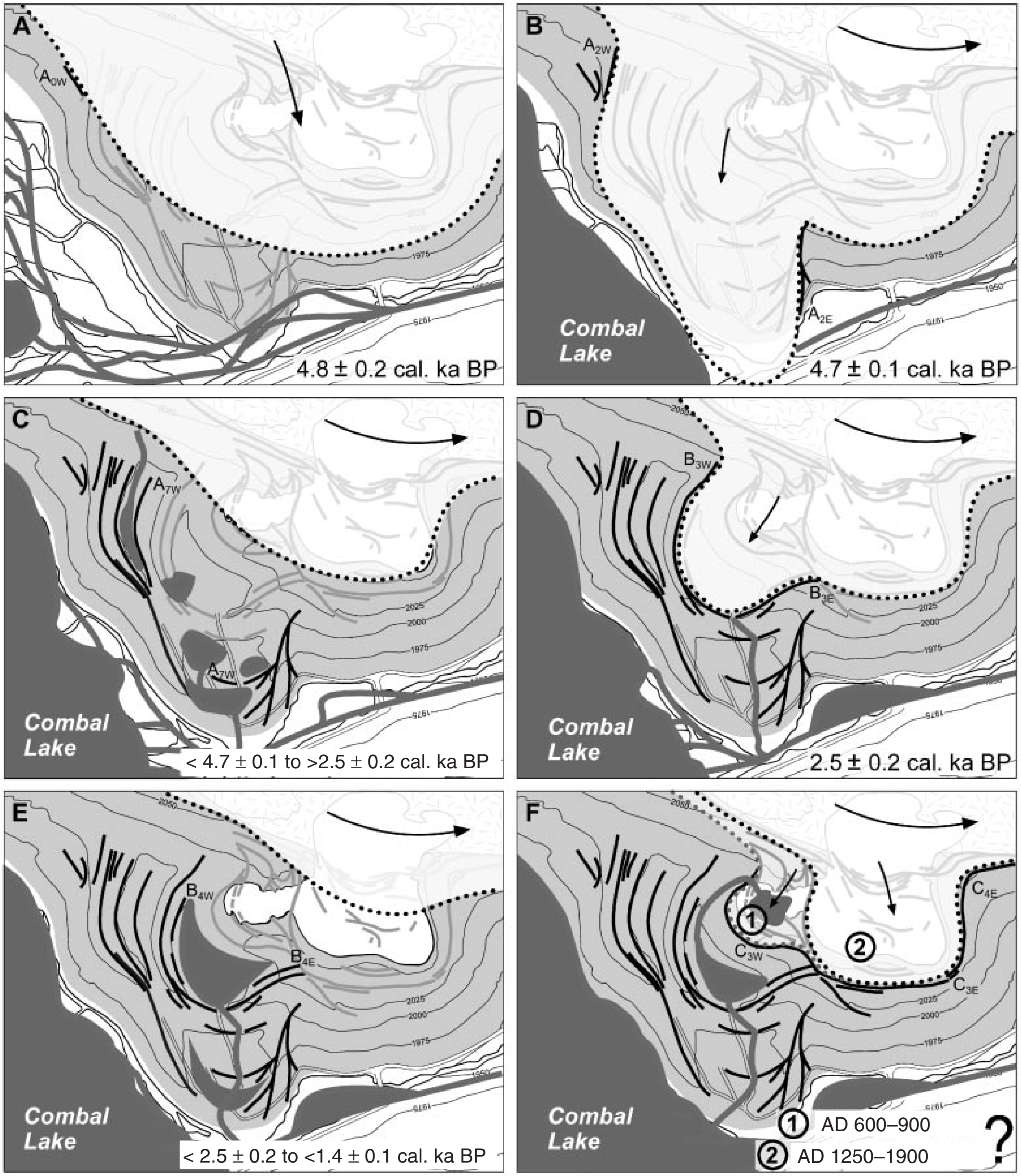

Fig. 9. Six stages of the Neoglacial construction of the Miage morainic amphitheatre (two possible stages are represented in F, the dates of which are those proposed in the literature). The location of lakes and ponds in C, E and F is generally hypothetical.

one (Deline *et al*. 2004), suggests a two-stage formation. Therefore, the formation of the inner/upper part of the MMA likely extends over more than one millennium, with two overflow stages (Fig. 9F: 1 and 2). These two stages were separated by a 3rd RLM build-up stage with a *c*. 10-m-thick morainic superposition which could correspond to the Medieval Warm Period (*c*. AD 900–1200).

