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DRAINAGE OF ICE-CONTACT MIAGE LAKE (MONT BLANC MASSIF, ITALY) IN SEPTEMBER 2004

Abstract: Deline P., Diolaiuti G., Kirkbride M.P., Mortara G., Pavan M., Smiraglia C. & Tamburini A., *Drainage of ice-contact Miage Lake (Mont Blanc Massif, Italy) in September 2004*. (IT ISSN 1724-4757, 2004).

Drainage of ice-marginal Miage Lake (36,000 m^2; maximal depth = *c.* 30 m) in early September 2004 occurred in two stages. Initial rapid loss (*c.* 325,000 m^3) over two days was due to increased outflow along the boundary between the glacier sole and the till substrate at a rate of up to 2 m^3/s. This lowered the lake surface until separate ponds were isolated from the subglacial drainage route. Subsequent loss over weeks took place at slower rates by leakage through permeable till, most rapidly in the deepest (SE) basin where a sealing matrix of fines was absent. This point is identified as a site of continuous leakage at all lake stages. Lake volume and water balance considerations indicate a low turnover of lake water. The exposed lake bed revealed an extensive ice foot connecting the subaerial ice cliff to the subaqueous continuation of the right-lateral moraine. The ice foot showed evidence of buoyant calving from its surface prior to lake drainage. The lake floor largely consists of moraine ridges covered by a sandy-silt drape which thickens downslope, from centimetres under shallow water to > 1 m in lake-bottom hollows. The innermost moraine relates to the latest «Little Ice Age» and the early 20th Century fluctuations of the glacier in the eastern basin. Drainage events are unlikely to pose a hazard, and occur infrequently (and seemingly randomly) whenever marginal crevasses link the perched ice-marginal lake to the subglacial drainage network.

Key Words: Mont Blanc Massif, Miage Glacier, Lake Miage, Glacial lake drainage.

Riassunto: Deline P., Diolaiuti G., Kirkbride M.P., Mortara G., Pavan M., Smiraglia C. & Tamburini A., *Lo svuotamento del Lago del Miage (Massiccio del Monte Bianco, Italia) nel Settembre 2004*. (IT ISSN 1724-4757, 2004).

Lo svuotamento del lago glaciale del Miage (superficie 36 000 m^2, profondità massima *c.* 30 m) all'inizio di Settembre 2004 si è sviluppato in due fasi. In due giorni si è prodotto uno svuotamento rapido (volume *c.* 325 000 m^3; portata 2 m^3/s) al contatto tra base del ghiacciaio e morena di fondo che ha ridotto il lago a quattro pozze isolate. Il drenaggio è proseguito con lentezza nelle settimane successive, più rapidamente nella pozza maggiore (SE) per la quasi assenza di sedimenti fini sul fondo. I rapporti tra volume del lago e bilancio di portate in ingresso ed in uscita lasciano intendere un lento ricambio dell'acqua. Lo svuotamento ha messo a giorno un esteso pavimento di ghiaccio di raccordo tra la caratteristica sponda di ghiaccio a falesia ed il prolungamento subacqueo della morena laterale destra; sul pavimento sono riconoscibili le tracce della disgregazione di iceberg precedente allo svuotamento. Depositi sabbioso-siltosi di spessore variabile da qualche cm ad oltre 1 m rivestono cordoni morenici subacquei, i più interni dei quali risalgono alle fluttuazioni della fine della Piccola Età Glaciale e dell'inizio del XX secolo. Lo svuotamento del lago, fenomeno che si è ripetuto più volte in passato senza una ciclicità apparente, non sembra costituire un pericolo naturale fin tanto che i crepacci a margine del lago risultano collegati al reticolo idrografico subglaciale.

Termini Chiave: Monte Bianco, Ghiacciaio del Miage, Lago del Miage, Svuotamento di lago glaciale.

Resume: Deline P., Diolaiuti G., Kirkbride M.P., Mortara G., Pavan M., Smiraglia C. & Tamburini A., *La vidange du lac juxtaglaciaire du Miage (massif du Mont Blanc, Italie) de Septembre 2004*. (IT ISSN 1724-4757, 2004).

