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Reviewed work(s):
Source: *Arctic and Alpine Research*, Vol. 26, No. 1 (Feb., 1994), pp. 86-92
Published by: INSTAAR, University of Colorado
Stable URL: http://www.jstor.org/stable/1551882
Accessed: 26/05/2012 11:25

Arctic and Alpine Research, Vol. 26, No. 1, 1994, pp. 86–92

Evidence for Floating Ice Shelves in Franz Josef Land, Russian High Arctic

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Abstract

Examination of digital Landsat TM and MSS imagery of Franz Josef Land, Russian High Arctic, reveals a number of ice caps with apparently very low surface gradients at their seaward margins. The largest of these low gradient areas is 45 km². The areas are dynamically a part of the parent ice mass, and have a marked break of slope at their inner margins. They generally occur in protected embayments and often have relatively deep water offshore. The presence of deep inter-island channels (up to 600 m) in the archipelago also suggests that deglaciation after the last glaciation may have proceeded rapidly due to enhanced iceberg calving. Tabular icebergs (maximum observed length 2.3 km) are produced from several of the low gradient ice cap margins today. Ice surface profiles, derived from analysis of vertical aerial photographs, show slopes of 0.5° on these features, as compared with 3.5 to 5° on other ice caps. At least some are likely to be floating ice shelves. They have similar ice surface gradients to a known ice shelf on Severnaya Zemlya. There is no requirement for deep water to occur beneath these features, but simply that they become buoyant over a significant part of their base. Glacier thinning, due to reduced mass balance since the termination of the Little Ice Age, may have contributed to the presence of these features. An origin for some of these low gradient margins by deformation of an unlithified substrate cannot be ruled out. Field radio-echo experiments could be used to test the interpretation of these features as ice shelves.

Introduction

The archipelago of Franz Josef Land in the Russian High Arctic (45–65°E, 80–82°N) has an area of 16,000 km² and is approximately 85% ice covered (Fig. 1). However, relatively little is known about its glaciology, apart from a monograph resulting from studies undertaken during the International Geophysical Year, 1957–58 (Grosswald et al., 1973). While examining digital Landsat Thematic Mapper (TM) and Multispectral Scanner (MSS) satellite imagery of Franz Josef Land, we observed a number of ice caps with smooth and apparently very low surface gradients at their seaward margins (Figs. 2, 3). These areas were often associated with the production of relatively large tabular icebergs. Both low surface gradients and the calving of tabular icebergs are characteristics often linked with the presence of floating ice shelves rather than grounded ice. Our digital investigations of Landsat imagery of these features are augmented with evidence from Russian stereoscopic aerial photographs and offshore bathymetry. The aim of this study is to describe and interpret these low-gradient ice surfaces observed on Franz Josef Land ice caps, and to discuss the likelihood that they represent floating ice shelves.

Background on Ice Shelves and Tabular Icebergs

Extensive ice shelves are relatively common in Antarctica, forming almost 45% of the periphery of the ice sheet and making up about 1.5 million km² of its area (Drewry et al., 1982). By contrast, ice shelves are found only infrequently in Arctic regions. A number of fast-flowing outlet glaciers of the Greenland Ice Sheet are known to have floating margins; Jakobshavns Isbrae (West Greenland), Daugaard-Jensen Gletscher (East Greenland), and Petermann Gletscher (North Greenland) are examples, with floating margins extending from about 10 to 40 km beyond the grounding line (Olesen and Reeh, 1969; Higgins, 1989; Echelmeyer et al., 1991). Ice shelves have also been reported from Ellesmere Island, Arctic Canada, where a number of floating ice masses have been observed along the island's northern coast (Jeffries, 1987, 1992). The best known of these is Ward Hunt Ice Shelf, with an area of about 450 km² (Jeffries and Serson, 1986). However, these Ellesmere Island ice shelves, together with several of those described from North Greenland by Higgins (1989), are fundamentally different from the ice shelves of Antarctica and the floating margins of outlet glaciers of the Greenland Ice Sheet. The Antarctic and Greenland floating ice masses are dynamically a part of a parent glacier system, and mass is transferred to them by flow from an interior drainage basin. By contrast, the Ellesmere Island ice shelves, and some from North Greenland, are formed predominantly from shorefast sea ice which has thickened by both surface accumulation and basal accretion (Jeffries, 1987).

It should be noted that the floating margins of fast-flowing Greenland and Antarctic outlet glaciers are sometimes referred to as "ice (or glacier) tongues" rather than "ice shelves," implying that floating glacier ice exists, but that it is narrow relative to its length and often constrained by fiord walls. It is arguable whether some of the features in Franz Josef Land, which we suggest may represent floating glacier ice, should be termed ice shelves or ice/glacier tongues. We have chosen to use only the term "ice shelf" in this paper, to avoid any arbitrary distinction between floating glacier ice of varying plan form and occurring in different topographic settings.

