Structural control of englacial drainage systems in Himalayan debris-covered glaciers

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ABSTRACT. Englacial cave systems were mapped using speleological techniques in three debris-covered glaciers in the Khumbu Himal, Nepal. Detailed three-dimensional mapping of the cave systems and observations of relationships with structures in the surrounding ice show conduits formed by a mechanism directly analogous to speleogenesis in limestone karst. The highest, oldest parts of all passages developed along debris-filled crevasse traces with hydraulic conductivity in the range 10^{-4} to $10^{-5}\,m\,s^{-1}$. Conduits form when these hydraulically efficient pathways bridge between areas with different hydraulic potential. They then evolve by grading (through head-ward migration of nick points and vertical incision) to local base level, often the surface of supraglacial lakes. Most supraglacial lakes on Himalayan glaciers are perched above the elevation of the terminal stream, and exist for a few years before draining through englacial conduits. As a result, near-surface drainage evolution is frequently interrupted by base-level fall, and conduits may record multiple phases of incision. Conduits commonly migrate laterally during incision, undermining higher levels of the ice and encouraging collapse. Voids can be created by fluvial processes and collapse of crevassed ice. The oft-noted resemblance of the surface morphology of debris-covered glaciers to karst landscapes thus extends to the subsurface, and karst hydrology provides a framework for understanding englacial drainage.

INTRODUCTION

The surfaces of stagnant or slow-moving debris-covered glaciers have frequently been compared to limestone karst, due to the presence of features such as swallow-holes, sink holes, caves and springs (e.g. Clayton, 1964; Kruger, 1994; Kirkbride, 1995; Benn and Evans, 1998). However, the extent to which the karst analogy extends to the subsurface has rarely been investigated (e.g. Pulina, 1984; Pulina and Rehak, 1991). In limestone karst, speleogenesis occurs where sufficient subsurface water flow exists to remove dissolved rock and keep undersaturated water in contact with the soluble walls. This is possible only where a pre-existing, interconnected network of openings, such as bedding planes or joints, links recharge and discharge zones (Palmer, 1991). The location and morphology of limestone caves, therefore, is a function of both secondary permeability and hydraulic gradient. While quantitative theories of englacial drainage evolution have traditionally assumed that ice permeability is uniform and isotropic (e.g. Shreve, 1972), recent work has emphasized the role of fractures in guiding water flow. Fountain and Walder (1998) argued that near-surface drainages along the bottom of crevasses could incise into the ice to depths where cryostatic pressures cause closure of the upper reaches of the canyon, creating trapped, sub-horizontal tubular conduits. Alternatively, Boon and Sharp (2003) and Alley and others (2005) have proposed that high hydrostatic pressures in water-filled crevasses could allow fractures to propagate to significant depths and perhaps to the bed. Although there is good evidence that both of these mechanisms operate within glaciers (Pohjola, 1994; Vatne, 2001; Boon and Sharp, 2003; Vatne and Refsnes, 2003; Fountain and others, 2005), their applicability to glacier karst evolution is unknown. Both mechanisms require significant tensile stresses at the surface to initiate and maintain open crevasses, conditions that are unlikely to be widespread on stagnant or near-stagnant debris-covered glaciers. Englacial drainage systems within such glaciers, therefore, must either be inherited from some earlier phase of ice flow, or form by some other mechanism.

Understanding the character of drainage systems within debris-covered glaciers and the factors that control their development is important because subsurface processes clearly influence surface hydrology and topographic evolution (Kirkbride, 1995; Benn and others, 2001). However, information on subsurface drainage systems in such glaciers is difficult to obtain with commonly used glacial-hydrological techniques. Dye-tracing (e.g. Hooke and others, 1988) and geophysical sensing of subsurface voids (e.g. Arcone and Yankielun, 2000; Stuart and others, 2003), for example, are impractical due to the ubiquity of coarse, inhomogeneous debris, combined with complex and irregular terrain and problems of access. In limestone karst, the most comprehensive and reliable data on subsurface features are obtained through direct exploration. Therefore, we have adapted speleological techniques to gain access to englacial cave systems in debris-covered glaciers, and to make detailed maps of their plan-form and morphology. The results allow the controls on drainage development and evolution to be identified, and provide new insights into the relationship between englacial speleogenesis and glacier surface evolution. We show that the karst analogy is more than skin-deep, and that the principles of karst hydrology provide a powerful framework for understanding the initiation and evolution of drainage within debris-covered glaciers.

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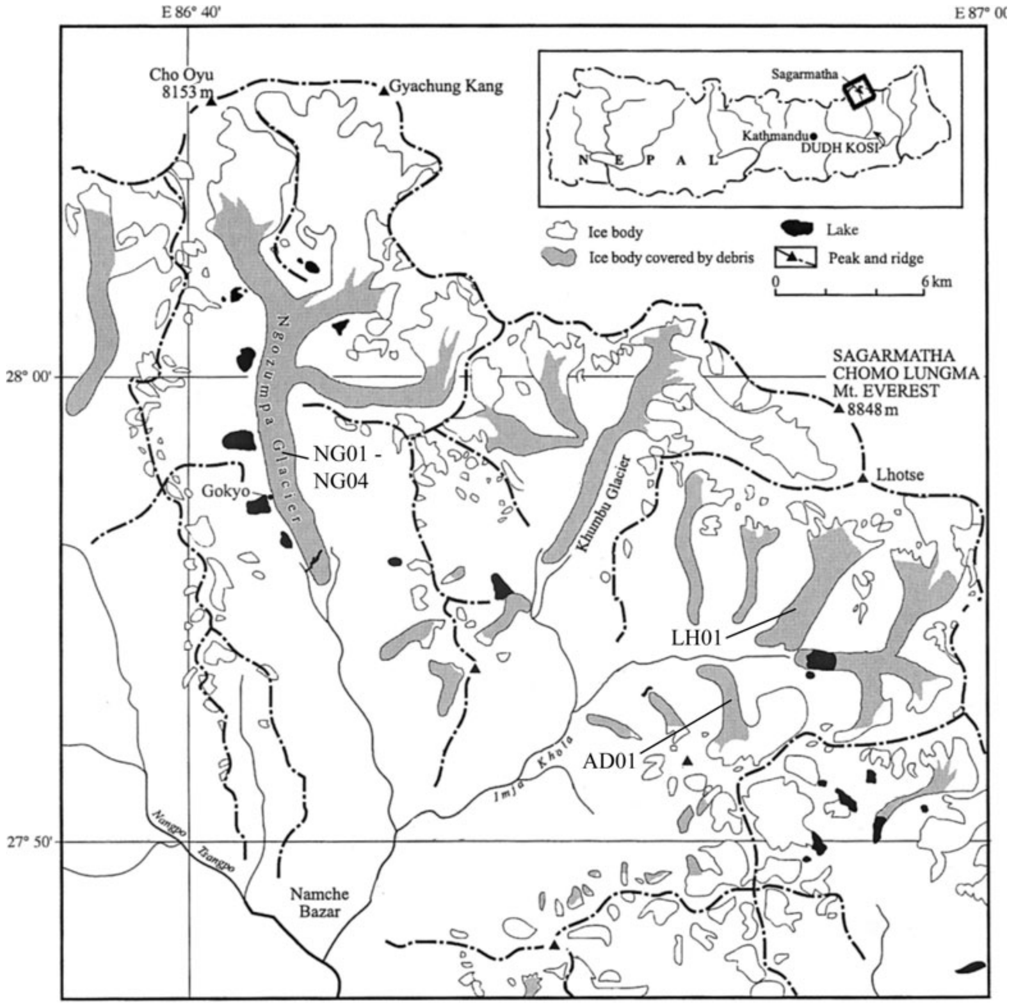

Fig. 1. Khumbu Himal, Nepal, showing locations of the englacial conduits explored in November–December 2005.