La vidange du lac juxtaglaciaire du Miage (36 000 m^2; profondeur maximale = *c.* 30 m) de début Septembre 2004 s'est déroulé en deux phases: pendant deux jours s'est produite une vidange rapide (volume =

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c. 325 000 m^3; débit = 2 m^3/s) *via* le contact entre base du glacier et till de l'amphithéâtre morainique. La surface du lac s'est abaissée jusqu'à isoler des petits lacs résiduels de l'axe de drainage sous-glaciaire. Dans un second temps, une infiltration lente à travers le till perméable s'est produite pendant plusieurs semaines, plus rapide dans le bassin le plus profond (SE) dont le fond, avec une couche de sédiments fins très réduite voire nulle, permet une infiltration permanente. Le volume du lac et le bilan entrées/sorties hydrologiques montrent un faible renouvellement de l'eau du lac. Le fond du lac est caractérisé par un vaste pied de glace qui relie la falaise de glace subaérienne au prolongement subaquatique de la moraine latérale droite. Ce pied de glace porte des traces laissées par le vêlage d'icebergs à partir de sa surface avant la vidange. Le fond du lac est largement constitué de cordons morainiques nappés par un dépôt sablo-silteux qui s'épaissit vers le fond, passant de quelques cm en eau peu profonde à > 1 m dans les dépressions les plus profondes. Les cordons morainiques les plus internes sont liés aux fluctuations du glacier dans le bassin oriental à la fin du Petit Age Glaciaire et au début du XX^e siècle. Les vidanges du lac, qui surviennent peu fréquemment et, semble-t-il, de manière aléatoire, ne constituent probablement pas un risque naturel tant que celles-ci résultent de la mise en relation par des crevasses marginales du lac juxtaglaciaire perché avec le réseau hydrographique sous-glaciaire.

MOTS CLES: Massif du Mont Blanc, Glacier du Miage, Lac du Miage, Vidange de lac glaciaire.

INTRODUCTION

Several alpine glaciers have recently been affected by unusual hydrological phenomena, in particular the formation of lakes which may attain large volumes. The supraglacial Effimero Lake developed on the Belvedere Glacier (Monte Rosa Massif, Italy) from 2001, growing to a maximum volume of 3 x 10^6 m^3 in July 2002 (Mortara & Mercalli, 2002). The ice-contact lake which has developed on the Rochemelon Glacier (Vanoise massif, France) since 1985 (Mercalli & *alii*, 2002) had grown to a volume of 0.6 x 10^6 m^3 in September 2004 before being artificially lowered in October 2004 to preclude the risk of an outburst flood (GLOF).

In contrast to these recently-formed lakes, Miage Lake (fig. 1) has existed since at least the 18th Century. It is marked on a map surveyed in 1797-99 (Raymond, 1820) and its presence was also suggested by an engraving by Bourrit (published by Saussure, 1786). Between 1930 and 1990, fifteen or so lake drainage events have been inventoried (Chiarle, 2000). The most recent took place in early September 2004 (fig. 2), allowing the morphological observation of the lake bed and ice-dam, and interpretation of the glacio-hydrological function of the lake. This short paper reports on a topographic survey and preliminary observations made immediately after the drainage event.

LAKE CHARACTERISTICS AND RECENT EVOLUTION

As the principal tourist site in Val Veny for many decades, Miage Lake constitutes a long-standing object of scientific study (Baretti, 1880; Sacco, 1917; Capello, 1940; Cerutti, 1951; Lesca, 1956). Recently, interest in the lake