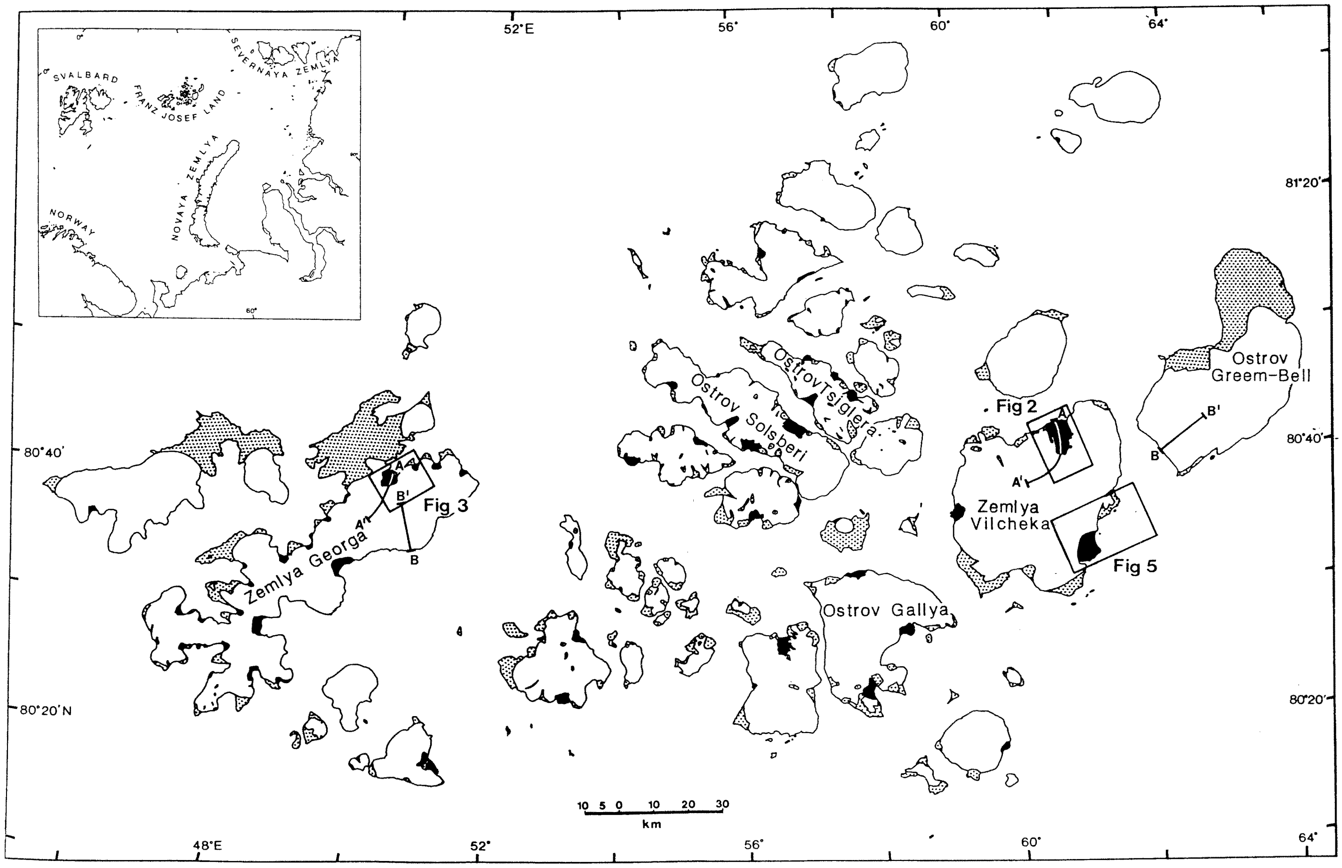

FIGURE 1. Map of the Franz Josef Land archipelago, Russian High Arctic. Most of the land area is ice covered, and bare ground is stippled. The marginal areas of ice caps with very low surface gradients are shaded black. Note that Ostrov Victoria (area 10 km²), at 37°E 80°N, is not shown although it makes up the most outlying island of the archipelago. Satellite images and ice surface profiles in subsequent figures are located on the map. The inset shows the location of Franz Josef Land within the European Arctic.

