MEDDELELSER OM GRØNLAND

The columns of ikaite tufa in Ikka Fjord, Greenland

Paul Seaman and Bjørn Buchardt

GEOSCIENCE 44 · 2006

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Front cover: Diver collecting spring water from a cut column in Ikka Fjord at 8 m water depth. Photo Richard Martin.

Back of cover: Ikka columns in Ikka Fjord covered by red calcareous algae (*Lithotamnion*) and seaweed.
Photo Richard Martin.

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Abstract

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In Ikka Fjord in Southwest Greenland, tufaceous material is found associated with ikaite (calcium carbonate hexahydrate) over alkaline submarine springs. Ikaite tufa forms where mixing of alkaline spring water and cold seawater leads to supersaturation and instant precipitation. The submarine springs are fed by meteoric water that was percolated through a carbonatite cored, alkaline ring complex, known as the Grønnedal-Ika complex, belonging to the rift-related Proterozoic Gardar episode. The Ikka tufa structures grow into a variety of forms, predominantly columns known as Ikka columns, many up to 18 m high. Distribution and form of the tufa deposits and the submarine environment in Ikka Fjord have been mapped for the first time using echo-sounder traverses, lines of side-scan sonar imagery and seismic profiles from a 'pinger' sediment profiler. The maps show the extent of Ikka tufa development and distributional trends within the deposits. Hundreds of observations and photographs made by divers within the fjord, together with the maps, have enabled us to classify the tufas into five morphotypes: columns, fin-like structures, mounds, and hard grounds. Many of the tufas are arranged into lines and clusters. GIS analysis has revealed that the outcrop of the Grønnedal-Ika Complex, the proximity to stream mouths and bedrock exposures all control the distribution of the tufa deposits. Field observations have also shown that carbonatite dykes passing under the fjord are influencing Ikka column location. Where ikaite tufas form in abundance, maps of their distribution also indicate the pattern of submarine springs about the fjord bed.

Key words: Ikaite, Ikka Fjord, Greenland, tufa columns, submarine springs.

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Introduction

Thousands of calcareous tufa structures grow in the cold waters along the bottom of a 2 km stretch at the head of Ikka Fjord in Southwest Greenland (Fig. 1). The area is known as "The Ikka Column Garden" (Buchardt *et al.* 1997). All are formed from the carbonate minerals: calcite, monohydrocalcite and most notably ikaite (calcium carbonate hexahydrate $CaCO_3 \cdot 6H_2O$, Pauly 1963a; Buchardt *et al.* 2001). The term 'tufa' is used here according to the classification by Pedley (1990) and Pentecost & Viles (1994), to describe cool water deposits of highly porous or spongy freshwater carbonate. All these structures form in seawater, but from interaction with freshwater, and the term is therefore considered adequate. The predominance of columnar forms has led to the term "Ikka columns" to be used generally for the deposits, but other non-columnar forms have also been found and are often referred to as "Ikaite tufas", "Ikka tufas" or "Ikka tufa structures".

Ikaite was so named after the mineral was first found by Hans Pauly in 1963 (Pauly 1963a & b) forming naturally in the sheltered waters at the innermost end of Ikka Fjord, an area known as Ikka Bund (Fig. 1). Pauly reported skerries and tufaceous columns of ikaite that he suspected were growing over submarine springs issuing from the bottom of the shallow fjord. This location is the type locality for ikaite (from Ika, the old spelling of Ikka, meaning shallow in Greenlandic). However, the reasons why ikaite grows in Ikka Bund, the extent of the deposits and the controls over its formation were never explained and have remained unknown until recently.

This publication presents the first maps of the distribution of tufa structures on the floor of Ikka Bund. The mapping was undertaken to determine