STUDY AREA AND METHODS

This study presents observations of englacial drainage systems within three debris-covered valley glaciers in the Khumbu Himal, Nepal (Fig. 1). Detailed surveys were conducted in Ngozumpa Glacier in the upper Dudh Kosi catchment, and additional observations were made of conduits in Ama Dablam and Lhotse Glaciers in the Imja catchment. We use the term 'conduit' simply to denote an englacial tunnel that conveys water and does not presuppose any particular genetic model. All three glaciers have extensive covers of supraglacial debris, which form almost continuous layers 1–2 m thick over most of their ablation zones, except where interrupted by steep ice faces or holes in the glacier surface. Strongly negative mass balance in recent decades has resulted in significant ice-surface lowering (downwasting) and stagnation (Kadota and others, 2000; Hands, 2004). The tendency of the lower parts of debris-covered glaciers to stagnate is a consequence of the insulating effect of surface debris, which tends to thicken down-glacier and thus progressively reduces ablation rates (Inoue, 1977; Benn and Lehmkuhl, 2000; Nicholson and Benn, 2006). Therefore, during periods of negative mass balance, surface-lowering rates in debris-covered areas increase up-glacier, so that downwasting results in a reduction of both surface gradient and ice-flow speed. Uneven patterns of ablation have produced highly irregular surfaces on all the debris-covered glaciers in the study area, with mounds and ridges up to 50 m high separating topographic lows, many of which contain supraglacial lakes or evidence of their former presence.

Supraglacial lake formation on Himalayan glaciers is encouraged by low surface gradients and irregular topography, and where glacier termini are impounded by large lateral-terminal moraines. In a study of supraglacial lake distribution in Bhutan, Reynolds (2000) found that lake formation occurs only where glacier surface gradients are $\leq 2^{\circ}$, a result that was confirmed by Wiseman (2004) for the Khumbu Himal. In the early stages of downwasting, lakes tend to be ephemeral and drain after a few years while they are still relatively small (Benn and others, 2001; Hands, 2005). In contrast, when downwasting is more advanced, supraglacial lakes can attain very large dimensions and pose significant outburst flood hazards to communities located downstream (Richardson and Reynolds, 2000; Quincey and others, 2005). Whether supraglacial lakes develop into major hazards depends to a large degree on their elevation relative to the outflow stream over the terminal moraine (Benn and others, 2001). The existence of large moraine-dammed lakes shows that Himalayan terminal moraines present effectively impermeable barriers to water flow (see Yamada, 1998; Richardson and Reynolds, 2000), and that the lowest point on their crests thus acts as base level for the whole glacier drainage system. Supraglacial lakes may be perched above this base level if no englacial conduits exist between the lake floor and lower points on the glacier surface. If a connection is made, partial or complete lake drainage will follow, thus limiting lake size and lifespan. In contrast, where a supraglacial lake develops at the same elevation as the spillway through the terminal moraine (i.e. at base level) drainage will not occur while the moraine dam remains in place. Lake growth can continue unchecked until the moraine dam is breached, and catastrophic drainage may ensue.

In addition to limiting the lifetime of 'perched' supraglacial lakes, englacial conduits can also play a role in the formation of new lakes. Subsidence resulting from conduit roof collapse creates new depressions on glacier surfaces where ponds can form. Because melting is inhibited beneath thick debris covers, ablation is strongly focused around lake margins where bare ice is exposed and calving is promoted by thermal undercutting (Sakai and others, 1998; Benn and others, 2001). By preconditioning lake formation and drainage, therefore, englacial hydrological systems exert a strong influence on long-term ablation rates and glacier response to climate change.

To obtain detailed information on subsurface drainage, and to determine the principal controls on their location and morphology, conduits were entered and mapped using a combination of speleological and mountaineering techniques. The five conduits described in this paper were at elevations of 4900–5300 m, making them the highest surveyed caves in the world. Conduit surveys were conducted in November and December 2005, when surface meltwater production was small. Surveys were conducted by measuring the distance, azimuth and inclination between successive marked stations using a fibreglass tape measure and a Brunton Sightmaster compass and inclinometer. The largest survey closure error was 0.72 m in the horizontal and 0.16 m in the vertical over a surveyed distance of 554 m. Maximum horizontal errors in the surveyed conduit planforms are therefore 0.12%. Passage cross-section dimensions were measured at every survey station. Scaled sketches of all passages in plan, profile and cross-section were rendered in situ, including details of passage morphology and the structure of the surrounding ice. Survey data were reduced using the COMPASS software program. Some of the caves were visited again in late 2006, and some pertinent observations are briefly reported here.

ENGLACIAL STRUCTURES

All of the conduits described in this paper were very closely associated with englacial debris bands cutting across the ice foliation. To clarify the characteristics and origin of these important structures, it is useful to describe briefly the main structural features of the glaciers.

Foliation

Glacier ice exposed in cliffs or inside ice caves typically displayed alternating bands of clear and bubbly ice, interpreted as primary stratification. Folia were typically tilted at high angles, and occasionally displayed upright or overturned folds.

Crevasse trace

Veins of ice were observed cutting across the foliation at several localities. Most of the vein ice was bubble-free, and was either clear or contained dispersed silt or coarser particles. Trains of bubbles were observed along suture lines in the centre of some veins, which are interpreted as crevasse traces similar to those described by Hambrey and Müller (1978).

Foliation-parallel debris bands

Lenticular debris bands, conformable with the surrounding foliation, cropped out in several places, particularly close to the glacier margins. The bands consist of coarse, poorly sorted debris and interstitial ice. Bubble content is generally low. These structures are interpreted as rockfall debris deposited on the accumulation areas of the glaciers and incorporated within the snowpack.

Discordant debris bands

Debris bands cutting across the foliation are very widespread on the study glaciers. The constituent debris is generally better sorted than in foliation-parallel bands and either lacks interstitial ice or has only sparse ice cement. Several examples were observed to taper downwards and terminate at a point. These structures are interpreted as the infills of former crevasses that have been advected down-glacier by ice flow. In the upper part of the ablation zone of debris-covered glaciers, coarse, poorly to moderately well-sorted supraglacial debris commonly falls into open crevasses. When crevasses close as they are advected down-glacier, in the absence of liquid water, the granular fill forms permeable, unfrozen planar structures within relatively clean ice (e.g. Figs 5a, 7d and 9a below), which may be subsequently rotated or structurally deformed. Hereafter, such structures are termed *debris-filled crevasse traces*.

Samples from debris-filled crevasse traces exposed in conduit walls were collected for grain-size and hydraulic conductivity analysis. Hydraulic conductivity was measured using a Darcy apparatus (Freeze and Cherry, 1979). Samples were wet-loaded into a 5 cm diameter PVC container to create a column of sediment 20 cm high. For practical purposes, clasts >2 cm in diameter were excluded. A constant head of water was applied to one end of the column and head loss between the input and output measured to the nearest millimetre in a manometer. Discharge was calculated by dividing the volume discharged through the sample chamber into a graduated cylinder (measured in mL) by time, measured with a digital stopwatch to the nearest second.

CONDUIT MORPHOLOGY

Ngozumpa Glacier

Detailed surveys were made of three conduit systems on Ngozumpa Glacier, all located approximately 7 km from the glacier terminus at altitudes of 4900–4950 m (Fig. 2). The sites were located up-glacier of lake basins 7092 and 7093 (discussed in detail by Benn and others, 2001), both of which contained only small residual ponds in 2005. Conduits NG01 and NG02 were located at the northern and southern margins, respectively, of a closed basin near the glacier centre line. In December 2005, several small ponds occupied the floor of the basin, and patches of laminated sand and silt indicated that lake level had formerly been higher. Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) scenes of the glacier show a lake occupying the basin in November 2002, which had almost completely drained by October 2003.

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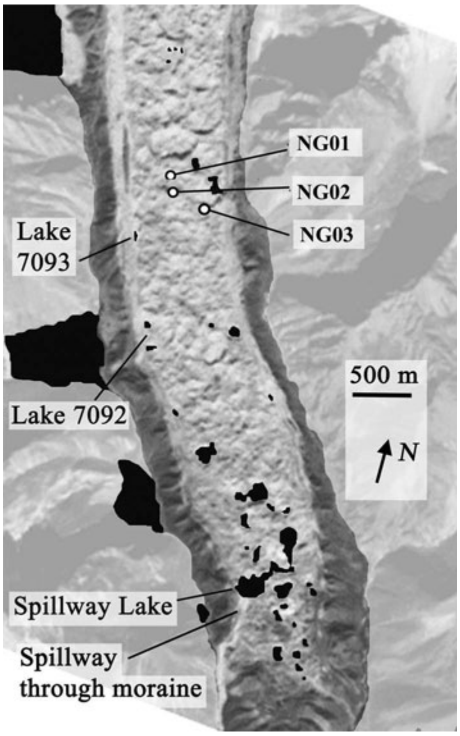

Fig. 2. The lower part of Ngozumpa Glacier, showing the position of cave entrances and other locations mentioned in the text. The base layer is an ASTER image for 15 December 2005.

