nature
433, 557–~~656~~ 10 February 2005
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no.7026
npg

10 February 2005
International weekly journal of science

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Fractures as the main pathways of water flow in temperate glaciers

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Understanding the flow of water through the body of a glacier is important, because the spatial distribution of water and the rate of infiltration to the glacier bottom is one control on water storage and pressure, glacier sliding and surging, and the release of glacial outburst floods[1–3]. According to the prevailing hypothesis, this water flow takes place in a network of tubular conduits[4,5]. Here we analyse video images from 48 boreholes drilled into the small Swedish glacier Storglaciären, showing that the glacier's hydrological system is instead dominated by fractures that convey water at slow speeds. We detected hydraulically connected fractures at all depths, including near the glacier bottom. Our observations indicate that fractures provide the main pathways for surface water to reach deep within the glacier, whereas tubular conduits probably form only in special circumstances. A network of hydraulically linked fractures offers a simple explanation for the origin and evolution of the englacial water flow system and its seasonal regeneration. Such a fracture network also explains radar observations that reveal a complex pattern of echoes rather than a system of conduits. Our findings may be important in understanding the catastrophic collapse of ice shelves and rapid hydraulic connection between the surface and bed of an ice sheet.

The prevailing view of englacial water flow through tubular conduits[4,5] is supported by observations of caves on the margins of glaciers and explorations into moulins (a vertical shaft in a glacier)[6]. Whether such features are unique to the margin and to moulins is unclear. Observations in holes drilled to the glacier bed indicate the presence of englacial cavities[7–9], some of which appeared to be conduits. However, the hydraulic characteristics of these cavities were not defined and water movement, when detected, was slow[10], much slower than expected theoretically.

To examine the physical and hydraulic characteristics of englacial water pathways we drilled into Storglaciären, a small ($3\,km^2$) polythermal glacier in Arctic Sweden[11]. The surface cold layer typically does not extend below about 40 m, and the maximum ice depth is 250 m (ref. 12). Using high-pressure hot water we drilled holes, over three seasons (July–August), in the upper part of the ablation zone of the glacier (Fig. 1). Each hole was drilled until we intersected either an efficient hydraulic connection or the glacier bottom. This strategy avoided hydraulic interference resulting from multiple englacial connections within the same hole. Drilling with hot water through impermeable ice causes excess water to flow out of the hole. When the water level drops rapidly in the hole and remains below visual range (~3 m), we presumed that a hydraulically efficient connection was made. A submersible camera imaged the geometry and orientation of the structure at the point of drainage. Tracers (ink, dye, teflon spheres) were injected via a vinyl tube to track fluid motion. In some holes we installed pressure transducers to record changes in water pressure. We also surveyed the subsurface with ice-penetrating radar to detect the presence of englacial features remotely.

Thirty-eight (79%) of our 48 holes intercepted an efficient englacial hydraulic passage and 80 cavities were imaged. Almost half of the holes had multiple cavities of which the uppermost must have been hydraulically isolated or poorly connected because the water level in the holes did not drop when the drill passed through them. We could not discern the geometry of about half of the cavities because the surrounding ice was clear, unlike the bubbly ice elsewhere, and so the walls provided insufficient reflection from the camera lights. Of the remaining 44 cavities, 36 (80%) were fracture-