Tabular icebergs with very flat, regular surfaces, often tens of kilometers in length, are calved from the termini of the large ice shelves of Antarctica (Swithinbank, 1988). In the northern polar regions, both glacier-derived and sea-ice-derived ice shelves also produce tabular icebergs (e.g. Jeffries, 1987; Higgins, 1989; Dowdeswell et al., 1992). These icebergs are characteristically at least an order of magnitude smaller than those calved from Antarctic ice shelves, and are typically a few hundred meters to a few kilometers, and exceptionally a few tens of kilometers, in length. It should be noted that floating ice masses calved from Ellesmere Island and North Greenland ice shelves have sometimes been referred to as "ice islands," but the more general term "tabular iceberg" is used throughout this paper.

There is some controversy in the early Russian literature as to the occurrence of ice shelves in Franz Josef Land. Spizharskiy (1936), Shumskiy (1949), and Govorukha (1968) each suggest that some small ice shelves may be present, whereas Grosswald et al. (1973) argue that none exists. Little direct evidence is offered in support of either case, although Govorukha (1968) states specifically that an ice shelf is present in the northeast of Zemlya Georga (cf. Fig. 3). Three ice shelves have also been reported from the Severnaya Zemlya archipelago (inset in Fig. 1), east of Franz Josef Land (Dibner, 1955; Zinger and Koryakin, 1965; Govorukha, 1988). These occur on Ostrov Komsomolets and Ostrov Oktyabr'skoy Revolutsii. The largest, Matusevich Ice Shelf, is about 240 km² with a surface slope of <0.2° near its margin (Govorukha, 1988). Ice surface profiles of the Matusevich Ice Shelf and its drainage basin, together with an outlet glacier of the Akademii Nauk Ice Cap on Ostrov Komsomolets, are given in Figure 4. The marginal 9 and 4 km of these profiles, respectively, represent floating ice shelves, and are compared below with similar features found in Franz Josef Land. The occurrence of tabular icebergs in Franz Josef Land waters, and of icebergs in the Barents Sea derived from the ice caps of Franz Josef Land, has also been reported (e.g. Sandford, 1955; Voevodin, 1972; Abramov, 1992).

Data Acquisition and Methods

Four sets of data are used in this study. Digital Landsat TM and MSS scenes from May 1983, July 1986, August 1987, and August 1988 provided visible and near-infrared imagery of almost the whole of Franz Josef Land at a resolution of 30 m (TM) or 79 by 56 m (MSS). These datasets were examined on a Sun Sparcstation-based image processing system in Cambridge. Stereopairs of Russian vertical aerial photographs, acquired in the 1950s, were analyzed photogrammetrically in Moscow to derive surface elevations in specific areas of low-gradient ice, identified from the satellite imagery. Bathymetry with a contour interval of 50 m was also available offshore of much of the archipelago from surveys by Russian hydrographic vessels.

FIGURE 2. Digitally enhanced Landsat TM image of the low surface gradient margin of Stremitel'ny Glacier, Zemlya Vilcheka (path/row 197/001, imaged on 8 August 1987). The image is located in Figure 1.

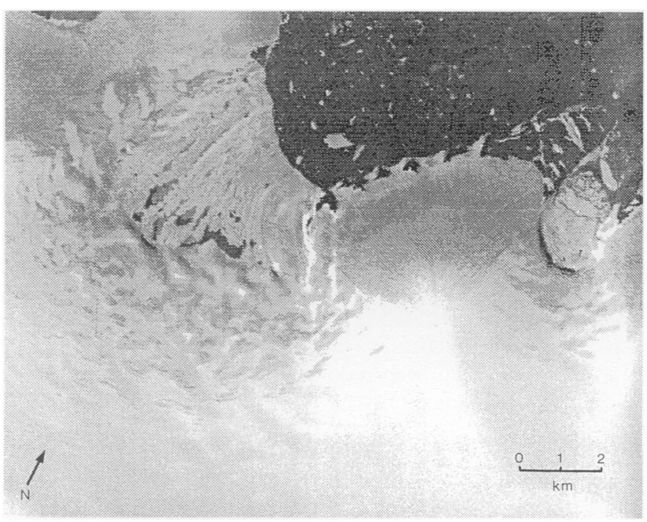

FIGURE 3. Digitally enhanced Landsat TM image of several low gradient ice-cap margins on Zemlya Georga (path/row 199/002, imaged on 25 July 1986). The image is located in Figure 1.

Evidence from Satellite Imagery

DISTRIBUTION OF LOW GRADIENT ICE CAP MARGINS IN FRANZ JOSEF LAND

Examination of digitally enhanced Landsat imagery of the archipelago indicated that a number of ice caps had marginal areas with apparently very low surface gradients. Landsat TM scenes show several of these areas within Franz Josef Land (Figs.