Conduit NG03 was at the southern margin of a similar closed basin near the eastern flank of the glacier. The ASTER imagery shows a lake occupying this basin in 2002. In subsequent years, the lake became less extensive in the southern part of the basin but more extensive in the north. Only small, shallow ponds remained in the southern basin by December 2005.

NG01 (27°57′58″ N, 86°41′50″ E)

This conduit system consisted of a highly sinuous, canyon passage with three main levels, labelled A (lowest), B and C (highest) (Figs 2 and 3; a legend for these and all subsequent maps is shown in Fig. 4). The conduit entrance, at the lower end of the cave, had an inverted J-shaped cross-section with levels A and B connected by a narrow, sub-vertically oriented canyon. Level C was not represented at the entrance, but >35 m into the passage a shelf formed ~5 m above level B. At a distance of 75 m from the entrance, this led into an independent passage with a low, broad and irregular cross-profile. Debris bands cropped out in the walls of level C throughout its length, either at the lateral margins of the passage or in the roof. Mostly, the debris bands formed planar structures which cut across, and in places displaced, the primary foliation. These are interpreted as debris-filled crevasse traces (Fig. 5a). Three sediment samples were collected for particle size and hydraulic conductivity analyses (sample locations are shown in Fig. 3). Samples NG01-a, b and c are poorly to moderately sorted, clast-rich sandy diamicts, and had measured hydraulic conductivity values of 1.2×10^{-4}, 7.0×10^{-5} and 4.5×10^{-4} m s^{-1}, respectively. These values are at the high end for tills (~10^{-12} to 10^{-4} m s^{-1}) and fall within the range for silty sand (~10^{-8} to 10^{-3} m s^{-1}) and clean sand (~10^{-6} to 10^{-3} m s^{-1}) (Freeze and Cherry, 1979; Fountain and Walder, 1998). The degree to which the measured values reflect the in situ properties of the debris bands is uncertain. The laboratory samples were unconsolidated, whereas the in situ material may have been compacted to some degree, reducing its hydraulic conductivity by perhaps one or two orders of magnitude (cf. Hubbard and Maltman 2000; Watabe and others, 2000). However, the ease with which the in situ sediment could be scooped out by hand during sampling suggests that it was not significantly compacted. Moreover, clasts >2 cm were removed before laboratory analysis, which may have reduced sample permeability relative to the original material. With these provisos, the measured values probably give a good indication of in situ sediment permeability.

Level B had a sub-horizontal floor, into which the canyon linking to level A had been incised. In several places, the floor of level B was littered with angular ice blocks, and similar blocks formed a cemented ice breccia choking parts of the canyon below, forming a 'false floor' (e.g. B6, B10). The walls of the level B passage were highly variable in form, commonly with one or more ledges between the main floor and level C above.

At a distance of 150 m from the entrance, level B narrowed to a partially collapsed constriction, then opened out into a large, flat-floored passage ~16 m wide and 8 m high, informally named the Soccer Field (Figs 3b and 5b). Levels A and C also connected with the Soccer Field: level C as a laterally elongated hole near the passage roof at its eastern end, and level A as an incised channel running first parallel to, and then across, the passage axis. The roof of the Soccer Field was highly irregular and traversed by numerous cross-cutting planar debris bands, one of which could be traced for ~20 m along the centre of the roof, parallel to the passage axis. The ice on either side of the debris bands displayed discordant foliation, and the whole mass is interpreted as formerly heavily crevassed ice which had been partially reconstituted. Passage enlargement at this locality was achieved partly by the collapse of ice blocks from the roof, as evidenced by numerous large, angular fragments littering the floor. The frequency of fallen blocks was greatest at the eastern end of the Soccer Field, above which was a short, poorly developed vadose infeeder passage (Fig. 3c).

Two constricted passages led out of the northwestern end of the Soccer Field. One extended from the innermost end of level A, and was almost entirely choked by fallen ice blocks, whereas the other was graded to level B and consisted of a 1.5 m high and 10 m wide slot between a floor of fallen blocks and a roof composed of semi-detached flakes (A31, Fig. 3b). Both passages opened dramatically into a large, ice-block floored room 49.1 m long by 15.2 m wide, informally named the Reptile Room (Figs 5c and 6b). The roof was highly irregular, consisting of numerous partially isolated ice blocks bounded by cross-cutting linear debris bands, indicating that, like the Soccer Field, the room had been enlarged by collapse of structurally weakened ice forming the roof. Small, partially collapsed passages extended from the rear of the Reptile Room, but were too small to permit entry.

The lowest level (level A, Figs 3a and 5d) was at the bottom of the canyon incised into level B. At its base, the passage averaged ~4 m in width and had a distinctive rectilinear cross-section, with unpaired sub-horizontal sills and overhanging lips at the lateral margins. The floor, which

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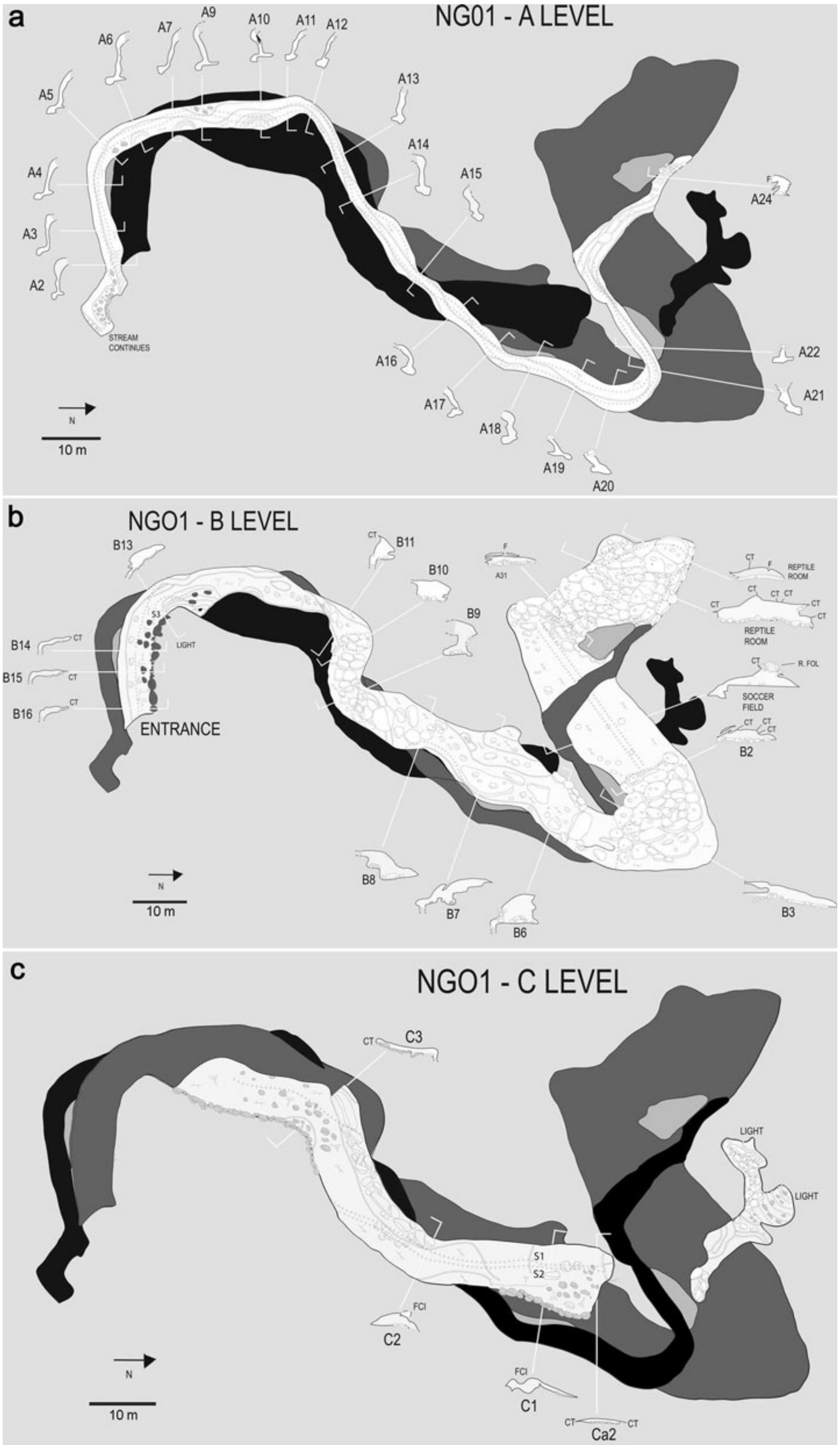