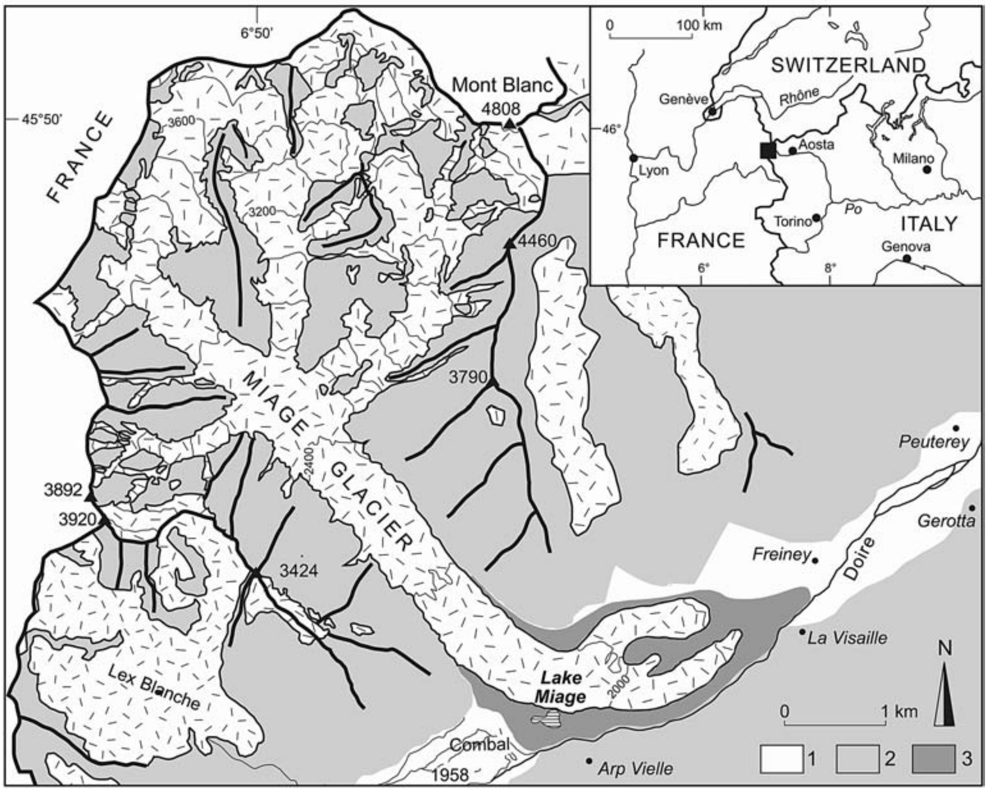

FIG. 1 - Location map of Glacier and Lake Miage (after Orombelli & Deline, 2002, modified). 1: alluvial plains and polygenetic fans; 2: rock slopes; 3: Holocene morainic complex of Miage Glacier.

FIG. 2 - Oblique aerial photography of the empty lake basin (A. Tamburini, 16.09.2004). The viewing angle is very similar to that of fig. 4.

has been renewed especially in the context of natural hazards associated with the dynamics of Miage Glacier (Deline, 1999; Chiarle, 2000; Diolaiuti & *alii*, 2004).

Miage Glacier is the third Italian glacier by area (11 km^2) and one of the main debris-covered glaciers of the Alps. Its supraglacial cover spreads over 4 km^2, from the terminus at 1 730 m on the south lobe (1775 m on the north lobe) to *c.* 2500 m altitude at *c.* 6 km upstream.

The lake is contained within a morainic amphitheatre formed by a staircase-like sequence of breach-lobe moraines (*sensu* Benn & *alii*, 2003) associated with the large right-lateral moraine, where the glacier curves out of the Mont Blanc massif to block the trough of Val Veny (fig. 1). Situated at 2 020 m altitude, Miage Lake is bounded to the north by an arcuate ice cliff of up to *c.* 30 m in height. The majority of the lake perimeter lies against the proximal slopes of moraine ridges which in the east extend to a height of 40 m above the summer lake surface. In July 2003 the surveyed area was 36 000 m^2 (Diolaiuti & *alii*, 2004). Water supply to the lake is principally of glacial origin, so the lake water is highly turbid. The only subaerial outflow is a small stream situated in the extreme west (fig. 3).

Lake bathymetry is determined by the distribution of subaqueous moraines which subdivide the lake into several basins. These range in depth from the ~ 6 m-deep west basin, to > 30 m in the east basin. During the warm season, calving of ice from the ice cliff is frequent. Bergs vary in size, the majority being < 50 m^3 volume, but on rare occasions calving involves a hazardous volume of ice. For example, the calving wave generated by a collapse of 7000-16000 m^3 on 9 August 1996 injured 11 tourists (Tinti & *alii*, 1999). Calved icebergs are distributed around the lake according to the local wind direction and the variable grounding depths of the bergs.