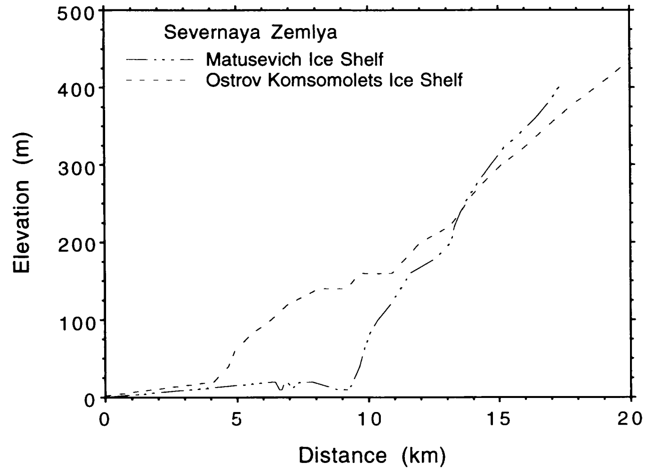

FIGURE 4. Ice surface profiles from two ice shelves and their interior basins in the Russian High Arctic archipelago of Severnaya Zemlya (located in Fig. 1). The Matusevich Ice Shelf is on Ostrov Oktyabr'skoy Revolutsii, and the other ice shelf (unnamed) drains a part of the Akademii Nauk Ice Cap on Ostrov Komsomolets.

2, 3). The lower 10 km of Stremitel'ny Glacier on Zemlya Vilcheka is one of the largest areas of low gradient ice in the archipelago (Fig. 2). Approximately 45 km^2 of the 275-km^2 drainage basin has a very low gradient surface, delimited by a marked break in slope up-glacier. A number of smaller areas of flat marginal ice are imaged on Zemlya Georga in Figure 3. These range in area from 1 to 14 km^2, and are also fed from steeper ice flowing from interior drainage basins.

Landsat TM imagery of almost the entire archipelago has been analyzed to identify the total extent of low surface gradient ice cap margins, similar to those areas shown in Figures 2 and 3. The distribution of these features within Franz Josef Land is shown in Figure 1. Most, although not all, of the low gradient margins are located in relatively protected embayments, rather than along sections of open coastline. These flat features account for 315 km^2 or 2.3% of the total area of the ice caps in the archipelago. They make up a total of 175 km or 6% of the ice-ocean interface from which iceberg calving takes place. The largest two features are on Zemlya Vilcheka, each with an area of about 45 km^2 (Figs. 2, 5).

SURFACE CHARACTERISTICS OF LOW GRADIENT ICE CAP MARGINS

Several surface features on these low gradient ice cap margins provide information important to their interpretation. First, surface lineations oriented parallel to ice flow direction are observed on Landsat imagery of a number of the flat marginal areas. These features extend from the steeper, upper drainage basin into the flat, lower part (Figs. 2, 3, 5). Such features have been observed on Landsat imagery of Antarctic ice sheet-ice shelf systems (e.g., Crabtree and Doake, 1980; Dowdeswell and McIntyre, 1987). They are sometimes referred to as "flowlines," and are interpreted to indicate that there is dynamic continuity and mass transfer between the ice sheet and ice shelf. In Franz Josef Land we suggest they demonstrate that the low gradient marginal areas are dynamically linked to ice feeding them from upper basins.

A second surface feature is the marked break in slope which defines the interior margin of the flat marginal areas. This can be seen on the satellite images in Figures 2 and 3, and is sometimes associated with the emergence of bedrock at the ice surface.

FIGURE 5. Digitally enhanced Landsat MSS image (path/row 197/001, imaged on 8 May 1983) of Znamenity Glacier, Zemlya Vilcheka. A number of tabular icebergs calved from the low gradient margin of the ice cap can be seen. A possible ice shelf grounding line is shown (arrowed). The image is located in Figure 1. Its scale is 27 km in length and 16 km in height. It is distorted in the ratio 79:56, which is the pixel size of Landsat MSS imagery in meters.

In these cases, bedrock appears to be linked with partly subglacial escarpments (Fig. 2). The break in slope is not always associated with a clearly defined subglacial scarp, however. An example is the inner margin of low gradient ice on Znamenity Glacier, Zemlya Vilcheka. Here, a marked break in the ice surface slope is shown on a digitally enhanced Landsat MSS scene in Figure 5.

A number of areas of low gradient marginal ice are also associated with the occurrence of supraglacial lakes (Figs. 2, 3). The presence of lakes indicates that the ice is largely free of crevasses, and that it is relatively flat.