Fig. 3. Map and passage cross-sections for NG01: (a) lower level; (b) middle level; (c) upper level. Overall water-flow direction was towards the south (left).

consisted of a partially frozen stream flowing down-glacier toward the entrance, rose up-glacier with a gradient of ~1 : 110 and gradually converged with successive lateral sills. The canyon walls were inclined alternately to the right and left, rising up towards the centre of each bend. In several localities, a frozen breccia of large (>1 m) ice blocks formed a false ceiling near the top of the canyon (e.g. A19 and A20, Fig. 3a). In places, blocks were buckled and shortened in the cross-passage direction, indicating narrowing of the passage following emplacement of the ice breccia. (This same breccia also formed the false floors in level B above.)

The glacier surface above NG01 was mapped to determine whether subsurface features had any surface expression. Surface crevasse traces were found at several points

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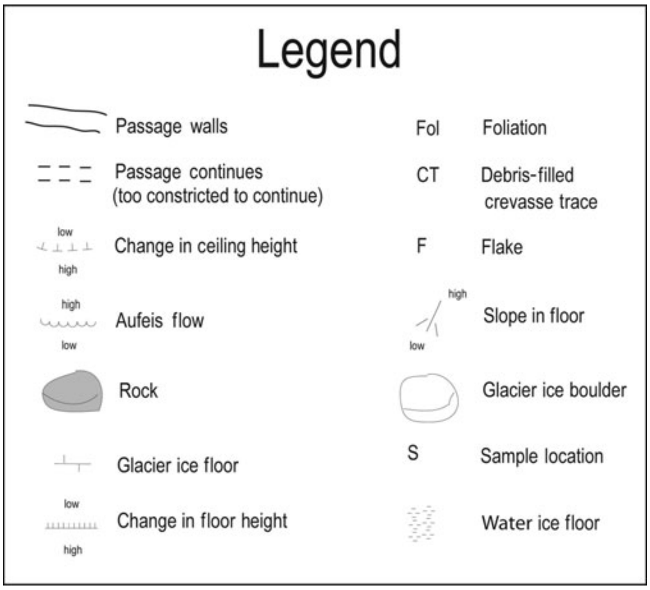

Fig. 4. Legend for conduit survey maps.

above level C, and around the entrance of the vadose infeeder at the eastern end of the Soccer Field. Neither the Soccer Field nor the Reptile Room was associated with any subsidence at the surface.

Interpretation

The uppermost levels of NG01 display very strong associations with debris-filled crevasse traces, indicating that initial conduit location was structurally controlled (Fig. 5a). For the most part, passage morphology reflects predominantly fluvial processes, but the two largest sections, the Soccer Field and Reptile Room, formed by a combination of fluvial erosion and gravitational collapse of the passage roofs. Collapse at these localities appears to reflect numerous structural weaknesses in the overlying ice. In the Soccer Field, ice blocks are absent from the floor closest to the incised level A canyon, suggesting that they had been evacuated at times of high stage. Additional evidence for fluvial transport of collapsed blocks is provided by the ice breccias between levels A and B, which appear to have been floated in, then frozen into place before the waters receded. Buckling of ice blocks in some of the breccias is interpreted as evidence of closure of the passage in response to stresses in the surrounding ice.

Steps in the lateral margins of the passage walls between levels A and B and levels B and C are discontinuous and could mark varying rates of lateral channel migration during incision. In contrast, the flat floor of level B is continuous throughout its length, compatible with channel grading to a stable base level, most likely a supraglacial lake occupying the closed basin at the downstream end of the passage. The dramatic change in morphology from flat-floored passage to sub-vertical canyon below level B is interpreted as the result

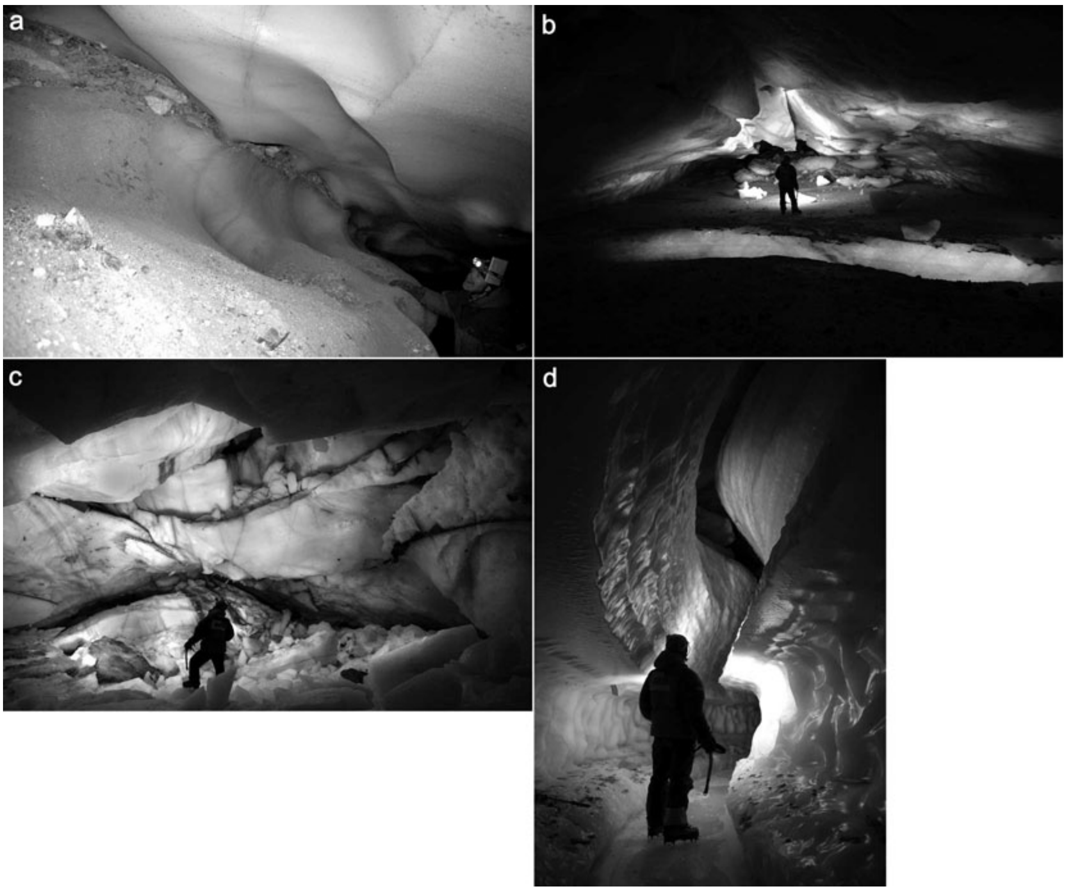

Fig. 5. Photographs of NG01, Ngozumpa Glacier. (a) Debris band cropping out along the uppermost part of level C. (b) The 'Soccer Field', level B. Note the level A canyon incised into the flat floor (running left to right), the fractured ice in the ceiling, and the fallen blocks in the farthest part of the picture. (c) The 'Reptile Room', level B. Blocks fallen from the heavily fractured ceiling litter the floor. (d) Canyon passage morphology, near station A11.