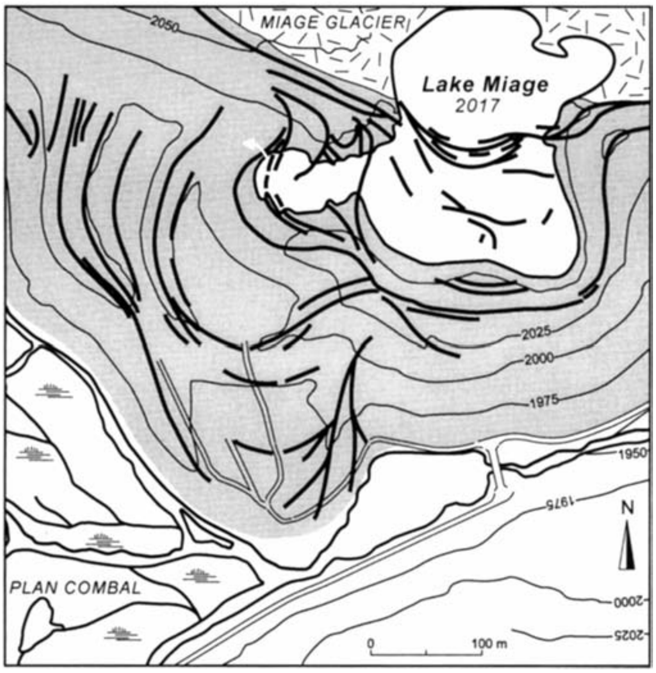

FIG. 3 - Geomorphologic sketch of the Miage amphitheatre (after Orombelli & Deline, 2002, modified). Black lines are moraine crests. White arrow is subaerial outflow.

An analysis of historical maps and the comparisons with recent data have shown changes in the retreat rate of the ice cliff. The lake area was *c.* 10000 m^2 in 1893 (Lesca, 1956) and had increased to 34600 m^2 in 1956 due possibly to the dominance of calving rate over other phenomena. Lake area has since stabilised, and survey in the summer of 2003 gave a water surface of 36000 m^2. The calving rate was calculated to be to 15 m/yr between 2002 and 2003 (Diolaiuti & *alii*, 2004).

Miage Lake has been affected by several drainage events in the 20th Century (Chiarle, 2000; Giardino & *alii*, 2001). The first documented case dates back to August 1930 (Capello, 1940), though observations of two separate basins in 1916 probably relate to a partial drainage of the lake (Sacco, 1917). The decrease in lake level was initially rapid, then at a slower rate until the lake emptied, as happened on 13 August 1950 (Cerutti, 1951; Saibene, 1951). The case of July 1955 is remarkable because lake water seeped through the right lateral moraine (Capello, 1956). The lake reformed at the beginning of June of the following year, but emptied again two weeks later. Notable episodes of lake surface lowering affected the lake in 1959, 1960, 1961, 1962, 1963, 1964, 1967, 1968, 1975 and 1986. Finally, the lake emptied completely during the night of 9 August 1990, last episode of the 20th Century (Chiarle, 2000).

THE DRAINAGE EVENT OF SEPTEMBER 2004

Observations and field data

The lake began to empty before evening on 3 September 2004 (Oscar Taiola, pers. comm.) the exact time when drainage began is not known. Around 18.00 on 4 September, observers near the lake felt a noisy shake (Mauro Radin, *pers. comm.*). Within 48 hours most of the volume of the lake had drained. An observer noted that the Doire downvalley of Val Veny (Plan Ponquet) was more turbid during this period than in the preceding days, presenting «a brown colour, like when the diggers work in its bed» (Marino Pennard, *pers. comm.*); on the other hand, its discharge was not noticeably different.

The authors first visited the lake on 7 September. After the initial period of lowering, the lake separated into four separate ponds with water surfaces at lower levels towards the east (fig. 2), and a weak flow between them. The level of the western pond lay 7.5 m above that of the SW pond. The ponds remained for several weeks, during which their levels reduced slowly but at different rates. The small NE and SE basins became completely empty on 14 September and 1 October respectively.

A Digital Elevation Model (DEM) of the lake floor topography of the eastern basin has been derived from LIDAR (Laserscan) measurement carried out on 8 September (fig. 4), using an Optech Laser Imaging ILRIS 3D ground-based scanning lidar instrument. In order to cover the whole area, 14 scans from three different positions were carried out. Point clouds were acquired with an average point spacing of 15 cm at 250 m. Point-cloud data have been processed with Innovmetric Incorporated's Polyworks CAD software. Individual scans have been merged together with a semiautomatic procedure based on user-defined control points from the overlap regions between the scans. After filtering data and removing unwanted points, a single point cloud has been obtained. A DEM has been generated from a triangulated irregular network of points (TIN). By subtracting the DEM from a flat surface representing the pre-drainage lake surface (fig. 4a), it was possible to obtain the overall volume of the lake and a contour map of the lake bottom (fig. 4b). The lake surface had lowered by 23.2 m at the time of the survey, and continued to lower over subsequent days.