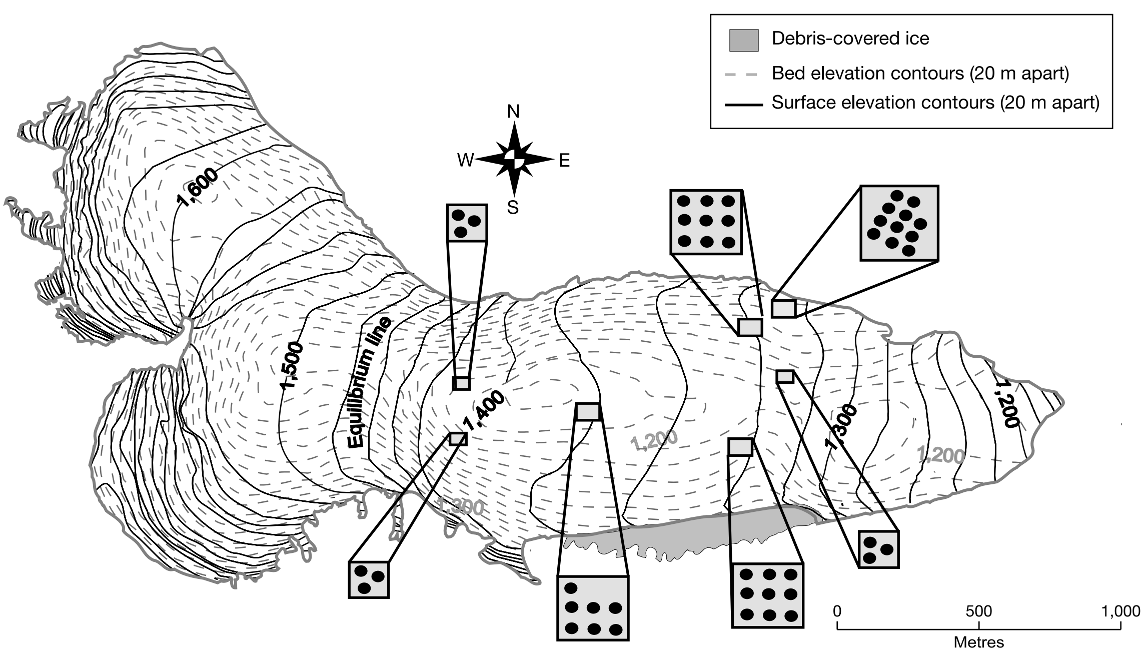

Figure 1 Map of Storglaciären showing the location of the drill sites. Four sites were composed of at least seven holes, each 10 m apart in a grid plan, and three sites were composed of three holes, each ~20 m apart in a triangular plan. All sites were drilled in the over-deepened section of the glacier with the exception of the first set in the upper right.

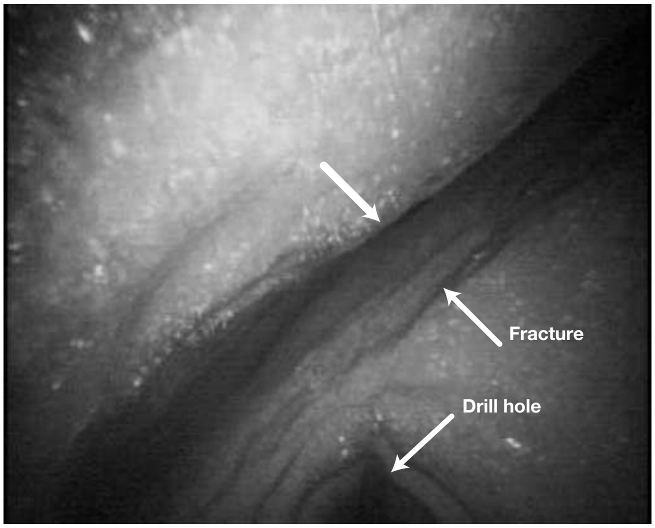

Figure 2 Video image of an englacial fracture. The fracture width is about 4 cm and the continuation of the vertical drill hole is identified. The camera is tilted obliquely downward towards the fracture.

like features, two (4%) were circular in cross-section and the remaining six (16%) were amorphous and appeared to be the intersections of multiple fractures.

The fracture-like features had near-vertical (~70°) subparallel walls (Fig. 2). Also, we made multiple drillings into the same feature over a horizontal distance of several metres and found a similar steep dip. All of these features appear identical to images taken in water-filled surface crevasses. Therefore, we consider them to be englacial fractures. Fractures were detected at depths from near the surface to 96% of the local glacier thickness; the deepest observed fracture was 131 m below the surface. Fracture orientation (strike) was generally parallel to strain-related features within the surface structure of Storglaciären including clear ice bands inferred to be refrozen crevasses[7,8]. A few strikes, particularly those at depth, were rotated tens of degrees and whether this represents a different structural control at depth or conjugate fractures is unclear. The width of fracture openings varied from 0.3 to 20 cm with a median of 4 cm and did not correlate with depth. These widths are maximum values because the openings must have been enlarged as the warm drill water drained into the fractures. Over distances of ~100 m the hydraulic gradient in the fracture system mirrors that of the surface slope of the glacier.

Water flow was observed in only ten fractures. Flow speeds were measured from particles moving past the camera view and from tracer tests between adjacent holes. They ranged from 0.5 to 4 cm s^{-1}, with typical speeds of 1–2 cm s^{-1}. These speeds are slow compared to expectations from models of flow in tubular conduits[4,5]. Reynolds numbers indicate that the flow is laminar. Sometimes holes 10–20 m apart were hydraulically connected via the fractures, as indicated by tracers leaking from one hole to another or by pumping water into one hole and observing a water level response in another. In one case, the connection depth in a pair of holes differed by 91 m. A flow test between holes, where water was pumped into one hole creating a constant head difference between holes, showed that the measured flow speed was 1% of that predicted on the basis of laminar flow between parallel plates. For the majority of fractures, which showed no observable flow, either flow speeds were below detection, or the fractures were side passages to the main flow routes.