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of a sudden drop of base level associated with partial drainage of the supraglacial lake. Initial base-level drop was ~8 m, followed by intermittent minor falls recorded by the sills at the margins of the level A passage. Channel incision below level B is likely to have occurred in response to base-level fall associated with the lake drainage event in 2004.

NG02 (27°57′55″ N, 86°41′51″ E)

This conduit system consisted of a highly sinuous, multi-level canyon passage with an entrance 97 m south-southeast of NG01, at the southern margin of the same former lake basin (Figs 2 and 6). Whereas NG01 had carried water into the basin, NG02 drained it out, so the entrance to the latter was at its upstream end. The entrance area was in a north-facing ice cliff, and took the form of a large alcove following the line of a prominent debris-filled crevasse trace with a dip angle of 45–50° (Figs 6 and 7a). Two major passages extended in a southwesterly direction from the back of the alcove, separated by a band of ice which was traversed by innumerable anastomosing tubes and blind holes, with a morphology akin to Swiss cheese. Most tubes were a few centimetres in diameter, but some were sufficiently large to permit entry (Fig. 7b) and were found to penetrate through to the lowermost passage (level A). The ice ceiling of this lower passage was perforated by anastomosing tubes and holes for several tens of metres (A4–A5, Fig. 6a). Most of the 'Swiss cheese' was developed in a band of frozen ice breccia, with individual openings following gaps or weaknesses in the ice cement between blocks. However, in some places, tubes and holes had exploited fractures in ice more or less in situ.

The upper passage leading from the entrance alcove (level B) passed behind some ice pillars, then formed a shelf terminating at a steep drop down to level A (shown in Fig. 7a for clarity). On the other side of a collapsed zone, level B continued as a sinuous, tubular conduit with a strikingly circular cross-profile, beneath which an incised canyon led down to level A (B12, Fig. 6b; Fig. 7c). In several places, a second, similar tubular passage could be seen between the upper conduit and the narrow, incised canyon leading down to level A (e.g. B4 and B6, Fig. 6b). Locally, the walls of this narrow canyon were in contact, strongly suggesting closure by ice creep. Indeed, some sections that had been open in 2005 were observed to have pinched shut by 2006. Level A formed an asymmetric, flat-floored passage with a series of sills along its margins. In common with the overlying canyon, it was much smaller in cross-section than the higher levels. A debris-filled crevasse trace was exposed along the entire length of the ceiling of level B, mirroring the plan-form of the passage to a remarkable degree (Fig. 7d). Bends in the level A passage were commonly substantially offset from those in level B above. As a result, the floor of level B was undermined in several places, and some large rooms exhibited localized collapse. Large numbers of sub-rounded ice blocks littered the entrance alcove and partially blocked the canyon between levels A and B, where they locally formed false floors of loosely ice-cemented breccia. There was a clear upper limit to the blocks, and they did not occur on the ledges bounding the uppermost conduit level.

Higher-level passages were observed at one locality. The first was a narrow infeeder that entered from the northwest, near the east end of the gap in level B (C2 and C3, Fig. 7b). Near the lower end of this infeeder, an elliptical conduit branched off then rejoined the roof of level B (C1, Fig. 7b). This conduit, which appeared to be genetically unrelated to

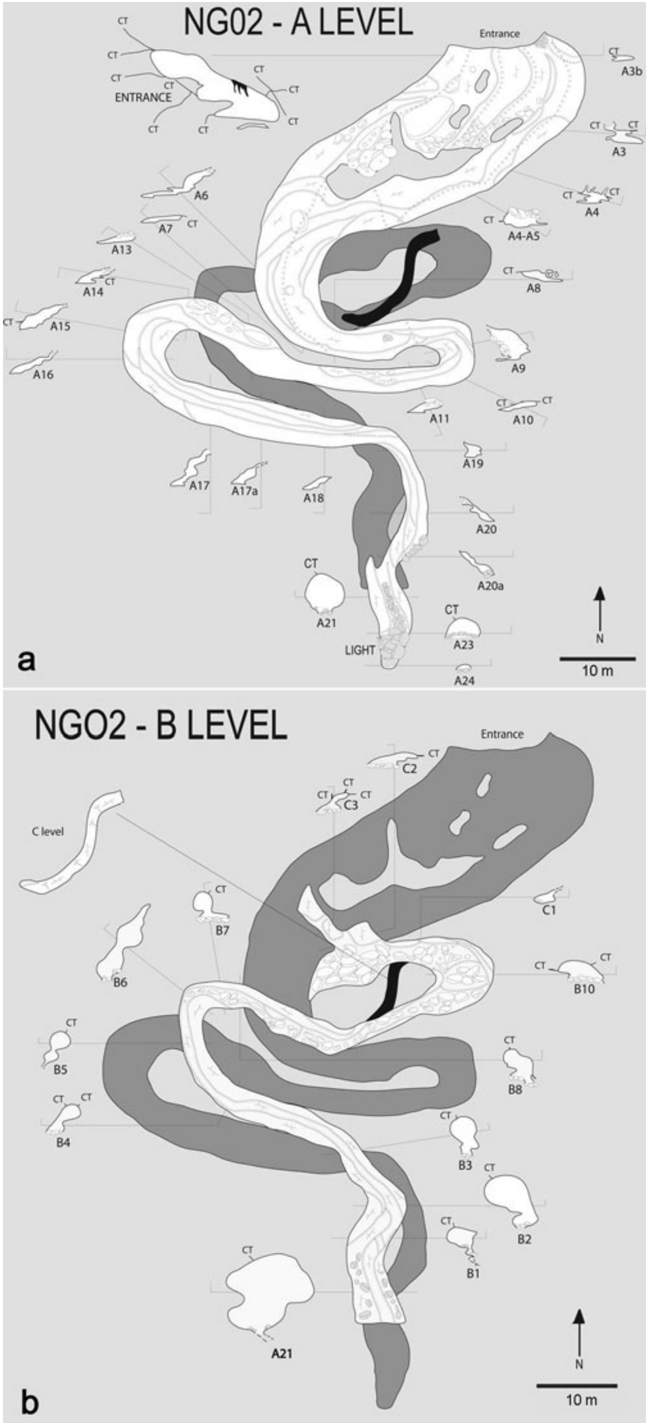

Fig. 6. Map and passage cross-sections for NG02: (a) lower level; (b) upper level. Overall water-flow direction was towards the north (top).

the infeeder, was 0.6–1.4 m in diameter, and bypassed a bend in level B before trending parallel to it following the same crevasse trace.

Interpretation

The tubular form of the upper conduit in level B indicates that the earliest phase of flow recorded in NG02 was under phreatic conditions. The relationship between this part of the conduit and the crevasse trace clearly demonstrates that the conduit did not form by incision from the surface. If the conduit had originated as a channel down-cutting through

Fig. 7. Photographs of NG02 and NG03, Ngozumpa Glacier. (a) Entrance alcove, NG02. (b) Part of the network of anastomosing holes, above station A4, NG02. (c) Circular conduit with incised floor, indicating phreatic–vadose transition, near station B12, NG02. (d) Crevasse trace in the ceiling of level B (station B9). Note close association between bends in conduit and crevasse trace, NG02. (e) Entrance area of NG03. (f) The inner passage of NG03, near station A10.

the overlying ice and subsequently becoming isolated from the surface by creep closure, evidence of this history would be preserved in the ice above and around the conduit. However, extensive outcrops of debris-filled crevasse traces in the ceiling of the conduit and around the entrance alcove show that the conduit did not cut down through these structures, but formed at its present position relative to the surrounding ice, leaving the adjacent structures intact. We conclude that the conduit was initiated in situ when a debris-filled crevasse trace provided an efficient pathway between areas with a large difference in hydraulic potential. For most of its length, the conduit is singular, although the short, higher-level, parallel offshoot (level C) may record bypass of the main conduit under pipe-full conditions.