On 8 September, the drained volumes of the eastern and western basins were 311,000 m^3 (measured) and 12 000 m^3 (estimated) respectively. Therefore, a volume loss from the combined basins of 323 000 m^3 over a period of 48 to 72 hours allows an average outflow of 1.25-2 m^3/s to be calculated. The average discharge of the Doire de Veny during this period exceeded 15 m^3/s, with maximum daily discharges being as much as 150-200% of the daily minima. Within this range of variation, the discharge contributed from lake drainage would not have been immediately noticeable in the main river.

Discussion

Observations of lake drainage in 2004 allows a test of the hypothesis put forward by several authors (e.g. Capello, 1940; Cerutti, 1951). They suggest that lake drainage is triggered by an excess of outflow over inflow when an englacial channel supplying water to the lake is re-routed. Reduced supply and ongoing outflow would cause the lake to empty over several days. Two factors seem to invalidate this hypothesis: (i) both the present and past lake drainage episodes were abrupt events which took place over a few days (48-72 hours). In 2004 an outflow discharge of 1.25-2.0 m^3/s was calculated from the rate of lake volume change, in contrast to a much more limited inflow (< 5 l/s according to Lesca's measurements in 1951). Cessation of inflow cannot therefore account for the observed rate of volume change of the lake. (ii) a unique englacial channel supplying the lake was not visible on the exposed floor of the drained lake in 2004. The only possible location for an englacial inflow conduit was a water-filled hollow in the surface of the ice foot where it met the base of the highest part of the ice cliff. It was not possible to establish whether a conduit had entered the lake at this point due to the turbid water in the hollow.

If changing meltwater supply is discounted as the main cause of lake drainage, the alternative hypothesis is a change in outflow. Direct observations of the lake floor immediately after lake drainage revealed a gap at the lowest point between the sloping sole of the ice foot and the proximal slope of the innermost moraine ridge marking the contact between the glacier margin and the lateral moraine. This implicates increased subglacial outflow as the cause. An increased discharge of water from the lake, due to the opening or enlargement of a passage by the interplay of marginal crevasses and subglacial cavities, could have lead to the emptying of the lake. The water would then have