After drilling 47 holes and not intersecting any tubular conduits, we searched in a field of moulins, where conduits are known to occur. At a depth of 42 m we intersected a conduit with a diameter of 10 cm and a water flow speed of ~10 cm s^{-1}. This feature was the only 'traditional' conduit found. It appeared to be gently sloping with an orientation parallel to the strike of nearby surface crevasses, which were perpendicular to the direction of ice flow.

To detect englacial cavities remotely we completed 247 radar (50 and 100 MHz) profiles covering ~25 km of surface travel. The profiles formed a series of closely spaced grids over the drill holes. As expected, the profiles showed a myriad of englacial echoes typical of radar surveys in temperate ice[13–15]. Although elongated echoes are not common in temperate ice, they are observed occasionally[16] and

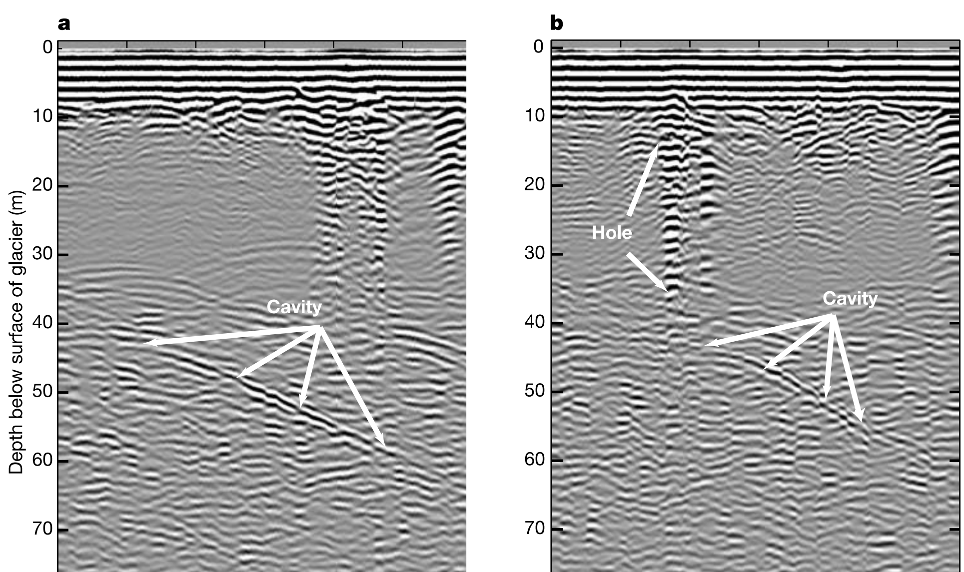

Figure 3 Radar (50-Mhz) reflections from the glacier interior showing a dipping reflector before and after drilling. **a**, The radar reflections before drilling with a hot water drill; **b**, the reflections after intersecting the top of the reflector at a depth of 38 m near a distance of 18 m. The reflector, inferred to be a fracture, dips to the north (right), with the strongest reflection between depths of ~40 and ~55 m.

we found a few on Storglaciären. One prominent dipping reflector was explored (Fig. 3). It originated at ~40 m depth and was ~20 m long when projected onto the glacier surface. We drilled to the inferred feature and intersected a hydraulically connected fracture at 38 m depth (Fig. 3b). The hole did not intersect the brightest segment of the fracture but probably encountered the upper part, which is not well depicted by the radar. The camera imaged a fracture, ~4 cm wide, dipping in the same direction as indicated by the radar.

The drilling and radar results point to copious water-filled cavities within temperate ice. Images showed that 80% of these cavities were steeply dipping fractures, most of which were hydraulically connected, forming an englacial hydraulic system. Although a few englacial fractures have been observed previously[7,10], we show here that they are ubiquitous and form an integrated hydrological network. The general absence of tubular conduits is surprising. Although one could argue that the probability of intersecting conduits with a drill is small[10] compared to the probability of intersecting a planar fracture, even a steeply dipping one, the ubiquitous presence of hydraulically connected fractures is undeniable. Our results support previous work that suggests an englacial hydraulic system that is not dominated by tubular conduits[17].