The large cross-section area of the uppermost conduit and the profusion of rounded ice blocks littering the entrance alcove and choking the cave are consistent with high discharges associated with drainage of a supraglacial lake. We suggest that the upper levels of NG02 were initiated and enlarged during the 2003 lake-drainage event identified above. The anastomosing tubes and holes in the ice near the entrance zone are closely similar to forms eroded under large head-gradients in limestone caves and are also likely to have formed during lake drainage, when turbulent, thermally aggressive floodwaters exploited fractures in the ice and interstices within ice-jams.

The ‘keyhole’ morphology of NG02, consisting of a circular upper passage with an incised slot in the floor, is identical in form to limestone cave cross-sections recording phreatic to vadose flow transitions. In this case, incision of the floor was probably associated with propagation of head loss upstream from the passage exit. Although the initial conduit plan-form was controlled by the trend of the parent structure, during incision it appears to have become independent of structural control, and shifted location due to lateral migration of meanders. The small cross-section of the incised canyon and level A, compared with the higher levels, indicates a substantial reduction in discharge between the early and later phases of cave development.

NG03 (27°57′52″ N, 86°42′02″ E)

This conduit formed a singular, meandering passage graded to the level of a frozen supraglacial pond, from where entry was made (Fig. 8). Passage ceiling height gradually increased upstream from 0.5 m near the entrance (Fig. 7e) to 1.0 m at a distance of 80 m and 4.0 m at 130 m, where passage morphology changed from a low, wide semi-elliptical cross-section to a more complex form with an elliptical upper section separated by a narrow neck from a lower A-shaped section (A6 and A7, Fig. 8). At a deeper penetration, much of the passage had a canyon-like morphology with a series of notches and shelves at the lateral margins (Fig. 7f). At the top of the canyon, the ceiling narrowed to a narrow slot, terminating in a band of coarse, unfrozen sandy diamict, interpreted as a debris-filled crevasse trace. Debris-filled crevasse traces cropped out almost continuously along the inner passage, except for two sections where the ceiling ice exposed intermittent debris and had a complex, irregular form with numerous blind holes and re-entrants (A9 and A12, Fig. 8). Sub-horizontal debris bands cropped out around A5, and parts of the conduit margins nearer the entrance, although passage dimensions were too restricted to allow systematic exploration. The conduit was followed for a total surveyed distance of 364.3 m until it terminated in a ramp of bouldery debris.

Interpretation

The low relief of the floor profile of the passage is indicative of grading to local base level, determined by the elevation of the supraglacial pond at the passage terminus. The wide, low semi-elliptical form of the outer passage is at least partly structurally controlled, as indicated by the presence of sub-horizontal debris bands, but it may also reflect preferential melting of the passage margins under non-full flow conditions (cf. Hooke and others, 1990; Hooke, 2005). Conduit flow was in an up-glacier direction, illustrating that drainage direction is strongly controlled by local structural and hydrological conditions.

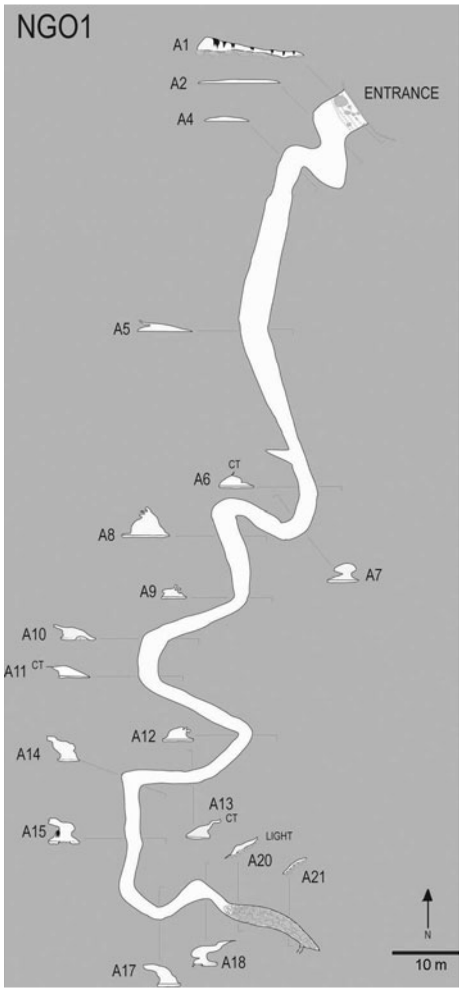

Fig. 8. Passage plan-form and cross-sections, NG03. Overall waterflow direction was towards the north (top).

Ama Dablam and Lhotse Glaciers

Conduit systems were also entered on Ama Dablam and Lhotse Glaciers (Fig. 1) in mid-November 2005, but were not surveyed because of melting conditions and extreme instability of the conduit roofs. However, observations made at these localities usefully supplement the more detailed results described above.

Ama Dablam Glacier

Three major englacial conduits were discovered close to the eastern flank of Ama Dablam Glacier, only one of which (AD01) was deemed safe enough to enter. This conduit had two entrances in a northwest-facing ice cliff at the margin of a relict supraglacial lake basin (27°53′03″ N, 86°52′52″ E; 5000 m a.s.l; Fig. 9a). The lefthand upper entrance (AD01A) had an elongated kidney-shaped cross-section with a major axis of ~15 m inclined at ~45°. The entrance led into a meandering passage, the ceiling of which was centred on an inclined debris-filled crevasse trace. After approximately 100 m, the passage turned 90° to the right, where further progress was halted by deep water and overhanging walls. The righthand lower entrance (AD01B) was ~12 m high and had an inverted J-shaped cross-section, with a sub-horizontal upper level perched above an inclined lower canyon (Fig. 9b). An inclined debris-filled crevasse trace cropped out in the ceiling of the upper level. The passage floor consisted of a series of thin horizontal ice layers perched above voids, marking successively lower water levels. Water was observed to flow beneath a thin ice skin ~1.5 m below the lowest of these false floors. The fragile nature of these features prevented exploration of the deeper parts of the passage, but teams in AD01A and AD01B were able to establish communication, demonstrating that both formed part of a single conduit.

Interpretation

The close association between conduit location and crevasse traces provides another example of tortuous englacial drainage controlled by secondary permeability. In addition, the presence of poorly sorted debris in crevasse traces in the passage ceilings demonstrates that the conduits did not form by closure of a canyon melted down from the surface, but formed in situ by the exploitation of permeable weaknesses within the ice. The lack of a catchment above the upper entrance (AD01B) indicates there has probably been significant ice-cliff retreat since the cave was formed.

Lhotse Glacier

Several conduits were observed in close proximity around the margins and floor of a small basin near the northwestern side of Lhotse Glacier (27°54′48″ N, 86°54′09″ E, 5300 m a.s.l.). Extensive laminated sand and silt deposits on the basin floor indicate that it was formerly occupied by a supraglacial pond. At the lowest part of the basin floor was a 0.5 m wide hole (LH01) leading to a short, downward sloping passage then a vertical shaft, at the bottom of which