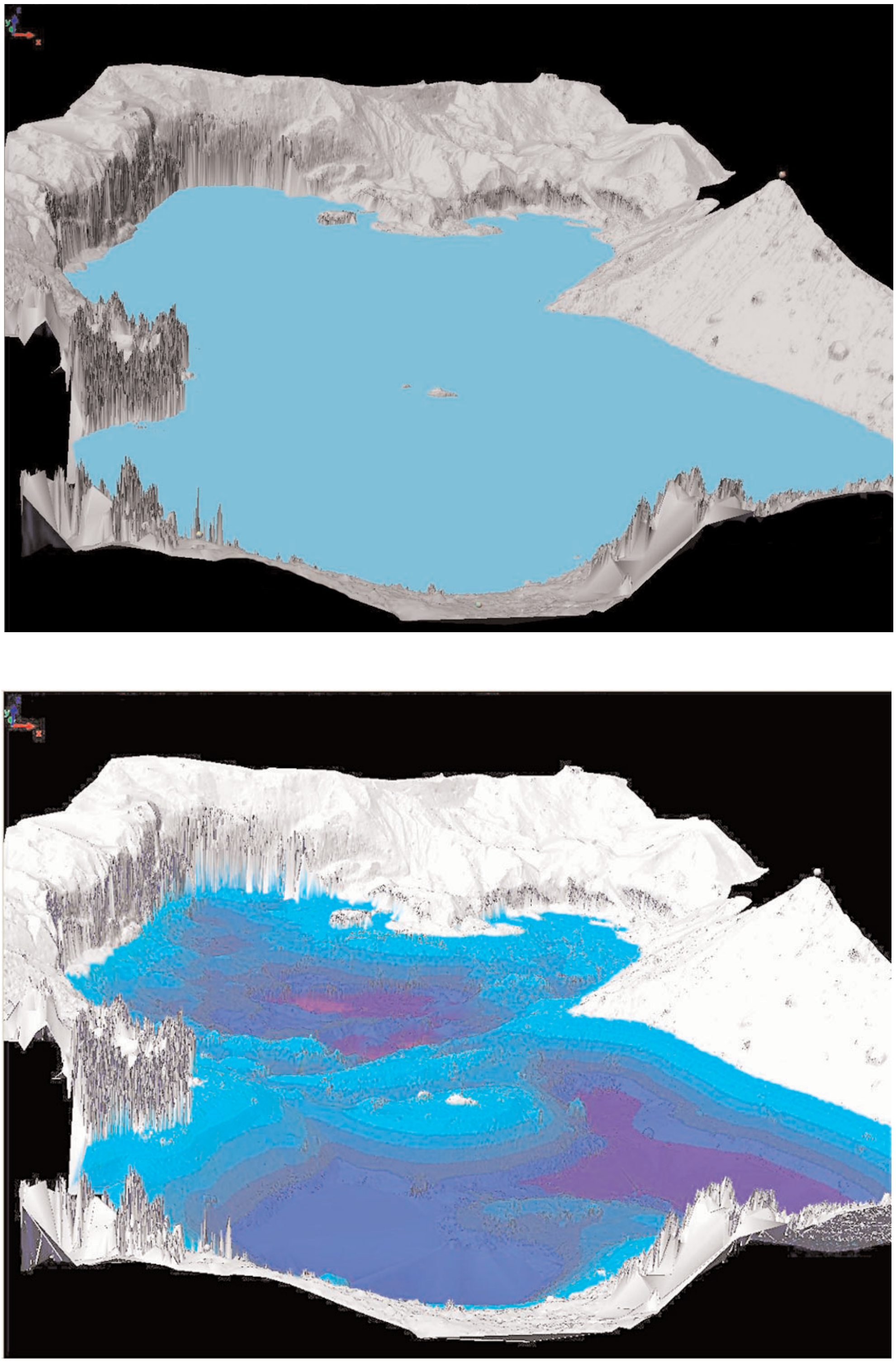

FIG. 4 - DEM realized from Laser scanning measurements on 08.09.2004. a: with normal lake level; b: four days after the onset of lake drainage.

been drained by the principal subglacial channel, exiting the glacier by the main outwash portal at the terminus of the north lobe, 1900 m further downvalley. Examination of the minor outlets at Jardin du Miage, Lac Vert, and at the front of the south lobe, revealed no evidence of recently elevated flow and supports a direct transfer of flow to the principal subglacial conduit network. The fast subglacial drainage conditions changes could also be linked to the unusual variation in the glacier surface velocity, which increased of about 60% in the last year (Diolaiuti, unpublished), and which may therefore have been associated with a greater density of subglacial cavities.

LAKE FLOOR MORPHOLOGY

Observations and field data

Direct access to almost the entire lake floor revealed a complex morphology and a bipartite subdivision into ice-floored and sediment-floored sectors (fig. 5). The northern half of the east basin is occupied by the ice foot. The surface of the ice foot was complex. The most notable feature was an approximately rectilinear depression *c.* 10 m deep in its central part, bounded by ice cliffs up to 5 m high on two sides and by debris-covered ice slopes on the other two (fig. 4). The debris cover on the ice foot resembled the supraglacial debris of the glacier, from which it is clearly derived by ablation of the main ice cliff. However, the floor of the central depression contained smaller areas covered only by a few centimetres of saturated mud interspersed with dirt cones of bouldery material and grounded icebergs. These are interpreted to be sites of subaqueous calving events prior to lake drainage, in which buoyant calving of bergs from the surface of the ice foot has lifted the debris cover off and dropped debris nearby as iceberg-dump cones.

The contact between the ice foot and the innermost subaqueous moraine is clear, and represents the lowest point on this sector of the lake floor. Given that ponding persisted in the deeper basins in the till-floored part of the lake, the gap between the glacier sole and the proximal moraine slope *must* have been the outlet for lake drainage. It lay > 23 m below the normal level of the lake, in close proximity to part of the ice foot whose upper surface was < 5 m below this level.