The presence of a network of hydraulically connected fractures may resolve several important questions in glacier hydrology. First, it has been unclear how tubular conduits form and how surface water is routed into them. In our view, surface crevasses provide ready entry[3,18] and a crevasse that is nearly filled with water can propagate to significant depths and perhaps to the bottom of the glacier[19,20]. Second, it was not clear how conduits survive a winter of closure and deformation due to ice shear, eventually to regenerate the following spring with the onset of melt[21]. Fracturing resolves both issues because it is a continuous process that generates passageways through the ice. Likewise, a ubiquitous fracture network helps to explain the often puzzling behaviour of water levels observed in many holes drilled all the way down to the bed that do not clearly correspond to diurnal surface forcing or the basal response[17,22]. It seems likely that these holes inadvertently established multiple hydraulic connections between englacial and subglacial systems, and the variations in water level are the result of interacting systems. Consequently, water level variations in such holes provide dubious information about subglacial water pressures[22,23]. Finally, the myriad of echoes detected by radar surveys, rather than the bright and elongated reflector expected from a water-filled conduit[16], probably originate as reflections from fractures that overlie echoes from other fractures.

Our results are generally applicable to other glaciers. Although most of our holes were drilled in the gently sloping over-deepened part of Storglaciären, our first set of holes was drilled along the glacier margin where the surface slopes steeply towards the valley wall. Observations of fractures in this first set were no different from those in holes in the over-deepened section and therefore no influence of glacier slope or depth can be detected. Also we reviewed video tapes from holes drilled during a previous project on Kennicott glacier, a temperate glacier in southern Alaska[24]. These holes also terminated englacially, intersected fractures, and were hydraulically connected. We conclude that fracture networks are common on temperate and polythermal glaciers and are probably not confined to any one region within a glacier. We infer that englacial fractures will also be common in the accumulation zone of glaciers.

The origin of englacial fractures is unclear but advection of surface crevasses[25] and *in situ* generation are possible mechanisms. *In situ* generation was observed at Bench glacier (Alaska) when an englacial fracture appeared in a hole wall, at 137 m depth, during a 10-day interval between observations (J. Harper, personal communication). Hydraulic linkages between fractures may develop as new fractures intersect relic, water-filled ones to form continuous water pathways. Because of the slow water speed, viscous shear heating and melting of fracture walls should not play a significant role in controlling water flow. Consequently, the hydraulics of englacial water flow in a fracture-dominated glacier will differ from expectations based on flow in conduits.

Tubular conduits probably develop in special circumstances where the water flux is sufficiently large to initiate shear heating and melting of the fracture walls. A surface stream discharging into a crevasse might create such conditions. Localized flow enhancement develops at the expense of flow elsewhere in the fracture, resulting in conduit formation. This process of destabilizing a fracture network to form a conduit may be analogous to that for destabilizing sheet flow at the base of a glacier in favour of conduits[26]. Other fractures will drain to conduits where they intersect.

The hypothesis of fracture networks in glaciers may be important in understanding other glaciological phenomena such as the catastrophic collapse of ice shelves[27] and rapid hydraulic connection (and dynamic response) between the surface and bed of an ice sheet[28]. □

Received 11 May; accepted 13 December 2004; doi:10.1038/nature03296.

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Supplementary Information accompanies the paper on **www.nature.com/nature**.

Acknowledgements We thank S. Frödin-Nyman, M. Nyman, R. Pettersson, and R. Hock. J. Walder and R. LeB. Hooke provided suggestions during the preparation of this manuscript. This work was supported by the Arctic Natural Sciences Section within the Office of Polar Programs of the US National Science Foundation. P.J.'s participation was funded by the Swedish Research Council. The Stockholm University, Tarfala Research Station provided excellent facilities and field assistance.

Competing interests statement The authors declare that they have no competing financial interests.

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Abrupt rise in atmospheric CO_2 overestimates community response in a model plant–soil system

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Attempts to understand the ecological effect of increasing atmospheric CO_2 concentration, [CO_2], usually involve exposing today's ecosystems to expected future [CO_2] levels[1,2]. However, a major assumption of these approaches has not been tested—that exposing ecosystems to a single-step increase in [CO_2] will yield similar responses to those of a gradual increase over several decades[3]. We tested this assumption on a mycorrhizal fungal community over a period of six years. [CO_2] was either increased abruptly, as is typical of most [CO_2] experiments, or more gradually over 21 generations. The two approaches resulted in different structural and functional community responses to increased [CO_2]. Some fungi were sensitive to the carbon pulse of the abrupt [CO_2] treatment. This resulted in an immediate decline in fungal species richness and a significant change in mycorrhizal functioning. The magnitude of changes in fungal diversity and functioning in response to gradually increasing [CO_2] was smaller, and not significantly different to those with ambient [CO_2]. Our results suggest that studies may overestimate some community responses to increasing [CO_2] because biota may be sensitive to ecosystem changes that occur as a result of abrupt increases.