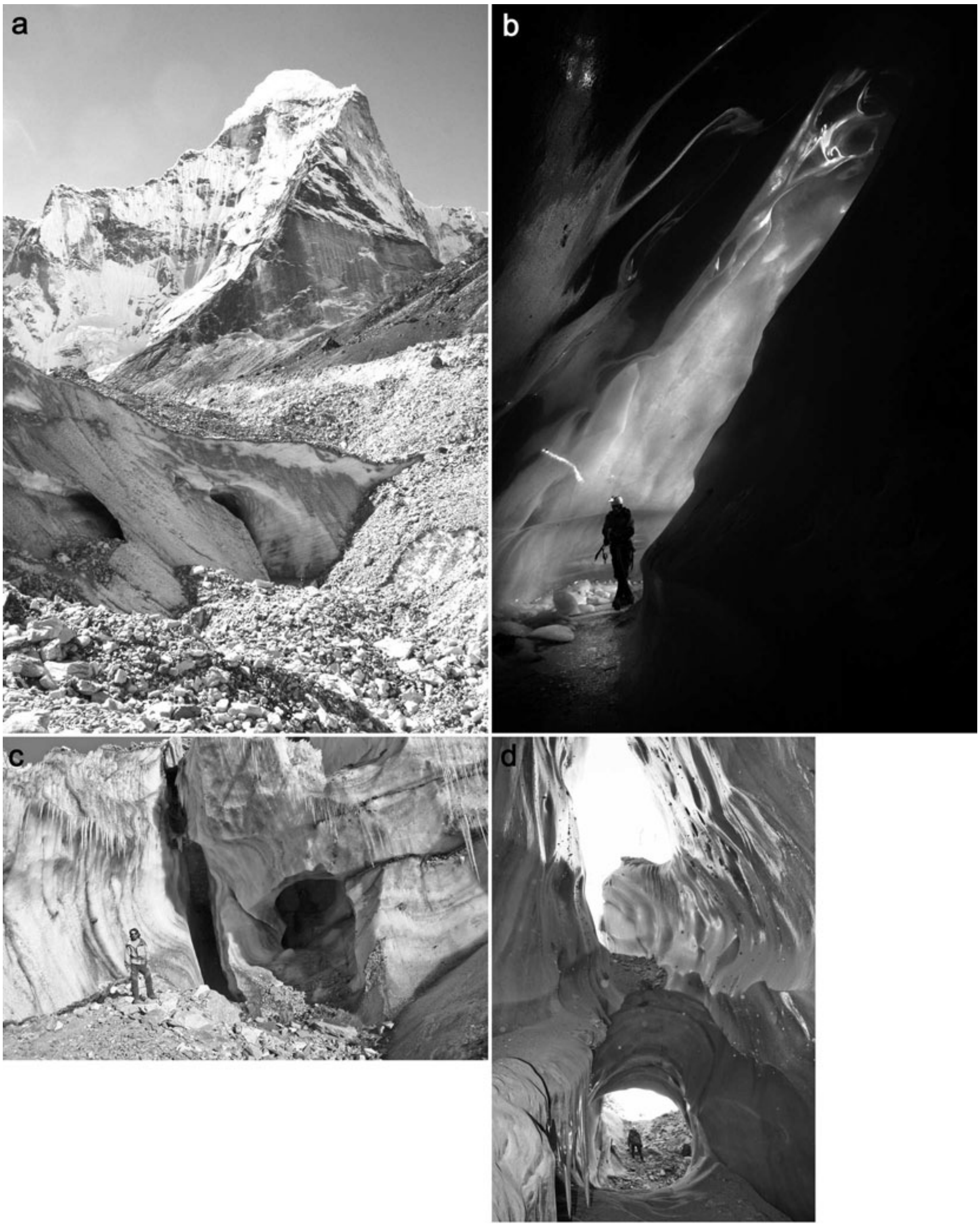

Fig. 9. Photographs of conduits on Ama Dablam and Lhotse Glaciers. (a) The two entrances of AD01. Both entrances are linked by a sinuous conduit. Ama Dablam (6812 m a.s.l.) is in the background. (b) Canyon passage morphology in AD01B. (c) Portals LH03 (left) and LH04A (lower right) and LH04B (upper right) viewed from outside. (d) Portals LH04A (lower) and LH04B (upper), viewed from inside.

flowing water could be heard. Approximately 20 m to the southwest of LH01, and ~2 m higher, was a crater-like depression in the basin floor (LH02), with a diameter of ~10 m. Rills in adjacent silt deposits indicated that water had formerly drained into the bottom of the depression, but boulders choking the floor prevented further investigation.

Three abandoned conduit portals were exposed in the walls of an 8 m high ice cliff at the northern margin of the basin, each of which formerly delivered water to the basin (Fig. 9c). The leftmost portal (LH03) consisted of a narrow, non-meandering canyon ~1.5 m wide and 8 m high, the upper half of which was infilled with coarse, poorly sorted debris. Approximately 2 m to the right were two circular portals, each ~2 m in diameter, one ~2 m above the other. The lower portal (LH04A) led into a short, gently ascending passage, then a vertical 3 m step led up to a narrow meandering canyon. Discontinuous sub-horizontal benches were developed on both margins of this upper canyon, graded to the level of the upper portal (LH04B, Fig. 9d). A vertical debris-filled crevasse trace occurred in the ice dividing the two portals, and along the entire length of the upper ceiling.

The floor of LH04A continued to rise with distance from the entrance, and passage dimensions progressively diminished. At the farthest accessible point, ~50 m from the entrance, a series of small holes connected with the glacier surface above and a deep pit appeared in the floor, at the bottom of which running water could be heard.

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Interpretation

Structural control on passage location is again clearly evident. However, the main interest of this locality is that passage morphology clearly shows the effects of intermittent lowering of base level. LH04B emerges at a similar elevation to the highest occurrence of laminated deposits, and appears to have been graded to the maximum level of the former pond. LH04A is graded to a second, lower lake elevation, and we infer that it was formed, and the upper level abandoned, when the pond partially drained through the conical depression (LH02). Significantly, lowering of the water efflux point did not occur by progressive incision, but by switching from LH04B to a new, lower-level outlet (LH04A, Fig. 9c and d). We conclude that this lower-level outlet was created when a potential gradient was developed through a permeable crevasse fill linking the upper-level passage floor and the newly exposed base of the ice cliff, and the resulting water flow melted a new conduit section. Once established, LH04A evolved by headward incision, but passage adjustment to the lowered lake level was interrupted by abandonment of the conduit. A second conduit formed in the adjacent crevasse trace (LH03), and the lake drained completely (through LH01). In turn, LH03 was abandoned when the feeder water accessed deeper weaknesses, and bypassed the older conduits.

SYNTHESIS AND DISCUSSION

Englacial conduit formation

All conduits examined in this study exhibited close association with discordant debris bands with little or no ice matrix, interpreted as debris-filled crevasse traces. With measured hydraulic conductivity values in the range 10^{-4} to 10^{-5} m s^{-1}, granular fills in relict crevasse traces provide high hydraulic conductivity pathways through otherwise effectively impermeable glacier ice, which serve as inception horizons for conduit development. Conduits observed in this study cut across foliation and bubbly ice veins without deviation, and we conclude that these features lack sufficient permeability to significantly influence englacial water flow at the macroscopic scale. The debris-filled crevasse traces are relict features which are no longer subject to tensile stresses, having been advected down-glacier from their site of formation. For this reason, there is no tendency for fractures to be reactivated and propagated to the bed by the hydrofracturing mechanism proposed by Boon and Sharp (2003) and Alley and others (2005). In 2006, we observed a hydrofracture-type conduit in a region of high longitudinal compressive stresses on Khumbu Glacier, where active ice was decelerating against stagnant ice down-glacier. The characteristics and significance of this conduit will be discussed in full elsewhere.

The downcutting-and-closure model of englacial conduit genesis proposed by Fountain and Walder (1998) cannot explain the origin of the conduits observed in this study. The relationship between conduit location and well-exposed intact crevasse traces (e.g. Figs 5a, 7a and 9c) clearly demonstrates that the conduits formed in situ relative to the surrounding ice, and did not cut downward from the surface. We conclude that conduits are initiated when gradients in hydraulic potential across permeable, granular horizons are sufficient to drive water through the medium, and grow by a combination of wall melting and evacuation of the debris fill (Fig. 10). This situation is analogous to speleogenesis in

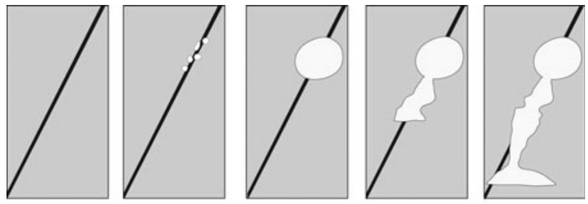

Fig. 10. Conceptual model of conduit evolution. 1: Debris-filled crevasse trace (aligned perpendicular to the page); 2: water flow creates network of proto-conduits; 3: elliptical phreatic tube; 4: vadose incision of conduit floor towards local base level; 5: incision becomes independent of parent structure, and passage floor stabilizes at base level.

soluble limestone, where water flow and passage enlargement is possible only where a pre-existing, interconnected network of openings links recharge and discharge zones. On debris-covered glaciers, pore spaces between grains in debris-filled crevasse traces linking adjacent lake basins could provide such an interconnected network, allowing sufficient through-flow of water to initiate a positive feedback between passage enlargement and discharge, leading to conduit formation.