High-resolution topography of the glacier bed beneath ice foot was measured by ground-penetrating radar on 10 September. A «Pulse Ekko» (Sensor and Software Company) GPR operating at a frequency of 50 MHz was used. The maximum ice thickness was *c* 90 m in the central area of the ice foot close to the ice cliff, decreasing to 20-25 m close to the contact with the marginal moraines. A kriging technique was applied to the radar data, using a 5 m grid, to interpolate ice thickness between the GPR profiles. A topographic map of the lake bed was then obtained by subtracting the ice thickness from the surface elevation determined by GPS survey.

The broad threshold which divides the eastern basin into northern and southern sectors comprises a series of subparallel moraine ridges of variable width (fig. 3). The outer moraine includes a large boulder which protrudes from the centre of the lake even when the water level is at its maximum (fig. 4a). In the southern part of the eastern basin, lake-bed topography is a result of very rounded moraines ridges. These contrast with the great height of the moraines damming the lake: for example, the moraine to the east of the SE basin exceeds 50 m, of which 27 m are usually submerged. The suite of lake-floor moraines are usually submerged and mark recent ice marginal positions within the eastern basin: for example, the ice cliff in this area advanced by 100-110 m between 1880 and 1893 (Lesca, 1956).

FIG. 5 - Oblique aerial photography of the empty lake basin (A. Tamburini, 16.09.2004). White line: normal lake level; white dotted line: ice foot boundary; W, SW, SE, NE: the four topographic basins where ponds were affected during the second stage of the drainage.

The floor of the eastern basin is draped by sediment ranging from several centimetres to decimetres in thickness, which comprises rhythmically laminated argillaceous silts with occasional centimetre-scale beds of coarse sand. In the western basin, the sediment drape is several metres thick. Iceberg rafting of dropstones from the ice cliff has deposited numerous scattered dropstones ranging from centimetres to decimetres in size. These also form isolated matrix-supported clasts within the laminated fine sediment.

Discussion

According to Cerutti (1951), the 1950 drainage event resulted from the cessation of inflow to the lake while outflow continued *via* two points, one near the ice cliff and the other through the bed of the SE basin. This second point must have played a minor role in lake drainage, since no subaerial seepage through the base of the amphitheatre moraines was observed. However, leakage through the lake bed appears to always be present, as two observations indicate:

- the bottom of the SE basin in October 2004 showed an openwork till covered by a centimetre-scale bed of argillaceous silt. The absence of a sealing matrix of silt within the coarse lake bed till indicates a continuous infiltration of water winnowing out interstitial fine material. By contrast, lake floor silts > 0.8 m thick mantle the neighbouring intermorainic cols.
- surface lowering of the residual pond water in the SE basin was measured at *c.* 10 m in 8 days, during which time the pond in the W basin only lowered by 0.45 m. This higher rate of leakage indicates a more permeable bed.

CONCLUSIONS

The drainage event of September 2004 allowed observations to be made which would otherwise have been difficult to achieve. These observations form part of ongoing research at the lake, and greatly assist our comprehension of the dynamics of the lateral ice-contact lake over a range of timescales covering its formation, post- «Little Ice Age» evolution, and interannual and seasonal behaviour:

1. Turnover in the lake is clearly low, with no significant glacial inflow channels being observed and only one small subaerial outflow. Much water is lost by seepage through the lacustrine and till sediments which form the bed, especially in the SE basin. Drainage only due to a reduced inflow from the glacier cannot explain the rate of emptying.
2. Emptying in 2004 occurred in two stages. First, relatively rapid surface lowering was facilitated by increased outflow between the glacier sole and the bounding moraine ridge. Once separate basins formed, their ponds were isolated from this outlet and slower lowering continued by leakage at different rates in each basin.
3. Survival of an extensive ice foot shows that part of the lake is perched on the glacier margin, where increased ablation due to calving has removed ice above the summer lake level, but very little ice loss has occurred in the subaqueous environment.
4. Periodic drainage events appear to be random and related to the occasional formation of linked subglacial drainage routes, facilitated by the intersection of marginal crevasses.

Half a century after Lesca's (1956) remarkable paper, Miage Lake remains a prime field site for investigations to better understand glacier dynamics and their relationship to calving phenomena. These events are increasingly common in alpine environments where deglaciation is creating favourable loci for the formation of ice contact lakes.

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