PRODUCTION OF TABULAR ICEBERGS

The calving of tabular icebergs from a number of the flat marginal ice cap areas of Franz Josef Land was also observed on Landsat imagery. The largest tabular icebergs imaged on the satellite scenes we have acquired are found offshore of Znamenity Glacier on Zemlya Vilcheka (Fig. 5). The tabular icebergs appear to have smooth upper surfaces and are up to 1.6 km in length in this scene, which also includes over 20 icebergs with long axis greater than 0.5 km (Fig. 5). Tabular icebergs >200 m in length have also been observed on TM imagery off other drainage basins of Zemlya Vilcheka, and offshore of Zemlya Georga, Ostrov Tsiglera, Ostrov Solsberi, and Ostrov Gallya (Fig. 1). We also examined photographic products of Franz Josef Land from the Russian KATE–200 satellite camera system, and the largest tabular iceberg observed on this imagery was 2.3 km in length.

Ice Surface Gradients and Offshore Bathymetry

Russian stereo-pairs of aerial photographs, acquired in the 1950s, were used to produce contour maps and ice surface profiles of low surface gradient areas identified from Landsat imagery (Figs. 1, 2, 3). A slope of 0.5° was measured on the 3-km-wide area making up the largest marginal feature on Zemlya Georga (Figs. 3, 6). The ice surface slope on the relatively flat 7 km-wide margin of Stremitel'ny Glacier on Zemlya Vilcheka is 0.6°, falling to less than 0.5° over the outermost 3 km (Figs. 2, 7). Above the break in slope marking the inner margin of flat

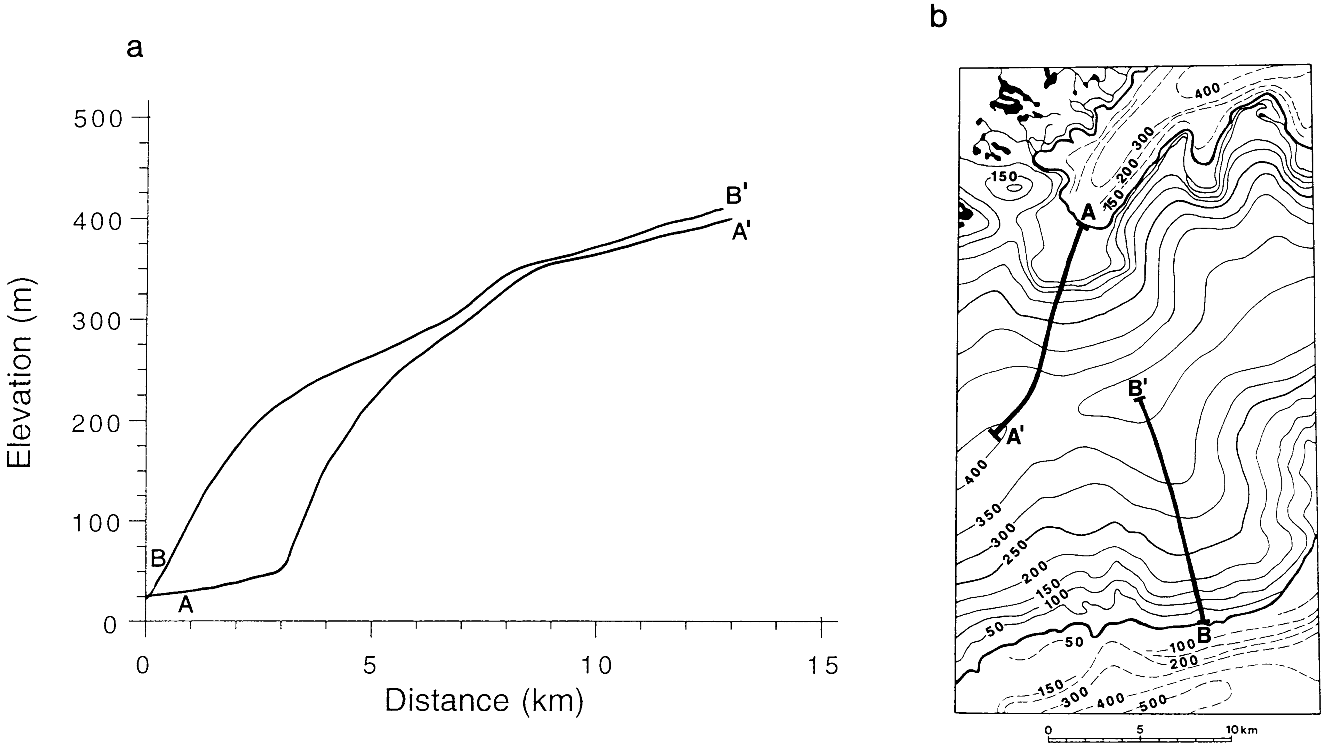

FIGURE 6. (a) Ice surface profiles derived from stereoscopic aerial photographs of the ice caps on Zemlya Georga (Fig. 1). (b) Contour maps of the ice cap surface and offshore water depth. The ice surface profiles are located on the map.