A major goal in climate change research is to predict the structure and functioning of ecological systems at a future date when the climate will be significantly different from that of today[4]. For example, atmospheric [CO_2] is expected to continue rising during the next century to concentrations of 550 p.p.m. or more[4]. A major research effort is under way to understand the changes that will occur in population, community and ecosystem structure and function in response to this increase in [CO_2][5].

A typical experimental approach used to predict the ecological effect is to expose current ecosystems to ambient and elevated atmospheric [CO_2] and compare the responses[1,2,5]. A major assumption in such [CO_2] experiments is that exposing today's ecosystems to an abrupt increase in [CO_2] will yield structural and functional responses similar to those that would be observed by exposing the same ecosystems to a gradual increase of the same magnitude over several decades. There is evidence that plants undergo microevolutionary changes in response to elevated [CO_2][6,7], and that there are compositional changes in communities[5,6]. Many organisms, especially those that grow quickly, will have gone through many generations, each one exposed to an incrementally higher [CO_2]. Subjecting organisms to a step increase in [CO_2] may exert a selective pressure on biota very different from the selective pressure exerted when each generation is subjected to an incrementally increased [CO_2]. Theory indicates that gradual increases in [CO_2] over many generations may elicit responses that are different from those following abrupt increases[3]. However, experimental support for this claim has been lacking.

Using a model experimental system, we tested the hypothesis that biodiversity and function would respond differently depending on whether a community is exposed to an abrupt or a gradual increase in [CO_2]. The arbuscular mycorrhizal symbiosis is ideal for testing this hypothesis for two main reasons. First, arbuscular mycorrhizal fungi (AMF) are affected indirectly by elevated atmospheric [CO_2], responding to changes in plant physiology and growth[8–10]. These fungi are obligate biotrophs that are intimately associated with plant roots and depend directly on plant photosynthate as a source of carbon[11,12]. Increasing atmospheric [CO_2] often results in increased allocation of carbon to roots. This increased carbon availability can influence microbial interactions in the rhizosphere and the structure of the AMF community[8,13–15]. Second, AMF and many of their plant hosts grow and reproduce quickly. This allows us to study the responses of several generations over a reasonably short period of time.

The experiment was conducted using *Bromus inermis* (a perennial C3 grass) and its associated mycorrhizal community from the Long-Term Mycorrhiza Research Site in Guelph, Ontario, Canada[16]. *B. inermis* was chosen because it is a common plant at the site, shows significant growth responses when associated with AMF[16], and preliminary studies have demonstrated that the plant significantly increases its dependency on AMF for growth in an elevated atmospheric [CO_2] environment (data not shown). Plants and fungi were grown for 21 generations, each generation lasting 15 weeks (about 6 yr in total). Plants were subjected to one of three treatments: (1) 350 p.p.m. [CO_2] at each generation (here referred to as 'ambient'); (2) 550 p.p.m. [CO_2] at each generation (here referred to as 'abrupt'); or (3) 350 p.p.m. [CO_2] at the first generation, increasing by 10 p.p.m. at each subsequent generation, with the final generation exposed to 550 p.p.m. (here referred to as 'gradual') (see Methods for more details).

After each generation we determined the biodiversity and functioning of the resulting fungal community. For biodiversity, we identified AMF taxa following a trap-culture bioassay and determined AMF species richness. For functioning, we determined the ability of the AMF community to influence plant biomass. On the first and final generations, we also measured a number of other variables that are highly influenced by AMF, including the concentration of phosphorus in plant tissue, [P], root length, per cent mycorrhizal colonization, mycelium production, and soil aggregate size distribution and aggregate water stability (both measures of soil aggregation).

We did not find any evidence of plant genotype selection over the course of the experiment. We grew seedlings from all generations in a common environment (on a field-collected soil under greenhouse conditions) and did not observe significant differences in gross photosynthesis rates, above- or below-ground plant biomass, or their mycorrhization (data not shown). Furthermore, measures of plant photosynthesis under 550 p.p.m. [CO_2] did not differ between gradual and abrupt treatments (data not shown). However, we did observe significantly higher below-ground plant production in the abrupt treatment, which suggests that the plants were responding to changes in the soil environment. The plants were most probably responding to changes in the composition of the mycorrhizal