During interstades such as the MWP or post-LIA period, the Miage glacier was debris-covered because of the active ablation associated with the slower glacier flow and the more intense rockfalls (Deline 2005). The last overflow stage, possibly during the LIA, was still active at the beginning of the 20th century. As shown by photographs, the Miage ice lobe had reached the C_9 moraine at that time, at the centre of the present lake (Fig. 3).

In synthesis, a curve of the Neoglacial variations of the Glacier du Miage can be established from the 'Neoglacial model' of the chronology of the MMA construction (Fig. 10). A and B moraine sets formed at the beginning of the Neoglacial and during Göschener I, respectively, while C moraines probably formed during Göschener II and the LIA. The MMA is therefore a good marker for the start of the Neoglacial in this region of the Alps, while the advance of the Glacier du Ruitor over a peat sequence after 5.6 cal. kyr BP (Porter & Orombelli 1985; Orombelli 1998) is the only other piece of evidence. The gap between the dates of the Neoglacial advance of the Ruitor and Miage Glaciers results from three elements: (i) 5.6 cal. kyr BP is a maximum age for initiation of the Neoglacial in the Ruitor area, where the youngest peat layers could not have been preserved during the glacier advance; (ii) if Glacier du Miage was largely a debris-covered glacier during the Neoglacial (Deline 2002, 2005), it reached Val Veny only when its debris cover was relatively extensive whereas a 'clean' glacier such as the Glacier du Ruitor reacted faster to the Neoglacial climatic change; (iii) peat formation downstream the front of Ruitor stopped very quickly when the glacier advanced, while valley damming by Miage took much longer.

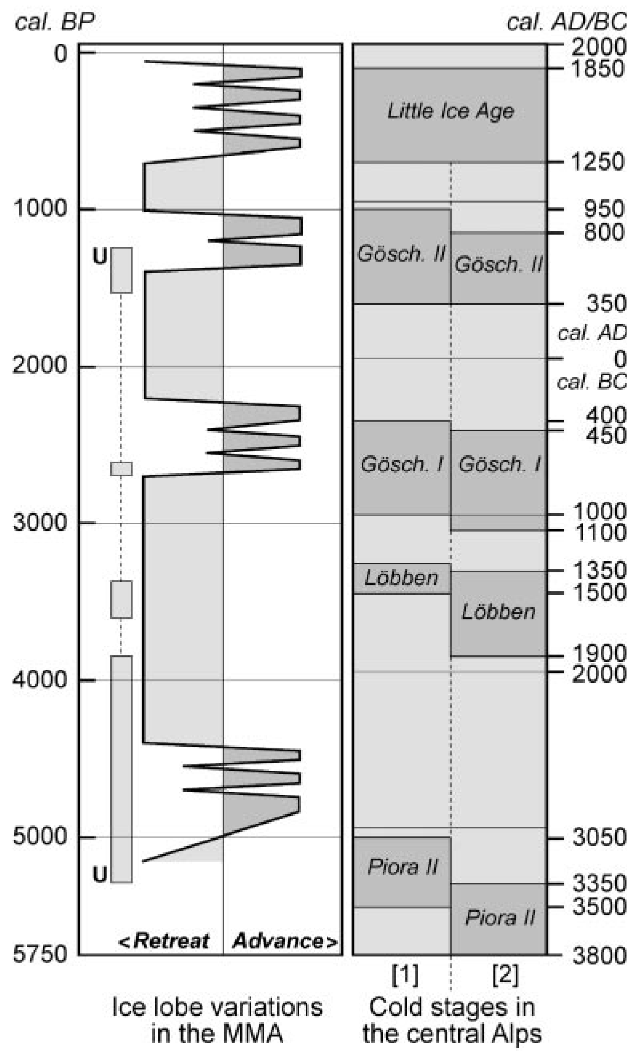

Fig. 10. Synthesis curve of the Miage ice lobe variations in the MMA during the Neoglacial (left column; small light grey boxes labelled U are Unteraargletscher smaller-than-today periods, from Hormes *et al.* 2001) and cold stages in the central Alps (right column; dark grey boxes, from Hormes *et al.* 2001 [1] and Maisch *et al.* 1998 [2]; Gösch. is Göschener).