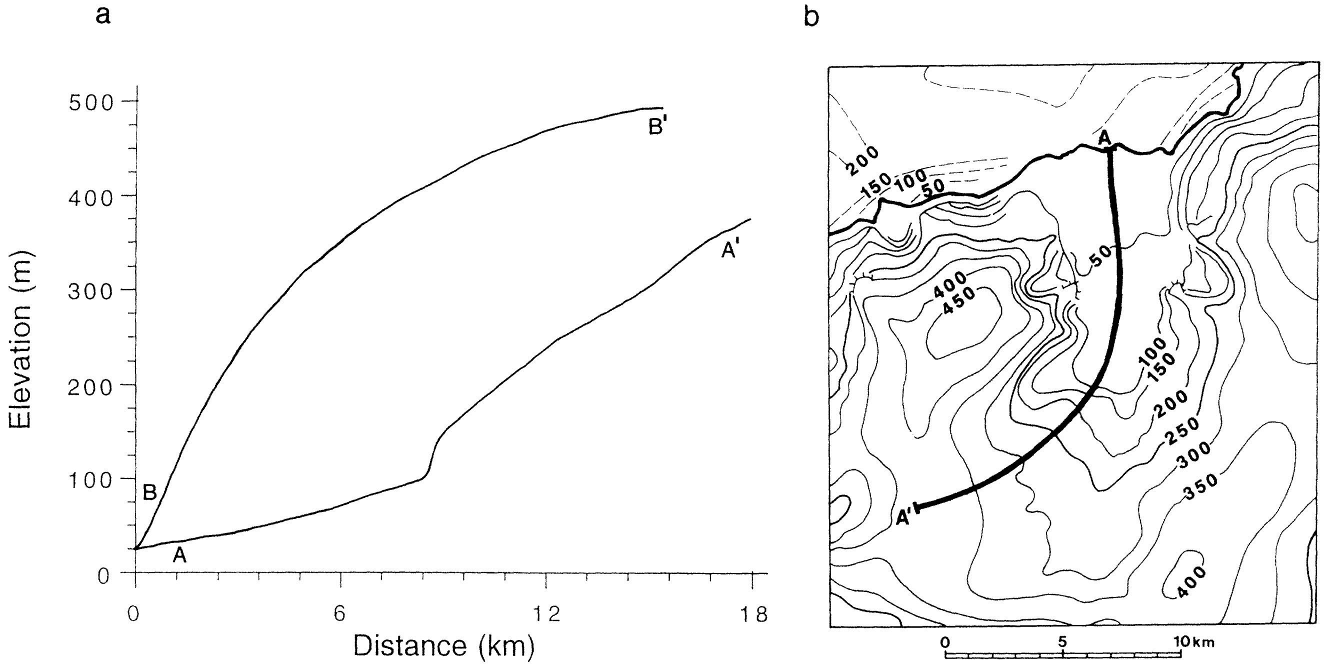

FIGURE 7. (a) Ice surface profiles derived from stereoscopic aerial photographs of Stremitel'ny Glacier on Zemlya Vilcheka (A-A') and a part of the ice cap on Ostrov Greem-Bell (B-B'). (b) Contour map of part of the Zemlya Vilcheka ice cap, including Stremitel'ny Glacier (Fig. 2), together with offshore water depths. The ice surface profile of Stremitel'ny Glacier (A-A') is located on the map. A contour map of the ice cap on Ostrov Greem-Bell is not illustrated here, but the ice surface profile is located as B-B' on Ostrov Greem-Bell in Figure 1.

ice, surface slopes on the two profiles increase to between 3.5 and 5° over the next 3 km inland.

These slope angles are compared with two other profiles, from Zemlya Georga and Ostrov Greem-Bell (Fig. 1), in locations where satellite imagery suggests that parabolic ice surfaces are present: steepest at the margins and declining to low values at ice cap divides (Figs. 6, 7). On these profiles, the marginal 3 to 5 km have slope angles of between 3.5 and 5°. These values are similar to those found inland of the break of slope for the profiles in Figures 6 and 7, but are significantly steeper than those recorded for the seaward margins appearing as flat on Landsat imagery (Figs. 2, 3).

The bathymetry offshore of the four profiles also falls into two distinct categories. For the two profiles with very low marginal slopes, water depth is contoured at between 100 and 150 m offshore of Stremitel'ny Glacier and between 200 and 300 m off the Zemlya Georga ice mass (Figs. 6b, 7b). By contrast, mapped water depths are less than 50 m and less than 20 m offshore of the steeper Zemlya Georga profile and that from Ostrov Greem-Bell, respectively (Figs. 6b, 7b). It should be pointed out that the contours are broken within 1 km offshore of the two relatively flat ice margins, and therefore the mapped bathymetric values can serve as no more than a guide to possible water depths at the ice cliffs themselves.

