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NEWSLETTER FOR THE

Canadian Antarctic Research Network

Inside

IPY Antarctic University Expedition: February 2009

Luke Copland

In early 2009, Students on Ice (SOI) will run the first ever ship-based university expedition dedicated to Antarctica. It will provide an incredible opportunity for students to earn course credits in one of the remotest and most exceptional places on Earth. Officially endorsed by the International Polar Year (IPY), the expedition represents one of its largest education and outreach initiatives. It will comprise approximately 70 university students, together with 19 faculty, scientists, experts and educators. Most of the students are undergraduates from Canadian universities, although several international and graduate students will also participate. The theme is 'Environmental Leadership' and the program will explore the history, science and politics of Antarctica. One of the main objectives is to provide students an opportunity to bridge the gap between theory and practice by providing experiential learning and field experience, and a firsthand experience of the effects of climate change.

All students are required to participate in one of three accredited courses being offered onboard. *Practical Study in Earth and Atmospheric Science* (EAS429), offered by the University of Alberta, is led Dr Marianne Douglas, director of the Canadian Circumpolar Institute. It will address areas such as the Antarctic Treaty System, evolution of Southern Ocean circulation, Antarctic climate and tectonic evolution of the Antarctic continent, as well as some basic oceanography. *Glaciology* (GEG4100), from the University of Ottawa, is led by Dr Luke Copland. It will review all topics related to the Antarctic cryosphere, such as sea ice, ice shelves, ice streams and the Antarctic ice sheet. *Antarctic Tourism* (ORTM433), from the University of Northern British Columbia, taught by Dr Pat Maher, will provide an in-depth examination of the environmental, social and economic impacts of Antarctic tourism. Faculty members from other universities will also participate to help develop a long-term strategy and program for future university expeditions to the Arctic and Antarctic.

Expedition members will depart Canada February 12, 2009, spending a couple of days undergoing orientation in Ushuaia and Tierra del Fuego National Park, Argentina, before boarding the M/V *Ushuaia* on February 16. This ice-strengthened ship has been chartered exclusively for the expedition, and includes dedicated lecture rooms and lab space for teaching. Students will spend the next 10 days onboard the M/V *Ushuaia* while it crosses from South America to the South Shetland Islands and the Antarctic Peninsula. Once in Antarctica, several shore landings per day will be made with zodiacs to locations such as Elephant Island, Whaler's Bay and Neko Harbour. Stops will also be made at the Argentinean Esperanza Station and the Uruguayan Vernadsky Station. Shore visits will provide direct hands-on experience of features of the Antarctic environment such as ice shelves, glaciers, penguins and seals, and complement the lectures given onboard. More information about the program and expedition details can be found at www.uantarctic.org/.

SOI has been running ship-based expeditions to the Arctic and Antarctic since 2000 for high school students, but this is the first time that they have organized a university trip. SOI was founded by Geoff Green, who has undertaken over 100 expeditions to the polar regions and has received numerous environmental, leadership and educational awards. Anyone interested in participating in future expeditions should make contact through www.studentsonice.com.

Luke Copland (luke.copland@uottawa.ca).

Aridity Today and Floods of Yesterday

John Shaw

Wright Dry Valley

Less than 50 mm w.e. of snow falls over most of Antarctica, the coldest and driest continent, and measurements by New Zealand scientists suggest that as little as 8 mm w.e. falls on some Alpine glaciers in the McMurdo Dry Valleys. There is little melting over Antarctic ice sheets; sublimation removes much ice and the wind blows snow to the Southern Ocean – outlet glaciers and fast-flowing ice streams calve icebergs into the ocean. Consequently, little liquid water nourishes meagre rivers. The longest river in Antarctica, the Onyx, runs inland along the Wright Valley, one of the McMurdo Dry Valleys (Fig. 1) from Wright Lower Glacier to Lake Vanda, a distance of about 40 km. Onyx River reaches a width of about 10 m and a depth of 0.5 m at its deepest. Flow lasts from the

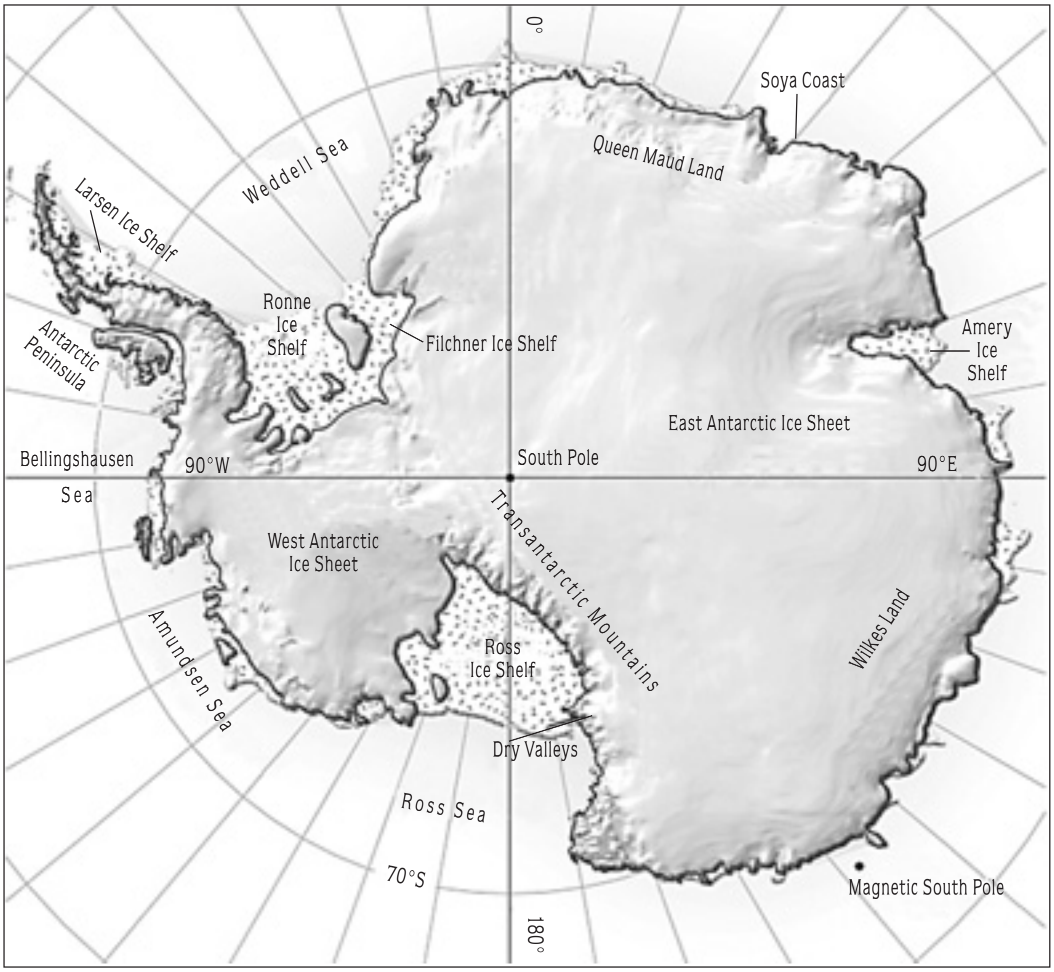


Figure 1
Location map. Cartography Hugo Ahlenius UNEP–GRID-Arendal.

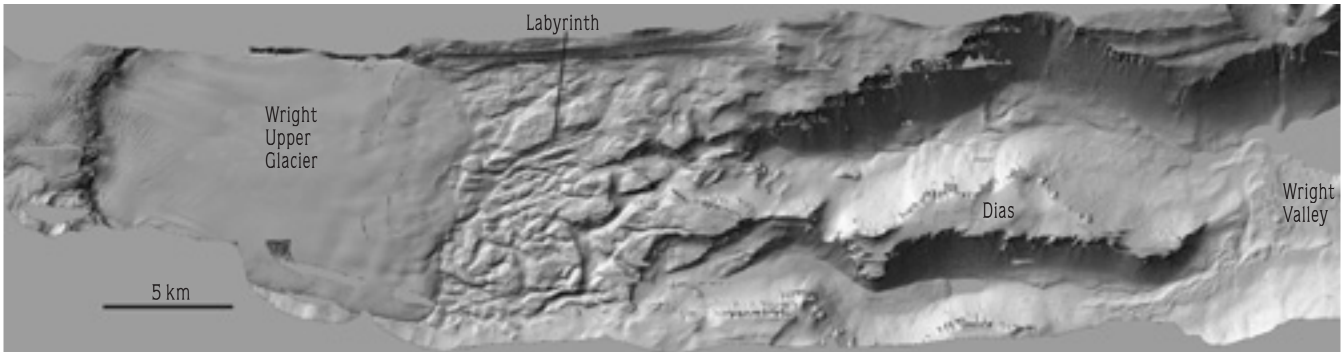
beginning of December to the end of February with maximum annual discharges of about 1 m^3s^{-1}.