Conclusions

Glacier advances and retreats in the central and eastern Alps during the Holocene are well documented (e.g. Maisch *et al*. 1998; Nicolussi & Patzelt 2000; Hormes *et al*. 2001), although a coherent pattern of glacier fluctuations has still to be established. Through study of the Ruitor proglacial area and Miage morainic amphitheatre (most southerly sites of western Alps that provided Neoglacial dating sets), a stratigraphy for the Neoglacial is gradually emerging for the western Alps, too, and confirms a generally larger extent and activity of glaciers during the second part of the Holocene with respect to the 'Holocene Climatic Optimum'. First, a systematic survey of the MMA replaced the old 'LIA model' for its formation by a 'late Holocene model', where A, B and C moraine sets were considered to correspond to Göschener I, Göschener II and the LIA, respectively (Orombelli & Deline 2002). However, in the new 'Neoglacial model' proposed here, main Neoglacial phases distinguished in other alpine regions are confirmed (Fig. 10). Our regional chronology of glacial advances begins with an early Neoglacial, bracketed by Ruitor (5.6 cal. kyr BP) and Miage (4.8–4.6 cal. kyr BP) advances as maximum and minimum ages, respectively. If the Löbben (3.8–3.3 cal. kyr BP) is not represented, a mid-Neoglacial stage occurred, which corresponds to the Göschener I (3.0–2.4 cal. kyr BP). This was followed by an early Medieval advance period, contemporary with the Göschener II (AD 600–900). Finally, the LIA (AD 1250–1860) is the last cold stage of the Neoglacial recorded by the MMA.

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References

Aeschlimann, H. 1983: *Zur Gletschergeschichte des italienischen Mont Blanc Gebietes: Val Veni – Val Ferret – Ruitor*. Ph.D. dissertation, Universität Zürich, 105 pp.

Arnod, P. A. 1968: (1691/94): Relation des passages de tout le circuit du Duché d'Aoste venant des provinces circonvoisines avec une sommaire description des montagnes, 1691 et 1694. Dressée par Philibert-Amédée Arnod des Conseillers commis, juge au balliat d'Aoste pour S.A.R., commissaire et intendant député par le Conseil des Commis [Manuscript, Archivio di Stato di Torino]. *Archivum Augustanum 1*, 11–72.

Baretti, M. 1880: Il ghiacciaio del Miage. Versante italiano del gruppo del Monte Bianco (Alpe Pennine). *Memoria della Reale Accademia delle Scienze di Torino II*, *38*, 3–36.

Benn, D. I. & Owen, L. A. 2002: Himalayan glacial sedimentary environments: a framework for reconstructing and dating the former extent of glaciers in high mountains. *Quaternary International 97–98*, 3–25.

Benn, D. I., Kirkbride, M. P., Owen, L. A. & Brazier, V. 2003: Glaciated valley landsystems. *In* Evans, D. J. A. (ed.): *Glacial Landsystems*, 372–406. Arnold, London.

Capello, C. F. 1952: Gli apparati morenici di diversione. *Bollettino del Comitato Glaciologico Italiano II*, *3*, 25–44.

Deline, P. 1999a: La mise en place de l'amphithéâtre morainique du Miage (Val Veny, Val d'Aoste). *Géomorphologie 1*, 59–72.

Deline, P. 1999b: Les variations holocènes récentes du glacier du Miage (Val Veny, Val d'Aoste). *Quaternaire 10*, 5–13.

Deline, P. 2002: *Etude géomorphologique des interactions entre écroulements rocheux et glaciers dans la haute montagne alpine: le versant sud-est du massif du Mont Blanc (Vallée d'Aoste, Italie)*, Ph.D. dissertation, Université de Savoie, 365 pp.

Deline, P. 2005: Change in surface debris cover on Mont Blanc massif glaciers after the 'Little Ice Age' termination. *The Holocene 15*, 302–309.