Passage evolution

All of the observed conduits exhibited clear evidence of incision along most or all of their length, in the form of canyon-like passage morphologies or slots cut in conduit floors. Such passage morphologies are very common in limestone caves, and represent passage adjustment to local base level under vadose flow conditions, whereby hydraulic potential is determined solely by passage elevation, and downcutting proceeds until hydraulic gradients are eliminated (Palmer, 1991). NG03 provides a very clear example of this process, where the passage morphology records progressive grading to local base level, in this case the supraglacial pond at the efflux point (Fig. 3). However, supraglacial lakes provide inherently unstable base levels, and base-level lowering consequent on lake drainage will trigger renewed downcutting, as demonstrated by the incised floor of level B in NG01 (Fig. 5c). The ultimate base level for each glacier system is determined by the elevation of the outflow stream at the terminus. In the case of Ngozumpa Glacier, base level is at the surface of Spillway Lake, which in turn is controlled by the elevation of the spillway through the terminal moraine. High base levels, either local (basin floors) or for the whole system (moraine crests), will prevent conduits from incising down to the glacier bed, since hydraulic gradients in vadose passages are eliminated when base level is reached.

Passage morphology reflects the interaction between structure, base-level changes and hydrodynamic factors. In some cases, steep-sided canyon-type passages clearly reflect incision through a vertically oriented crevasse trace (e.g. AD01, LH04), but more commonly the lower incised portions of conduits show increasing independence from parent structures (e.g. NG01, NG02). In many of the observed conduits, incision was accompanied by lateral channel migration. Meander migration during conduit incision has, in several cases, undermined higher parts of the system, leading to collapses and the development of large rooms (e.g. NG02). Collapses were also observed in areas of structurally weak ice, i.e. where ice is intersected by numerous debris-filled crevasse traces (NG01). This type of ice apparently originates in heavily crevassed areas, possibly icefalls in the upper ablation zones. A combination of fluvial erosion and gravitational collapses has the potential to open up large voids within the glaciers, which ultimately may initiate surface subsidence such as that described by Benn and others (2001).

There is clear evidence for creep closure of passages in NG01 and NG02, in the form of deformed ice breccias, and opposite walls brought into contact. Significant closure rates may seem surprising, given the shallow depth of the cave systems described here (<40 m in all cases). However, closure may also occur in response to longitudinal or transverse compressive stresses. NG01 and NG02 are located in a part of Ngozumpa Glacier where velocities diminish rapidly down-glacier as ice discharging from high cirques decelerates against the stagnant lower tongue (personal communication from A. Luckman). It is therefore possible that the observed passage closure is mainly in response to longitudinal compressive stresses rather than ice overburden pressure.

Conduit formation and surface topography

Four of the conduits explored in this study intercepted the glacier surface at both ends (NG01, NG02, AD01 and LH04). In the case of AD01, there is likely to have been significant ice-cliff retreat since the conduit was formed, and the relationship between it and the original glacier surface topography is not known. However, the other three conduits clearly were created after the glacier surface attained more or less its present form. NG01 and NG02 extend between adjacent basins on the glacier surface. Conduit formation in this setting is readily understood using a karst-type model of speleogenesis. Large hydraulic potential gradients can occur between surface basins on debris-covered glaciers if they are at different elevations or contain lakes with different surface levels. Where a debris-filled crevasse trace traverses the intervening ice, ideal conditions are created for the development of drainage pathways. If a high-permeability pathway exists between a supraglacial lake and an area of lower hydraulic potential, water will be driven outward away from the lake. Seen in this way, perched supraglacial lakes may, in some cases, be the agents of their own destruction and could drain along conduits that they helped to create, rather than by simply intercepting pre-existing conduits as proposed by Benn and others (2001).

On the highly irregular surfaces of Himalayan debris-covered glaciers, topographic hollows define a complex system of potential sink points, which act as recharge and inception foci for local englacial drainage evolution. Where hydraulically efficient pathways towards such wells follow a structurally deformed crevasse trace or a system of intersecting traces, they may be extremely tortuous and trend across- or even up-glacier for considerable distances, regardless of local ice-surface slope. Thus, gradients in ice pressure exert no discernible influence on englacial water-flow paths at the macroscopic scale. This conclusion is not simply a function of the shallow depths of the observed conduits. Theoretical englacial potential gradients are independent of overburden pressure (e.g. Shreve, 1972). Given the large local ice slopes in the study area (basin margins typically slope at 20–40°), classical theory predicts that near-surface water should always be driven strongly towards basins. The fact that this is not the case reflects the extremely low permeability of intact glacier ice and the necessity of high permeability pathways for effective drainage.

It is clear, though, that conduits do not only develop between adjacent basins. In the case of the conduits explored in Lhotse Glacier, evidence was found for drainage re-routing beneath a former lake basin by a process of bypass. There, water was able to exploit a new, deeper pathway following lake drainage and base-level fall, presumably because steep hydraulic gradients and hydrologically efficient pathways coincided where they had not done so before. Clear evidence for this process in a subaerial setting was provided by the conduits exposed in the basin margins (LH04, Fig. 9c and d). Meltwater routing beneath lake basins has also been described by Benn and others (2001). Between Lake 7093 and NG04 near the western margin of Ngozumpa Glacier (Fig. 2), a large moulin was observed in 1998 and 1999, at the bottom of which rushing water could be heard. This water passed beneath Lakes 7093 and 7092 at a time when both lakes had high levels and were apparently unconnected with the englacial drainage system (both lakes had almost completely drained in 2005). The only possible outlet for this water was a portal near the western end of Spillway Lake near the glacier terminus (Fig. 2), indicating an englacial transport distance of at least 5.6 km. Although little is known about long-distance englacial water transport within debris-covered glaciers, it is likely that marginal locations such as this will provide hydraulically efficient pathways because infilled crevasse traces are likely to be particularly abundant near former shear margins (cf. Stenborg, 1968, 1973), and efficient water flow will likely occur along the interface between the glacier and the flanking moraine.

CONCLUSIONS

The flow paths of shallow englacial conduits on the four debris-covered glaciers investigated are determined by pre-existing lines of high hydraulic conductivity rather than cryostatically determined potential gradients. Debris-filled crevasse traces serve as speleogenetic inception horizons. The direction of water flow is governed by the direction of least-resistive hydraulic potential and not in the direction of steepest hydraulic gradient.

Once initiated, conduits evolve by grading to local base level. Grading is accomplished by headward retreat and downcutting, producing a canyon-like passage morphology. Many of the conduits showed evidence of phreatic to vadose transitions, in the form of upper levels with circular or elliptical cross-sections and canyon-shaped lower levels, indicating that throughout most of their existence passages were at atmospheric pressures.

Channel migration during incision and collapse of structurally weak ice roofs can create large voids within the glaciers. Such voids may develop into centres of surface subsidence if the overlying ice is thin.

Local base level for many conduits is provided by supraglacial lakes occupying basins on the glacier surface. Lake drainage results in a sudden drop in base level, triggering rapid conduit adjustment.

Conduits at different elevations within the ice can have very different base levels, and conduits may pass beneath water bodies to discharge at lower, more distant outlets. The ultimate base level is provided by the elevation of the outlet stream passing over the terminal moraine.

By locally elevating hydraulic potential in basins, supraglacial lakes may help to drive water out through debris-filled crevasse traces to areas of lower potential, such as adjacent basins. Therefore, supraglacial lakes may, in some cases, facilitate their own destruction, rather than simply intercepting existing conduits during growth.

Formation of the englacial conduits described in this paper is analogous in all important respects to speleogenesis in soluble limestones. In both cases, cave inception relies on a continuous and pre-existing hydraulic connection between areas of different potential, which is then exploited and enlarged by water flow. The in situ formation and evolution of subsurface drainage networks in stagnant or near-stagnant debris-covered glaciers is closely similar to that in limestone, and relationships between subsurface hydrology and surface topographic evolution are also closely similar.

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