This extreme aridity has prevailed for perhaps millions of years, though, at times, the Wright Valley carried great floods, equal to the flow in all the world's rivers. Evidence for these floods lies in the channeled landscape in the western part of the valley, which might have been imported from Mars. A complex network of channels completely unrelated to modern conditions makes up the so-called Labyrinth. Perhaps the name is misleading because the channels are not arranged in the designed pattern of the Cretan Labyrinth at Knossos, but both the Antarctic and Greek labyrinths belong in the realm of myth.

The Labyrinth

Landscape

The floor of Wright Valley rises abruptly in a prominent step to the west of the Onyx River and Lake Vanda in the Dry Valleys (Fig. 1). The landscape changes dramatically at the step from a smooth-sided valley to a rugged topography in hard igneous rock (Fig. 2). Deep and broad channels, bounded by steep cliffs, dissect an ancient valley floor as though a hundred miniature Grand Canyons were eroded simultaneously (Fig. 3a and b). Fractured blocks of rock balanced precariously on fractured cliffs topple and fall onto the scree below. More effective mechanical weathering on north-facing cliffs



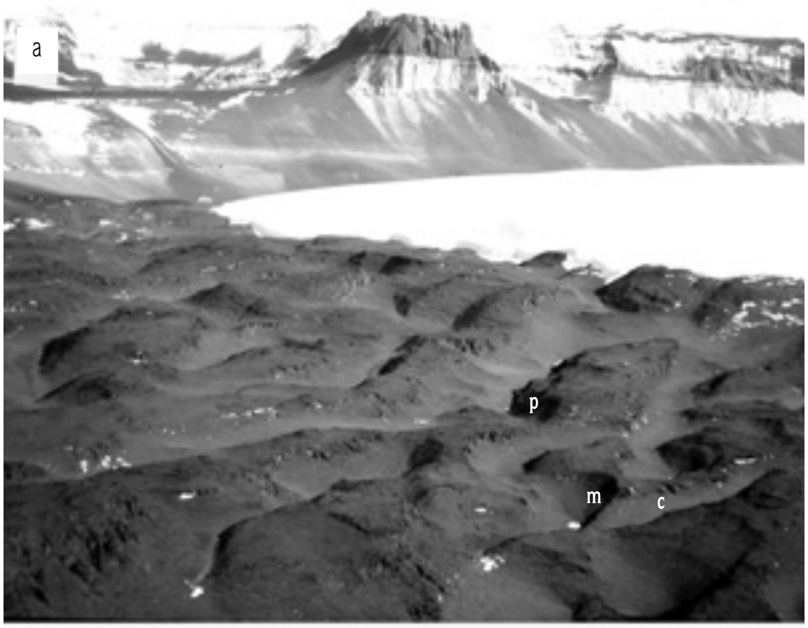


Figure 2
Shaded relief map of the Labyrinth, Wright Dry Valley, from a digital elevation model. NASA survey mission of the Dry Valleys. Post processing by Ohio State and Brown Universities. Courtesy of Adam Lewis.

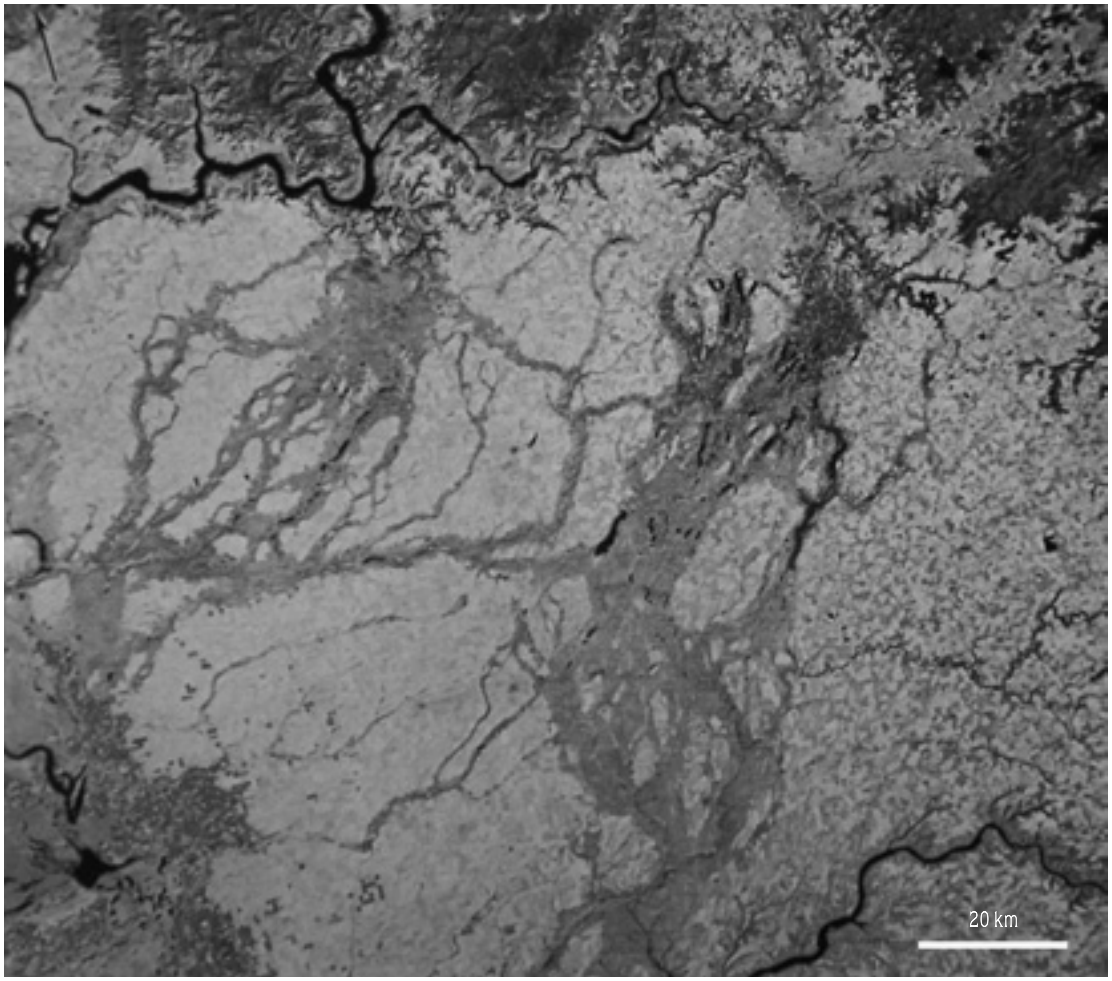
Figure 3
The Labyrinth: (a) west towards Wright Upper Glacier and Transantarctic Mountains (p = pothole, c = channel, m = muschlebruche [erosional mark or s-form with sharp, upstream rims]), note discontinuous channels; (b) east towards the Dias and Wright Valley, channels are deeper than in (a). Near vertical cliffs signify jointed dolerite and toppling of joint blocks. High screes reflect antiquity.

records higher frequency freeze-thaw cycles than for cliffs with a southern aspect. Consequently, higher screes accumulate beneath north-facing cliffs.