A more general study of bathymetric maps of the Franz Josef Land archipelago (prepared by G. G. Matishov) indicates that a number of the inter-island channels are between 300 and 500 m in depth, and reach a maximum of over 600 m. These areas are deeper than the surrounding Barents Shelf, and similar in depth to the St. Anna Trough to the immediate east of the archipelago. Most of the low gradient ice surface features mapped out in Figure 1 occur at the head of relatively deep troughs.

As well as being important for the modern distribution of possible ice shelves within the archipelago, these deep channels have implications for the nature and rate of disintegration of the larger ice masses that covered Franz Josef Land during the late Weichselian (Forman et al., 1992). As ice retreated into these relatively deep water channels from the generally shallower shelf during deglaciation, the rate of iceberg calving is likely to have increased significantly, forming an important mechanism of enhanced mass loss from the retreating ice dome or domes. This effect takes place because iceberg calving has been shown to be strongly dependent on water depth (Brown et al., 1982), and is related to increased buoyancy at the ice-ocean interface. Deglaciation may therefore have been relatively rapid once the retreating ice margins came off the relatively shallow shelf and reached the deep inter-island channels within Franz Josef Land. A modern analogue for the deep-water effect outlined above is found in Glacier Bay, Alaska, where receding ice margins encountering deep water have undergone average rates of retreat of over 0.5 km yr^{-1} sustained over observation periods on the order of 50 years (Powell, 1991).

Discussion: Possible Ice Shelves on Franz Josef Land

There are several interpretations for the low-gradient ice-cap marginal features described above (Fig. 1), including the possibility that at least some of these flat areas are floating ice shelves. Each of these interpretations is now evaluated briefly.

FLOATING GLACIER ICE

Several lines of evidence suggest that a number of the features described above may be floating ice shelves. They have smooth surfaces (Figs. 2, 3, 5) and low surface gradients of about 0.5° (Figs. 6, 7), consistent with a frictionless bed. These surface slopes are greater than those expected from floating ice in hydrostatic equilibrium, but this can be explained by their relatively narrow widths (often <2–3 km). This implies that they are partially supported by the rock walls at their sides (cf. Sanderson, 1979). They have marked breaks of slope at their inner margins, which are morphologically somewhat similar to grounding lines or zones at the inner margin of Antarctic ice shelves (Fig. 5).

Comparison of ice surface profiles from Franz Josef Land (Figs. 6a, 7a) with those of two ice shelves in Severnaya Zemlya (Fig. 4), including the relatively well known example of the Matusevich Ice Shelf (Zinger and Koryakin, 1965; Govorukha, 1988), show several similarities. Ice surface gradients are of the same order (about 0.5° or less) on the Severnaya Zemlya shelves as on the features described from Franz Josef Land. In both cases there is also a marked inflexion in the ice surface profiles, which is inferred to be associated with the change from floating shelf ice to grounded ice inland.

The features are, for the most part, located in embayments (Fig. 1) which provide lateral pinning points and protection from open ocean waves and swell, which would enhance iceberg calving. Water depths offshore of the features are generally 100 m or greater, and many are formed at the heads of fiord-like troughs. There is no requirement for deep water to occur beneath the features we observe, but simply that these low gradient marginal areas become buoyant over a significant part of their base. A minimum water depth of about 90% of ice thickness is needed, assuming that the shelf is composed of glacier ice rather than lower density firn. Tabular icebergs from 0.1 to 2.3 km across are observed on satellite imagery to calve from several of these ice fronts (Fig. 5), whereas it is generally only more irregular bergs of smaller dimensions that are calved from grounded ice margins (e.g. Dowdeswell, 1989).

THICK FAST ICE

Some ice shelves in Ellesmere Island and North Greenland are made up largely of sea ice, which has stabilized and thickened by surface and basal accumulation. This is unlikely to be the case for the Franz Josef Land features, since surface "flowlines" on Landsat imagery (Figs. 2, 3, 5) indicate that they are dynamically a part of the parent ice cap. The Ellesmere Island ice shelves are also characterized by regularly undulating surfaces, with linear meltwater ponds forming in the troughs (Jeffries, 1987). Undulations of this form are not observed on the surfaces of the Franz Josef Land features (Figs. 2, 3, 5).