Deline, P., Diolaiuti, G., Kirkbride, M. P., Mortara, G., Pavan, M., Smiraglia C. & Tamburini, A. 2004: Drainage of ice-contact Miage Lake (Mont Blanc massif, Italy) in September 2004. *Geografia Fisica e Dinamica Quaternaria 27*, 113–119.

Diolaiuti, G., Kirkbride, M. P., Smiraglia, C., Benn, D. I., D'Agata, C. & Nicholson, L. In press: Calving processes and lake evolution at Miage Glacier (Mont Blanc, Italian Alps). *Annals of Glaciology*.

Forbes, J. D. 1843: *Travels Through the Alps of Savoy and Others Parts of the Pennine Chain*. 460 pp. Adams & Black, Edinburgh.

Hormes, A., Müller, B. & Schlüchter, C. 2001: The Alps with little ice: evidence for eight Holocene phases of reduced glacier extent in the Central Swiss Alps. *The Holocene 11*, 255–265.

Ivy-Ochs, S., Schäfer, J., Kubik, P. W., Synal, H.-A. & Schlüchter, C. 2004: Timing of deglaciation on the northern Alpine foreland (Switzerland). *Eclogae Geologicae Helvetiae 97*, 47–55.

Kinzl, H. 1932: Die grössten nacheiszeitlichen Gletschers (Mont-Blanc-Gruppe). *Zeitschrift für Gletscherkunde 20*, 269–397.

Maisch, M., Wipf, A., Denneler, B., Battaglia, J. & Benz, C. 1998: *Auswirkungen von Klimaänderungen auf die Gletscher und deren Vorfelder. Schlussbericht NFP 31*. 376 pp. Vdf Hochschulverlag AG an der ETH, Zürich.

Mayr, F. 1969: Die postglazialen Gletscherschwankungen des Mont Blanc-Gebietes. *Zeitschrift für Geomorphology, Supplement-Band 8*, 31–57.

Nicolussi, K. & Patzelt, G. 2000: Untersuchungen zur Holozaenen Gletscherentwicklung von Pasterze und Gepatschferner (Ostalpen). *Zeitschrift für Gletscherkunde und Glazialgeologie 36*, 1–87.

Orombelli, G. 1998: Le torbe del Rutor: una successione significativa per la storia olocenica dei ghiacciai e del clima nelle Alpi. *In* Ghelardoni, P. (ed.): *Studi in onore di Mario Pinna (Il clima e la storia del clima). Memorie della Società Geografica Italiana 55*, 153–165.

Orombelli, G. & Deline, P. 2002: L'anfiteatro morenico del Miage (Courmayeur, Valle d'Aosta): nuovi dati sulla sua genesi. *Istituto Lombardo (Rendiconti Scienze) B 134 (2000)*, 115–133.

Orombelli, G. & Porter, S. C. 1983: Lichen growth curves for the southern flank of the Mont Blanc massif, western Italian Alps. *Arctic and Alpine Research 15*, 193–200.

Porter, S. C. 1981: La 'piccola glaciazione' nelle Alpi italiane e nella Catena delle Cascades. *Geografia Fisica e Dinamica Quaternaria 4*, p. 198.

Porter, S. C. & Orombelli, G. 1982: Late-glacial ice advances in the western Italian Alps. *Boreas 11*, 125–140.

Porter, S. C. & Orombelli, G. 1985: Glacier contraction during the middle Holocene in the western Italian Alps: evidence and implications. *Geology 13*, 296–298.

Richards, B. W. M. 2000: Luminescence dating of quaternary sediments in the Himalaya and High Asia: a practical guide to its use and limitations for constraining the timing of glaciation. *Quaternary International 65–66*, 49–61.

Sacco, F. 1917: L'apparato morenico del ghiacciaio del Miage (gruppo del Monte Bianco). *Bollettino della Società Geologica Italiana 36*, 323–354.

Schneebeli, W. & Röthlisberger, F. 1976: *8000 Jahre Walliser Gletschergeschichte. Ein Beitrag zur Erforschungdes Klimaverlaufs in der Nacheiszeit*. 152 pp. Verlag Schweizer Alpen-Club, Bern.