Geomorphology and Process

At the eastern end of the Labyrinth, flow which eroded the channels divided and plunged steeply over what must have been two enormous waterfalls, leaving the Dias as an upstanding residual (Fig. 3b). Deeper and wider eastern channels dwarf those to the west – the largest channel is

Figure 4
Landsat image of Washington Channeled Scablands with two prominent anastomosing flood tracts.



about 600 m wide and 250 m deep. Deeper channels to the west probably reflect erosion in steep reaches above the drop to the lower valley. Anastomosing channels divide and rejoin in complex patterns and, unlike normal stream channels, junctions are commonly discordant: the floor of one channel hangs above the floor of another. Discordant junctions arise where one channel erodes faster than the other, and the water level is about the same in the two channels. In this situation, the higher channel does not have the advantage of a steeper slope because there is no enhanced water-surface slope at the junction. Blind channels end abruptly and do not connect with other channels (Fig. 3a); the eroding flows abandon the channels by rising into overriding sheet flows which inundate interfluves. Thus, blind channels were submerged in a broad flow. Powerful vortices scoured potholes as much as 30 m deep at channel junctions and on channel interfluves (Figs 3a and b). Potholes on interfluves and blind channels give evidence that large parts of the landscape were inundated. Evidence from relic waterfalls to the east and s-forms (erosional bedforms in rock) on interfluves, establishes flow from west to east. Thus, valleys sloping upwards to the east have reverse gradients, others have undulating long-profiles, and both require pressurized flow.

Floods and Flood Routes

Extreme erosion excavated valleys and potholes and powerful currents transported boulders of Beacon Sandstone up to 3 m

Figure 5
Dry Falls, Washington Channeled Scablands. The falls are about 110 m high. Maximum flow probably completely submerged the falls, producing a slight steepening of the water surface.

in diameter. As well, meltwater sculpted parabolic, streamlined bedforms from dolerite on extensive interfluves. These streamlined landforms resemble sculpted erosional forms in Canada resulting from erosion of rock by powerful meltwater currents. Thus, abundant evidence points to powerful flow over the interfluves as well as through the channels.

To the west of the Labyrinth, the Upper Wright Glacier sweeps down from the East Antarctic Plateau and through a broad gap in the Transantarctic Mountains (Fig. 2). Cataclysmic flows that eroded the Labyrinth must have followed a similar route.

The Channeled Scablands

The Labyrinth records one of Earth's most spectacular erosional episodes, and we might still be at a loss to explain the steep-sided valleys, potholes, erosional marks and giant waterfalls were it not for a remarkable, parallel landscape in the Channeled Scablands of Washington State, USA (Figs 4 and 5). From the early 1920s to the 1950s, J Harlen Bretz compiled a wealth of evidence from the Scablands supporting his hypothesis that cataclysmic floods scoured coulees, relic waterfalls, split by long dividing ridges, streamlined hills, buttes and basins, with potholes tens of metres across, and giant ripples (Bretz, 1969). But, geology had long moved away from catastrophism, and landforms were explained by gradual processes acting over a long time – a misapplication of the uniformitarian principle. Bretz was not popular when he argued that the sheer scale of the Scabland landforms demanded flows of enormous magnitude (~10^6 m^3s^{-1}). For those unable to visualize regional landscapes, satellite images now allow easy appreciation of the extent of these floods (Fig. 4).

Bretz's outrageous proposal raised the ire of eminent members of the American geological community who lambasted him at every opportunity. Even with the discovery of Glacial Lake Missoula, the flood source, opposition continued unabated, and many of his detractors remained unconvinced for the rest of their lives. Following a remarkable conversion in 1962 of a group of Quaternary scientists on a field trip organized as part of an International Association for Quaternary Research conference, almost everyone with a background in geomorphology came away from the Scablands enthralled by megafloods. The conference participants sent him a famous telegram, "We are all catastrophists now." Fortunately, he lived long enough to enjoy his success with the satisfaction that he had outlived his detractors.

Linking the Scablands and the Labyrinth

A skeptic accompanying Bretz on a 1952 Scabland field excursion was Harold Theodore Uhr Smith; he became thoroughly convinced of cataclysmic floods. In a couple of pages, illustrated by a spectacular oblique photograph, Smith (1965) eloquently explained the Labyrinth as a scabland, though with some significant differences. The valleys of the Labyrinth are the coulees of the Scablands, and its water-sculpted rocks are the streamlined hills of the Scablands. The two landscapes have giant waterfalls in common. Though deposition created giant ripples in the Scablands, erosion sculpted similar ripple forms in bedrock on the floor of the Wright Valley, downflow from the Labyrinth. But, while the Scablands floods had an obvious source in Glacial Lake Missoula, an ice-dammed lake with a volume about 2100 km^3, no location exists for a similar subaerial lake source for Labyrinth floods – the Labyrinth lies too close to the Transantarctic Mountains divide and the East Antarctic ice sheet.

Water Source for Labyrinth Floods

Discordant junctions, blind valleys, channels with reversed gradients and undulating long profiles point to enormous floods; indicating subglacial flow under hydrostatic pressure. Water beneath the Wright Valley Glacier, under extreme pressure gradients, must have eroded the Labyrinth channels. But, with inadequate room for water storage between the Labyrinth and the Transantarctic Mountains to the west, the reservoir probably lay beneath the East Antarctic ice sheet, with cataclysmic flooding along the path of the modern Wright Upper Glacier. The Wright Valley is not unique in this respect; other floods crossed the Transantarctic Mountains and quarried scablands to the north.

In 1965, when Smith wrote of the Labyrinth, Antarctic scientists knew of only a few, poorly understood, subglacial lakes, and Bretz's ideas had only recently been accepted. As a student at the time in the United Kingdom, I knew nothing of the Scablands or the Labyrinth, and even by 1976, the most prominent British textbook on glacial geomorphology did not mention them. Although he did not realize it, Smith's observations and reasoning pointed to very large, unstable meltwater lakes beneath ice sheets. Today, Robin Bell (2008) reports on a multitude of lakes beneath the modern Antarctic ice sheets and ice streams some of which drain suddenly from one to another. Undoubtedly, drainage from much larger lakes eroded the Labyrinth. These larger lakes might well return.

Flow Magnitude and Age of Labyrinth Floods

What was the rate of water flow in the Labyrinth, and when were the floods? Flood peaks probably submerged the large valleys, although they might not have been fully formed at the time of inundation. A similar argument applies to the anastomosing Scablands channels. From estimates of flow cross-sections, assuming full channels, and the velocity required to transport the largest boulders in the channels, Adam Lewis and others (2006) calculated water discharge at $1.6 - 2.2 \times 10^6$ m^3s^{-1}, well within the range of estimates for Scablands floods.

Argon dating of sanidine, a mineral found in volcanic ash on channel floors, gives a minimum age around the middle of the Miocene Epoch, about 12 Ma before present (Lewis and others, 2006).