DEFORMABLE GLACIER BED

Glaciers flowing over unlithified, deforming beds are also associated with low gradient ice surface profiles and very low basal shear stresses (Boulton and Jones, 1979). Where substrate transmissivity is low, basal water flow is retarded, water pressure builds up and bed deformations takes place. In extreme cases this may yield ice surface profiles similar to those for ice shelves (Boulton and Jones, 1979). Unlithified marine sediments, rather than a rock bed, are likely to provide the substrate where the seaward margins of Franz Josef Land ice caps are below sea level. It is difficult to rule out bed deformation as an explanation for at least some of the low gradient ice cap margins in Franz Josef Land without undertaking experiments in the field.

TRANSIENT EFFECTS DUE TO CLIMATE CHANGE

Little is published on climate change in Franz Josef Land over the last few centuries. However, on Svalbard and Novaya Zemlya, the islands to the west and south of Franz Josef Land (inset in Fig. 1), significant warming has taken place since the termination of the Little Ice Age at the beginning of the 20th century (Grosswald et al., 1973; Simoes, 1990; Hansen-Bauer et al., 1990). This has resulted in the retreat of many glaciers from prominent terminal moraines, and measurements of glacier mass balance in northwest Spitsbergen conducted annually since 1967 show consistently negative balance years (Hagen and Liestøl, 1990). If a similar climate warming has taken place in Franz Josef Land, then thinning of glacier margins would be expected, which could in turn lead to the development of floating ice shelves which were a transient phenomenon associated with ice cap readjustment to a lower net mass balance. Little direct evidence from Franz Josef Land is yet available to test this hypothesis, but Miller et al. (1992) report minor ice terminus recession of some terrestrial ice fronts from a Little Ice Age maximum.

QUIESCENT PHASE SURGE-TYPE GLACIERS

Low ice surface profiles are produced by stagnation during the quiescent phase of the glacier surge cycle. There is no evidence in the literature that glacier surges have taken place in Franz Josef Land, although large numbers of glaciers in the neighboring archipelago of Svalbard are known to be of surge-type (Dowdeswell et al., 1991). Examination of Landsat imagery of Franz Josef Land has also failed to find the looped medial moraines characteristic of surge-type glaciers elsewhere (Meier and Post, 1969). However, this may be due in part to the high proportion of ice caps, rather than valley glaciers, where medial moraines originating from rock outcrops do not form. An origin for at least a proportion of the low gradient marginal features through stagnation and thinning in the quiescent phase of the surge cycle cannot be ruled out. However, satellite observations on the adjacent Svalbard archipelago suggest that quiescent surge-type glaciers have greater apparent surface roughness than the Franz Josef Land features (Dowdeswell and McIntyre, 1987), and surface altimetric studies show that steeper surface gradients than those observed in Franz Josef Land (Figs. 6a, 7a) usually characterise the margins of Svalbard surge-type glaciers (Dowdeswell, 1986).

Conclusions and Further Work

We conclude from this discussion that the most likely interpretation is that at least a proportion of the flat, smooth ice cap marginal areas observed on satellite imagery of Franz Josef Land are floating, forming ice shelves that are linked dynamically to parent, grounded ice caps inland. We emphasize that deep water need not occur beneath the features, but simply that they are buoyant over a significant part of their base. Thinning of glacier ice, due to a shift towards more negative glacier mass balance since the termination of the Little Ice Age, may also have contributed to the presence of floating marginal ice shelves in Franz Josef Land today. Some low gradient ice cap margins may also be explained by deformation of an unlithified substrate, leading to low ice surface profiles.

Our continuing investigations of satellite imagery of the archipelago will include analysis of the stability or otherwise of the ice-ocean interface since the time acquisition of Landsat data began in 1973, and for the period between the availability of satellite data and the 1950s, when Russian vertical aerial photographs were first obtained. This will enable us to assess whether these floating ice shelves are a transient artifact of recent climate change or a more stable feature of the glaciology of Franz Josef Land.

Field experiments are also necessary to test whether our interpretation of the features described in this paper is correct. We suggest the deployment of radio-echo sounding equipment operating at VHF or UHF frequencies, together with drilling for shallow temperature measurements. Radio-echo sounding data can then be used to calculate power reflection coefficients at the ice-substrate interface, and a knowledge of temperatures would assist in specifying losses within the ice due to absorption. An ice-ocean interface would be expected, from theory, to be identified by a high reflection coefficient relative to an ice-rock or ice-sediment interface (Neal, 1979).

Acknowledgments

U.K. funding was through NERC Grant GR3/8507 to JAD. The Royal Society also provided financial support for satellite image purchase and for collaborative meetings in Cambridge and Moscow with Russian colleagues. We thank S. L. Forman, M. O. Jeffries, B. Lefauconnier, and M. F. Meier for helpful comments. Anne Jackson drafted the diagrams.

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Ms submitted May 1993