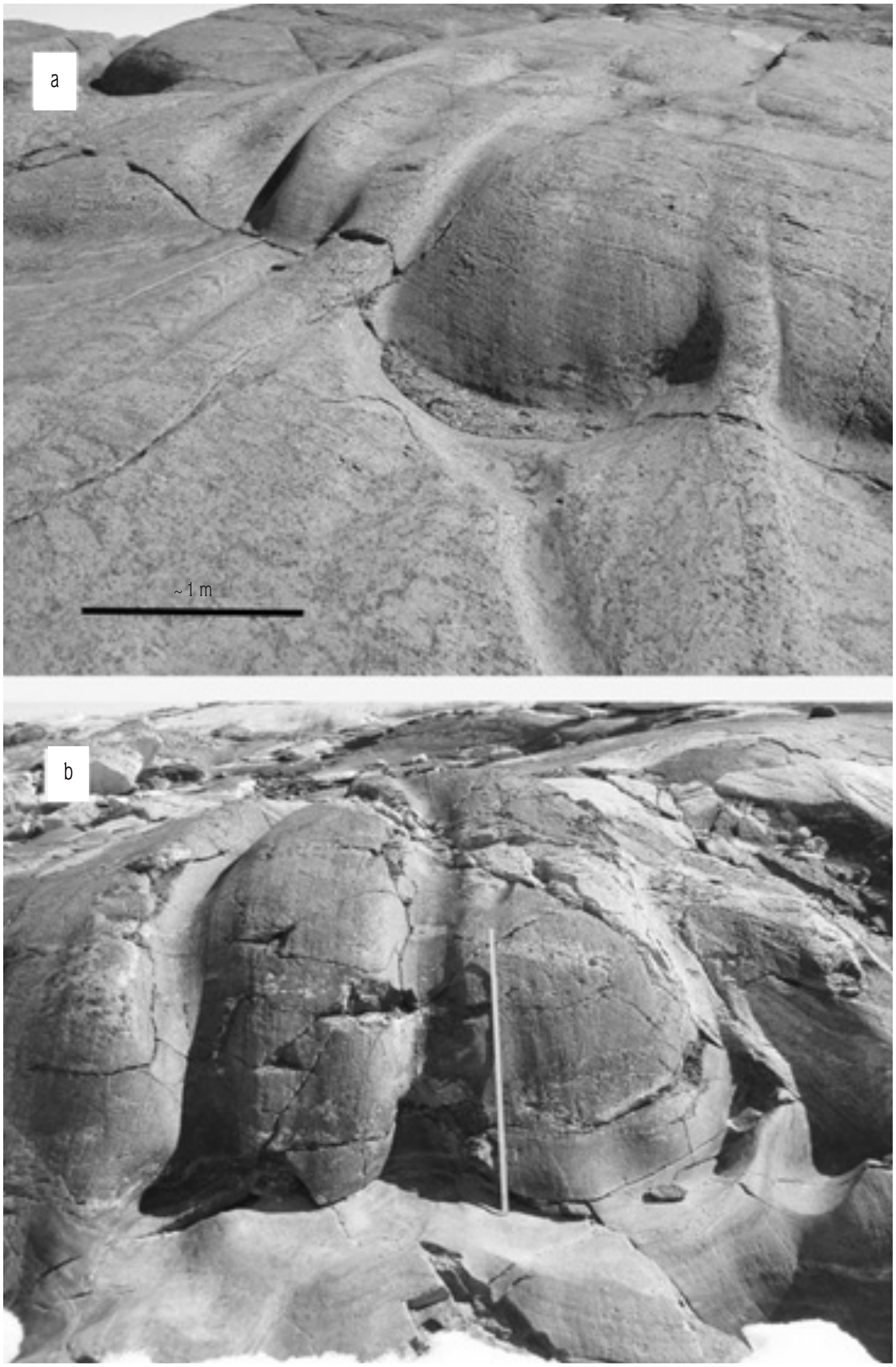
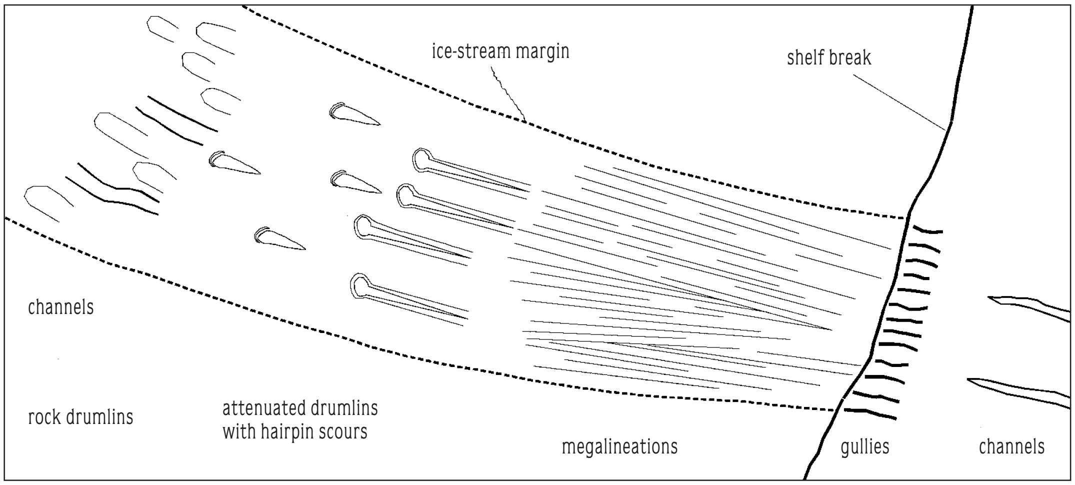


Figure 6
Meltwater erosional marks (s-forms) resulting from sheet floods beneath the East Antarctic ice sheet, Soya Coast, Antarctica. Flow away from viewer. Both images show crescentic scours related to vortex generation around the upstream side of bedrock obstacles. Courtesy of Takanobu Sawagaki.

Figure 7
Geomorphology of shelf-crossing troughs.



Soya Coast

Sculpted Rock (s-forms) and Floods

Is there evidence for other Antarctic megafloods? Takanobu Sawagaki and Kazuomi Hirakawa (1997) found intricately sculpted rock surfaces scoured by high velocity meltwater flow along the Soya Coast (Figs 1 and 6). These surfaces show the same crescentic scours, asymmetric depressions, comma forms, potholes and rock drumlins (s-forms) as the water-eroded rock on granite and gneiss of the Canadian Shield. They lie at the margin of the East Antarctic ice sheet and record meltwater flows crossing bedrock hills over 300 m high. Because the flows crossed such high relief, they required subglacial discharge under high pressure. Minimum width for the sheet flows that eroded the Soya Coast bedrock is on the order 80 km, and by comparison with Canadian flows over sculpted rock, discharge estimates of 10^6 m^3s^{-1} approximate discharges for subglacial flows in the Scablands and the Labyrinth. It goes without saying that subglacial, steady-state geothermal heat supply and pressure melting or supraglacial melting cannot supply discharges of this magnitude. Therefore, Sawagaki and Hirakawa concluded that meltwater released from very large lakes beneath the East Antarctic ice sheet eroded bedrock along the Soya Coast.

Some subglacial floods beneath the Antarctic ice sheet were almost certainly ancient – the Labyrinth originated in the Miocene. Heavily weathered dolerite and extensive scree slopes rising against canyon cliffs dissected by steep chimneys reflect this great antiquity. However, much less-weathered surfaces along the Soya Coast witness younger erosional events – long periods of weathering remove delicate erosional marks. Sawagaki and Hirakawa suggested outburst floods at approximately the time of the Last Glacial Maximum (LGM), about 15 ka before present.

The Continental Shelf

Research Background

Research on the Antarctic continental shelf, particularly west of the Antarctic Peninsula (Fig. 1), reveals a fascinating and repeated pattern of erosional forms associated with deep, shelf-crossing troughs (Fig. 7). Swath bathymetry, by which multiple sonar beams provide a bathymetric grid of the sea floor, made this research possible. Reconstructions, in the form of relief-shaded maps, present striking, photo-like images of the seascape (Figs 8 and 9). Bathymetric images capture broad swaths of bedforms on the sea floor which allows mapping with unprecedented detail. Technological advances foster intellectual progress and discovery.

Inner, middle and outer sections subdivide shelf-crossing troughs tens of kilometres wide, hundreds of kilometres long and up to 1000 m deep. The seabed rises towards trough

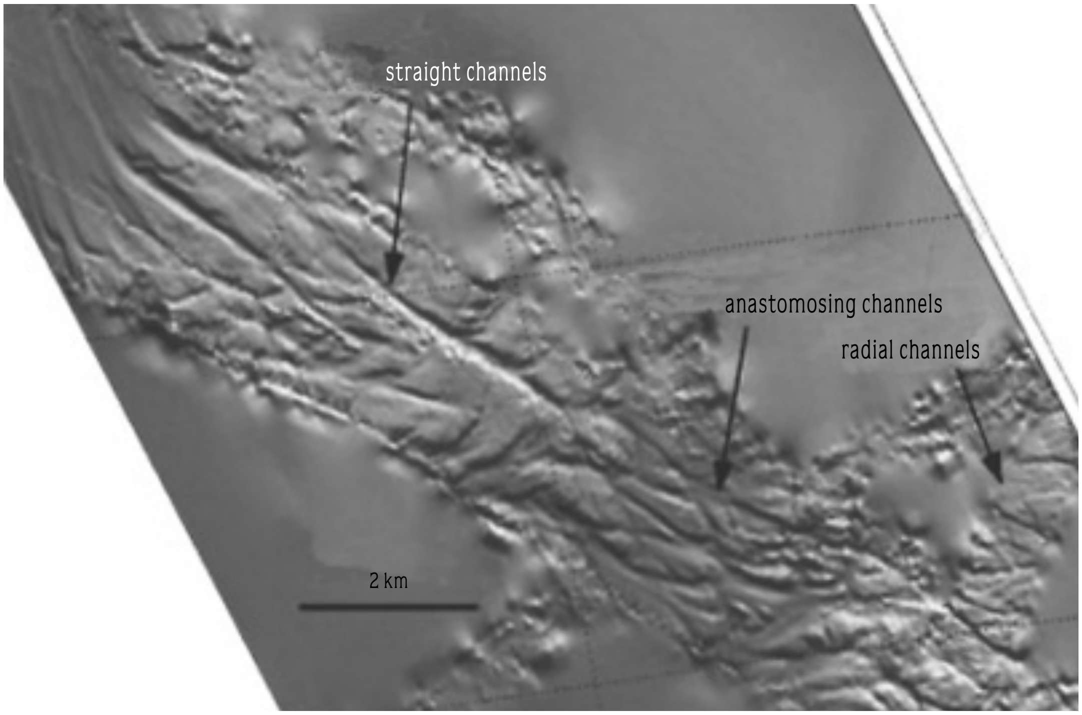


Figure 8
Swath bathymetry image of a channeled scabland at the onset of a paleo-ice stream in Maguerite Bay (Anderson and Fretwell, 2008). Courtesy of John Anderson.

mouths. Deep basins scoured in resistant bedrock occupy the onset zones of former ice streams in some troughs.

Inner Shelf Channeled Scabland

Crystalline bedrock, which underlies inner shelves, produces a rugged seascape with plateaux and deep channels – a scabland identical to the Channeled Scablands and the Labyrinth (Fig. 8). Ashley Lowe and John Anderson (2003) described one channel 2.5 km wide and 400 m deep – much larger than Scabland and Labyrinth channels. Blind, shelf channels have no outlet, and the long profiles of other channels undulate. Many channels anastomose in complex patterns, with discordant, hanging anabranches. Lowe and Anderson reported meltwater-sculpted s-forms (they referred to these erosional marks as p-forms – plastically moulded, though I prefer s-form – sculpted) on bedrock interfluves. Clearly, for the reasons given regarding Labyrinth flows, floods submerged these large channels.

The seascape of the inner shelf bears witness to large meltwater events. Under similar conditions as those for excavation of the Labyrinth, meltwater dissected hard bedrock, scouring channels on the inner shelf. Undulating long profiles of some channels mark pressurized, subglacial flow. Many inner shelf tunnel channels dwarf Labyrinth and Scablands channels and probably carried equal if not greater discharges – conservatively estimated at ~10^6 m^3s^{-1}. Lowe and Anderson realized the possibility of such extreme flows and suggested abundant meltwater beneath a paleo-ice stream in the Pine Island Bay trough.

Drumlins on the Inner and Middle Shelves

Drumlins (streamlined bedforms commonly with blunt upstream ends and tapered tails) are one of the most easily recognized landforms, but one of the most difficult to explain. The drumlin problem, which has thwarted many famous scientists, continues to be thorny. It may be that Antarctic shelf bedforms, with their fine resolution on swath bathymetric images and clear glaciological context, hold the key to understanding these enigmatic streamlined hills. This possibility attracted André Pugin, of the Geological Survey of

Canada, Robert Young, from the University of British Columbia, and me to Antarctic seascapes. Until very recently, the leading explanations for drumlin formation came from ideas on deformation of sediment beneath ice streams and erosion of the bed by meltwater outburst floods. However, Tom Bradwell and others (2008) demonstrated that drumlin genesis by deformation is an unlikely general theory because bedrock composes many drumlins in northwest Scotland. They suggested abrasion by ice as an alternative formative mechanism. But this implies that drumlins with the same form result from deformation in soft sediment and from abrasion of hard bedrock; an unduly complicated explanation.

The channeled scabland on the inner shelf includes relatively short, broad and high drumlins, contrasting with elongate drumlins on the middle and outer shelves (Figs 9a and 10a). Rock drumlins are common together with crags and tails. Hairpin scours wrapped around these drumlins combine crescentic scours around blunt upstream ends and flanking furrows which widen as drumlins taper downflow – drumlin shape depends on the form of the bounding scour.

Sediment-covered troughs on the middle shelf include small bedrock exposures that served as obstacles for drumlin formation. Hairpin scours wrap around these obstacles and define tapered, attenuated drumlins on the inner and middle shelves (Fig. 9a). Erosional marks (rat tails), sculpted from plaster of Paris by flowing water in a flume, provide a close analogy for these drumlins (Fig. 9b). Experiments show horseshoe vortices wrapped around the upstream face of obstacles, eroding hairpin scours and leaving remnant rat tails. We might even describe attenuated drumlins on the middle shelf as mega rat tails. Introducing horseshoe vortices to the explanation of drumlins and rat tails establishes a fluid dynamical link which increases the power of the analogy.

Figure 9
(a) Swath bathymetry of attenuated drumlins with crescentic scours (arrowed) and downflow-widening lateral furrows, Marguerite Bay; flow towards top, km scale. After Ó Cofaigh and others (2002). (b) Rat tail eroded in a flume from plaster of Paris by turbulent, slightly acidic water. Arrow marks crescentic scour; flow towards top, cm scale. Note how the tapering results from flanking, widening-downstream scours.

Megalineations on the Middle and Outer Shelves

With little exception, sediment covers much of the middle shelf and almost all of the outer shelf where scientists, mainly from the United States and the United Kingdom, have mapped extensive tracts of highly elongate ridges and troughs known collectively as mega-scale glacial lineations (MSGL: Fig. 10a, from Ó Cofaigh and others, 2002). These distinctive bedforms dominate the seascape on the outer shelf. The widely held belief that subglacial deformation moulds MSGL presumes a glacial origin for these bedforms. The simpler

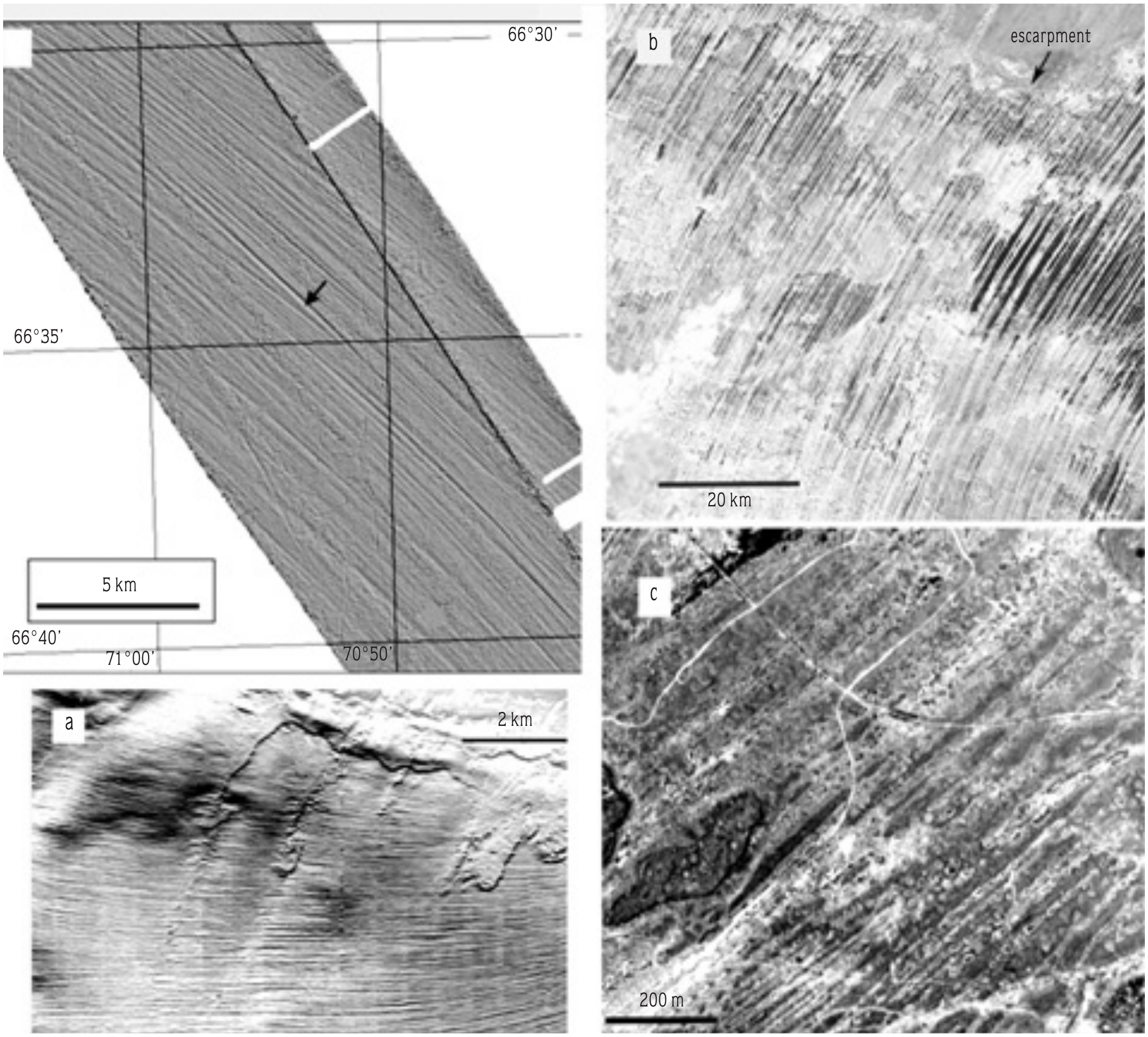


Figure 10
Megalineations in a variety of settings: (a) Swath bathymetry image of subglacial megalineations eroded into soft diamicton on the bed of Marguerite Bay (after Ó Cofaigh and others, 2002); (b) Satellite image of eolian megalineations (yardangs) eroded in sandstone, Borkou area, Chad (Google Earth); (c) Megalineations (furrows) eroded in mud by marine currents on the sea floor, Gulf of Mexico (after Lee and George, 2004); (d) Satellite image of Scablands megalineations (bedrock fluting) eroded in basalt by outburst floods, Dry Falls, Washington State.

term, megalineation, avoids this presumption. With amplitudes up to 30 m, though usually closer to 15, transverse spacing of a few hundred metres and lengths up to tens of metres, megalineations rank amongst the largest bedforms on Earth. They have much higher length-to-width ratios than drumlins, such that the two bedforms exist as separate populations. Remarkably parallel and regularly spaced, megalineations extend for tens of kilometres and may show broad, sweeping curvature following bends in associated troughs. Cross-cutting lineations mark changing flow directions, and lineations preferably located at forward-facing steps illustrate that bed morphology influenced the flow.

Shelf-crossing Trough Hydrology

Minimal Meltwater

Vastly different opinions on the hydrology of shelf-crossing troughs leave lots of room for debate. As already noted, Ashley Lowe and John Anderson suggested "abundant meltwater" in an early interpretation of channels and s-forms in bedrock. Bob Gilbert and others (2003) used the rat-tail analogy to argue for erosion of rock drumlins by large floods in Palmer Deep off the Antarctic Peninsula. But, these proposals prompted skepticism on the part of other scientists who denied all evidence of high meltwater discharges beneath ice streams in troughs – understanding the nature of the evidence and its interpretation is critical here. The skeptics adopted a minimal meltwater approach to shelf bedforms and proposed that shelf meltwater sources could be explained by melt due to geothermal and frictional heat, pressure melting and strain heating. However, these sources of subglacial water cannot sustain the discharges estimated for tunnel channels. The minimal meltwater alternative explanation ignores tunnel channel flow, explains crescentic scours around drumlins as local-scale, late-stage features, and suggests that s-forms are glacial, not fluvial. Proposed mechanisms for transmission of meltwater across shelves include Darcian flow and advection as pore water in deforming subglacial sediment, both of which would fail by several orders of magnitude to transmit tunnel channel discharges, or even appreciable discharges. As well, minimal meltwater explanations for crescentic scours and s-forms lack theoretical, observational and experimental justification.

Abundant Meltwater

In view of difficulties encountered by the minimal meltwater approach, the alternative of abundant meltwater should be reconsidered. Most importantly in this debate, steady-state melting obviously cannot supply water for outbursts that formed tunnel channels on the inner shelf: meltwater was stored in large subglacial lakes and released in cataclysms. This reconstruction fits our conclusion that the inner shelf seascape is a labyrinth or scabland. Outbursts from these lakes probably released discharges of 10^6 m^3s^{-1}, yet there are no channels or eskers (ridges of sand and gravel deposited in glacier tunnels) indicating narrow conduits on the two outer shelves. Consequently, flood discharges from tunnel channels must have spread in broad, high velocity sheet flow across the middle and outer shelves. High velocity sheet flow over a soft, erodible bed inevitably creates bedforms as it interacts with the bed, *e.g.,* wind and desert dunes, and tidal currents and sand waves.

Megalineation and Abundant Meltwater

Megalineations

Persistent mechanisms generated megalineations on the outer shelf (Fig. 10a) where there are no obvious obstacles on the seabed. Groove ploughing by keels on glacier beds may mould such megalineations, but, in places, they extend downflow from broad areas of unlineated, soft sediment. With this spatial relationship, two unlikely possibilities ensue: either keels on glacier beds did not plough the soft sediment in unlineated areas, or keels first formed at the onset of lineations. Keel formation is unlikely in the absence of resistant bedrock which might mould glacier beds. Either way, groove-ploughing faces insurmountable difficulties. As well, ploughing fails to account for megalineation bifurcation and their preferred location at steps. However, Christian Schoof and Garry Clarke (2008) recently proposed that large-scale fluting may result from spiral flows in the basal zone of glaciers – a very promising avenue for research on Antarctic megalineations.

André Pugin, Robert Young and I (2008) suggested that meltwater erosion sculpted megalineations. After demonstrating the likelihood of very large flows in shelf-crossing troughs, we tackled the most common objections to the meltwater hypothesis for megalineations in glacial settings: turbulently flowing water cannot generate cross-cutting bedforms; and it cannot erode its bed in extensive, regularly-spaced parallel, lineations. These objections stem from Chris Clark's (1993) benchmark paper on megalineations.

The problem of cross-cutting bedforms is easily resolved by simple logic:

> It takes time for a stable meltwater sheet flow to erode a set of longitudinal bedforms with a given orientation. If the flow direction changes as a result of changing geometry, it takes additional time to remove the first set and to erode a fresh set of bed-forms with the new orientation. Thus, between the initiation of the second set and the complete removal of the first set, there will be at least two sets of cross-cutting erosional marks. Several changes of flow direction might generate multiple, cross-cutting sets.

Evidently, cross-cutting does not contradict the formation of megalineations by meltwater.

In the absence of a general fluid dynamical theory for bedforms, analogy best answers the question of extensive, parallel and regularly spaced lineations: if extensive parallel and regularly-spaced bedforms result from erosion by turbulent flows in non-glacial settings, these characteristics cannot be used as evidence against lineation formation by subglacial turbulent flow. In fact, convincing geometric analogies establish the case for meltwater megalineations.

Abrasion by sand and silt carried by the northeasterly trade winds sculpts desert rock into remarkably parallel yardangs (ridges and troughs) that serve as perhaps the best analogs for megalineations in glacial settings. Wind-sculpted rock ridges up to 100 m high, with transverse wavelengths of about 200 m, and lengths measured in tens of kilometres rib extensive desert surfaces (Fig. 10b). Yardangs in fields hundreds of kilometres wide track trade winds in broad, sweeping curves. Both sets of lineations, megalineations in glacial settings and yardangs in deserts, commonly begin at forward-facing (upflow-facing) steps (Fig 10b). Thus, yardangs are megalineations with relatively high amplitudes. Their formation in broad, turbulent flow suggests a strong fluid dynamical analogy between glaciofluvial and eolian lineations.

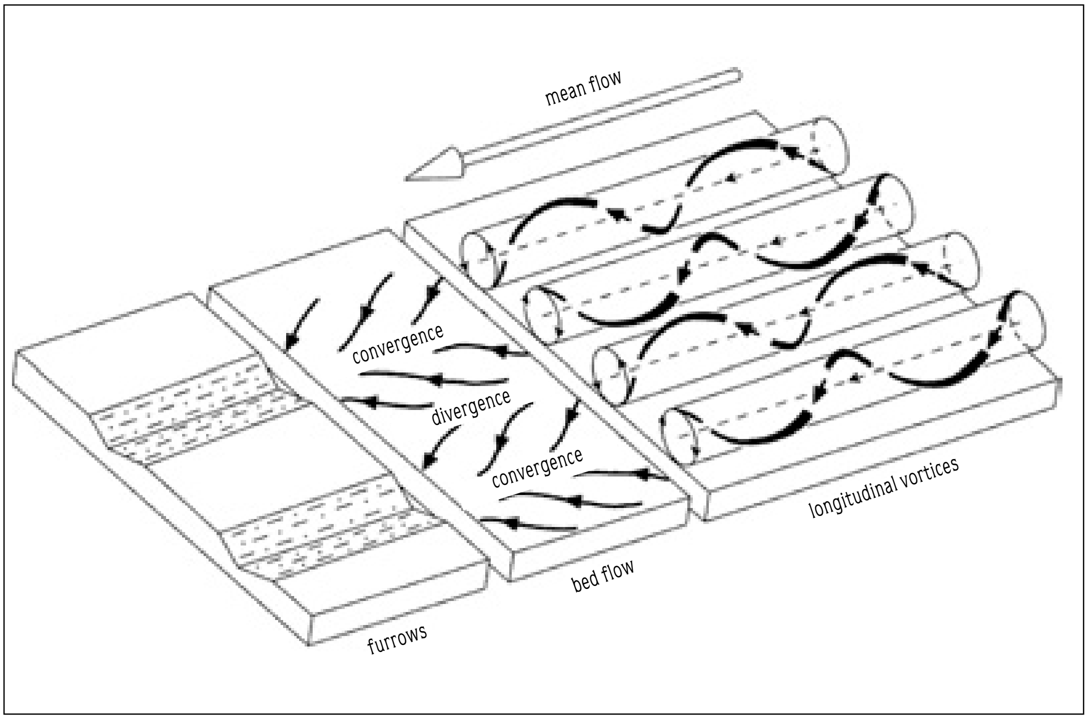
Eddie Lee and Tony George (2004) reported vigorous bottom currents driven by saline density gradients eroding furrows on the floor of the Gulf of Mexico at about 3000 m depth (Fig. 10c). These flow-parallel furrows mimic megalineations in glacial environments and yardangs in deserts. They lie 50–150 m apart, with depths of 5–10 m, and can be traced over 50 km. Their broad curvature follows the seabed bathymetry, sets of furrows cross-cut and individual furrows may bifurcate. These marine megalineations compare closely with those on Antarctic shelves and counteract the claim that shelf lineation cannot form in turbulent flows.

On the basis of the above analogies, we would expect to find megalineations in areas scoured by well documented floods, in the Scablands for example. Therefore, their appearance in basalt just upstream from the largest relict Scablands waterfall, Dry Falls, comes as no surprise (Figs 5 and 10d). Since the Scablands lie well beyond the extent of Pleistocene ice sheets, outburst floods not glacial processes sculpted these lineations. They extend over 1 km – the location of Dry Falls limits their length – reach about 5 m in amplitude, and lie about 50–100 m apart. Furrows display U-shaped cross-sections. Glacial hydrology ties Scablands and subglacial lineations in this analogy.

Meltwater also eroded megalineations in sedimentary and metamorphic bedrock in Scotland, in sedimentary rocks of the English Channel, in limestone in Ontario, in granite and gneiss on the Canadian Shield, and in glacial sediment and poorly cemented sedimentary bedrock on the Canadian Prairies. Many other landscapes, especially in the Canadian north, which encompasses the largest area of subglacial bedforms on Earth, exhibit megalineations that might be glaciofluvial. The Antarctic shelf seascape and glacial context may provide a powerful model for the genesis of such landscapes.

Our analogy is strengthened if erosional process can be tied to fluid dynamics. Most researchers studying megalin-

Figure 11
Formation of megalineations by the action of longitudinal vortices. After Flood (1983).



eations in non-glacial environment follow Roger Flood (1983) and attribute them to erosion by longitudinal vortices (Fig. 11). Experimental field evidence supports this view for longitudinal (sief) dunes, and empirical research by Jon Williams and others (2008) demonstrates the role of longitudinal vortices in the formation of flow-parallel ridge-runnels on tidal flats in the Severn Estuary, UK. Recent developments in computational fluid dynamics for turbulent flow at forward-facing steps show vortices streaming downflow from the steps. Thus, fluid dynamics accounts for the location of lineations at steps in eolian and formerly glaciated settings. This spatial arrangement goes beyond coincidence.

Conclusion

Spectacular Antarctic erosional landscapes in the Labyrinth, along the Soya Coast, and in scablands seascapes on the continental shelf furnish evidence for cataclysmic outburst floods from beneath the Antarctic ice sheets. The sheer volume of these floods cannot be explained by steady-state melting: it requires storage in much larger subglacial lakes than those found beneath the modern ice sheets. The locations of the Labyrinth, close to the Transantarctic Mountains, and erosional marks along the Soya Coast, close to the East Antarctic ice sheet, point to subglacial meltwater storage in lakes. Storage and release of this meltwater require mechanisms for sealing such lakes and for breaking the seal abruptly. Ed Shoemaker (1991) modeled a very large, unstable lake beneath the Laurentide ice sheet, but his ideas about subglacial lakes meets with skepticism today.

Analogy, the favoured tool of G.K. Gilbert, the founding father of modern process geomorphology, prompts much geomorphological research. Thus, the Scablands landscape is analogous with the Labyrinth; and bedrock erosion marks on the Soya Coast are analogous with sculpted granite and gneiss in Ontario. These analogies extend to erosional landscapes on Antarctic shelves and provide a starting point for investigating shelf hydrology. Steady-state, gradual melting and flow of meltwater on the shelf cannot explain even the smallest erosional features. Abundant meltwater, however, accounts for the full suite of shelf bedforms.

Debate on drumlins and megalineations continues today with as much vigor as ever. These features make up a large percentage of the shelf seascape, and our research tests the meltwater model for their genesis. Our conclusions depend to a large extent on the fundamental premise that large meltwater discharges flowed over soft sediment on the shelf and generated extensive bedforms. By analogy, the shelf bedforms may well have formed in meltwater flows. Horseshoe vortices explain drumlins, and longitudinal vortices explain megalineations. Recent work demonstrates the power of these longitudinal vortices to erode soft beds and explains the common observation of megalineations at forward-facing steps. Thus, the hydrologic context and the detailed mechanisms of turbulent flow support a meltwater origin for subglacial drumlins and megalineations. Proponents of a deformational genesis for these bedforms make similar claims for their favoured processes. A general solution to the problem may well emerge from studies of bedforms in Antarctic shelf-crossing troughs.

A journey through different worlds leads us from the aridity of the present day Wright Valley to huge floods beneath the Antarctic ice sheets. Lakes beneath the present ice sheets may be signs of larger, unstable lakes to come, and cataclysms may resume excavation of the Labyrinth and the channeled scablands of shelf onset zones and carve new drumlins and megalineations on the middle and outer shelves. Who knows what the effects of such floods might be on the Southern Ocean and the Earth's climate?

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Sander Geophysics Explores the Antarctic

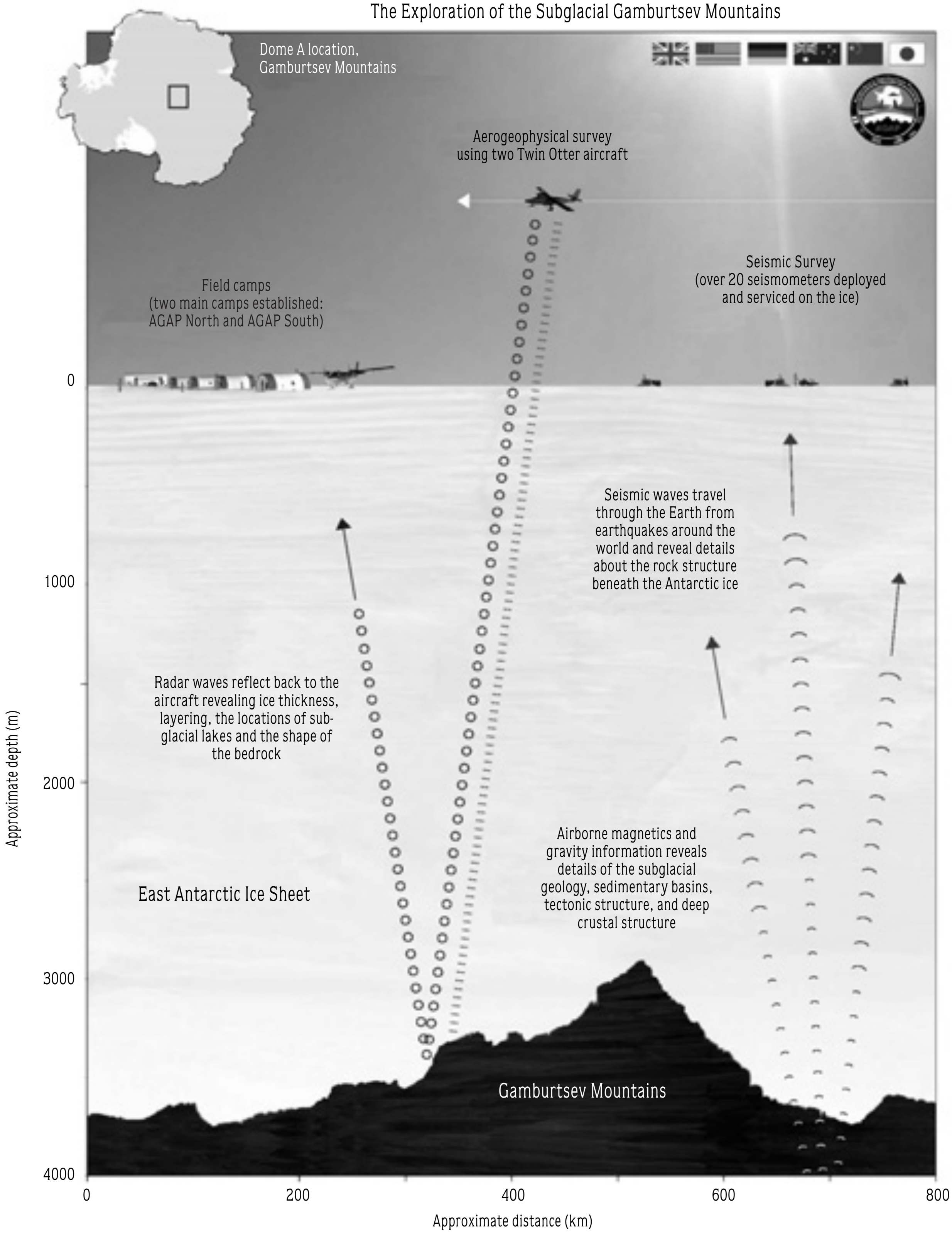
Sander Geophysics Limited (SGL) has earned the privilege of participating in the Antarctica's Gamburtsev Province Project (AGAP). This is a project funded by the US National Science Foundation's Office of Polar Programs for International Polar Year (IPY). In May and June of 2007, teams from SGL and the Lamont-Doherty Earth Observatory of Columbia University installed SGL's Airborne Inertially Referenced Gravimeter (AIRGrav) in a Kenn Borek DCH-6 Twin Otter aircraft in Calgary. Once installed, the aircraft performed test flights over the Rocky Mountains and was then flown to Ellesmere Island in Nunavut to test the system at high latitudes over the North Pole. The tests proved very successful in terms of AIRGrav data quality, noise levels, and GPS control. This success led the AGAP team to select AIRGrav over other gravimeters for the demanding Antarctic survey. The Rockies tests have been described by Studinger and others (2008). In May and June 2008, teams from SGL and AGAP returned to Calgary where they installed the AIRGrav system along with the full suite of AGAP geophysical equipment in the Twin Otter. The aircraft flew a set of successful test flights over the Greenland ice sheet as a final verification of the survey platform before heading south to Antarctica.

The AGAP's central focus is to gather information to accurately characterize the tectonic origin of the Gamburtsev Subglacial Mountains, approximately 3 km below the million-year-old ice sheet in the deep interior of East Antarctica (Fig. 1). In addition, the project will study the relationship between these mountains and the overlying ice sheet and subglacial lakes, and identify the location of the oldest ice to enable the recovery of the oldest climate record. The survey will take place from December 2008 to January 2009. The team from SGL, that will join the AGAP team in Antarctica, consists of SGL Data Processing Manager Dr Martin Bates, Senior Geophysicist Stefan Elieff and Technician Daniel Geue. SGL's AIRGrav system will collect information about the buried mountains' structure during the combined airborne gravity and magnetic survey. The Lamont-Doherty Earth Observatory of Columbia University will operate a laser altimeter that will simultaneously scan the surface of the ice during flights to provide information on surface elevation, a synthetic aperture radar (SAR) that will measure ice thickness and layering in order to map the shape of the buried bedrock, and magnetometers to map the magnetic fields of the bedrock.

Sander Geophysics' AIRGrav system (Fig. 2) offers a number of advantages over competing systems, including:

1. Significantly better resolution and accuracy;
2. Ability to operate under normal daytime flying conditions;
3. Ability to provide high quality gravity data while flying in drape mode;
4. Ability to provide good quality aeromagnetic data concurrently with the AIRGrav data;
5. Significant operational efficiencies;
6. Shorter time required for data acquisition and processing.

The Exploration of the Subglacial Gamburtsev Mountains



These advantages are all a result of the unique design and construction of the AIRGrav system. It accurately records and compensates for aircraft movements due to turbulence, aircraft vibrations, and drape flying, allowing for the removal of these effects from the final data during processing. Very high quality GPS, combined with SGL's proprietary GPS and gravity data processing software complete the AIRGrav system. AIRGrav system details are available on SGL's website (www.sgl.com) as well as in our Technical Papers.

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Additional information on this project is available from the Lamont-Doherty Earth Observatory website for the AGAP (www.ldeo.columbia.edu/res/pi/gambit).

Figure 1 (left)
Diagram showing the various geophysical techniques being used to study the Gamburtsev Mountains. Illustration courtesy of AGAP.

Figure 2
Photo of AIRGrav installed in the Kenn Borek DCH-6 Twin Otter ready for surveying. Courtesy Michael Studinger, Doherty Research Scientist for AGAP.

News in Brief

Wilhelmina Roa Clavano has received one of three SCAR fellowships, the first ever for Canada. Wendy, a remote-sensing scientist who works at the University of Alberta, with Martin Sharp, as a postdoctoral fellow, is analysing information from ground penetrating radar (GPR) data over Arctic glaciers. The Antarctic interest was facilitated by a collaboration with Christian Haas, who had been invited by Wolfgang Rack, of Gateway Antarctica in New Zealand, to visit Scott Base and fly a helicopter-borne inductance meter (HEM) over land and sea ice. Because the HEM does not provide information on the surface layers of the snow/ice, Wendy will run coincident transects with a GPR instrument in the austral summer of 2009. The SCAR support will allow her to coordinate this GPR data collection and processing at the University of Canterbury, where she will be hosted by Wolfgang Rack who is supporting all the field logistics. The GPR measurements, along with other ground measurements, will provide data directly for calibration and validation of the instrument on board CryoSat, a satellite to be launched by the European Space Agency for cryospheric research, and will also be useful for NASA's ICESat.■

Indian and Northern Affairs Canada formally announced February 11, 2009, that it had signed a memorandum of understanding which establishes how the United Kingdom and Canada will share polar facilities and infrastructure. This will provide new opportunities for joint field studies, shared access to scientific expertise, training and public outreach. Canada is expected to seek expertise from the UK in the design of the High Arctic research station that the federal government has promised to help build.

The new agreement should simplify the sharing of resources such as bush planes, and include a system for funding research. It is expected there will be a quid pro quo to deal with accommodation, logistics and travel for UK scientists to work in the Canadian Arctic and for Canadian scientists to work in the Antarctic.■

CARN Newsletter

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