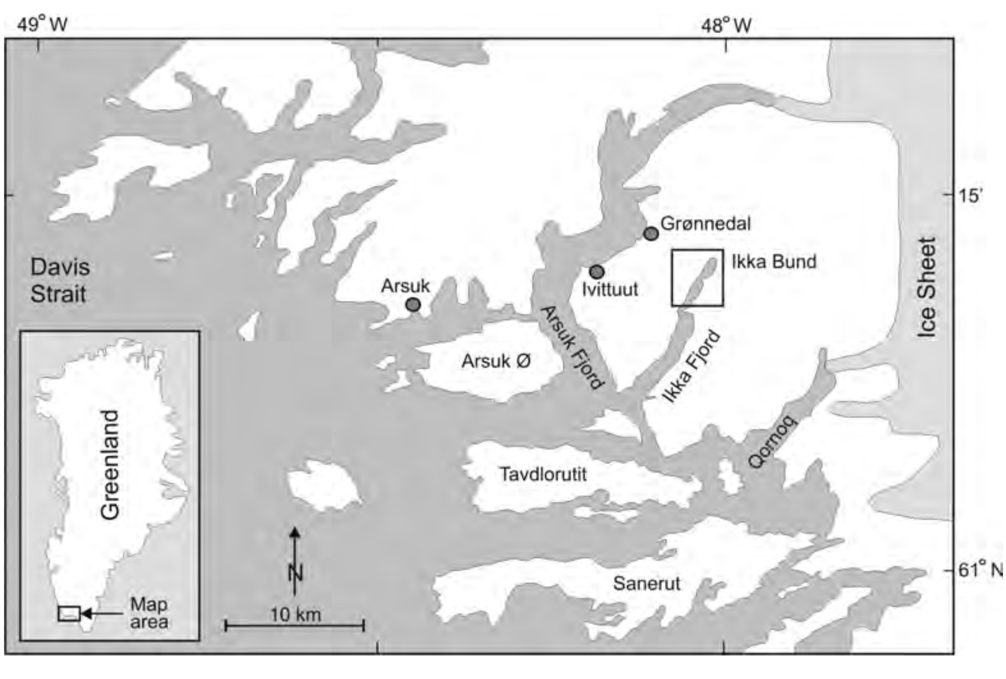

Fig. 1. The location of Ikka Fjord in SW Greenland. Ikka Bund is the identified area at the head of Ikka Fjord.

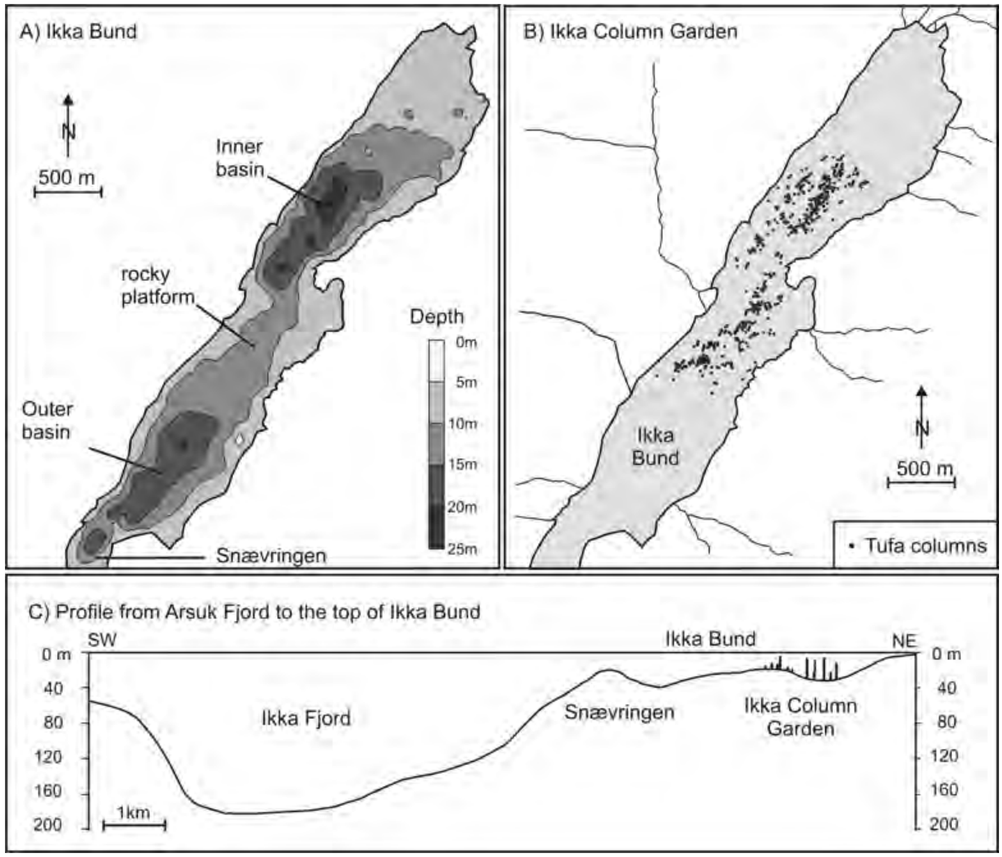

Fig. 2. Topography of Ikka Bund. A) Ikka Bund is divided into two basins separated by a shallower, rocky platform. B) The ikaite tufas are found in the inner basin and over the rocky platform. The tufa area has been named the Ikka Column Garden by Buchardt et al. *1997. C) A profile of Ikka Fjord shows how Ikka Bund and the Ikka Column Garden are located in a hanging valley that is only just flooded and presently below sea level.*

the extent of the deposits in Ikka Bund, to describe their distribution and morphology, and to investigate the relationship of their spatial distribution to the environment of the fjord. Geophysical surveys formed the basis of the mapping supported by direct observations using scuba diving equipment (Seaman 1998).

Since the summer of 1995 four expeditions – known as 'The Ikka Project' – have been made to the Ikka Fjord area by multinational groups of geoscientists, zoologists and botanists from the University of Copenhagen (Buchardt *et al.* 1996a & b) and Imperial College London (Seaman *et al.* 1997). The primary aim has been to provide an understanding of the formation of Ikka columns in Ikka Bund (Buchardt *et al.* 2001) and to document and study the abundant marine life associated with these columns (Thorbjørn 1996; Kristiansen & Kristiansen 1999; Petersen 1999; Sørensen & Kristiansen 2000; Stougaard *et al.* 2002; Thorbjørn & Petersen 2003). A wider goal included the public interest in the protection of the unique Ikka columns. This has been exceedingly successful, as the Greenlandic Home-rule Government (Grønlands Hjemmestyre) in the year 2000 passed a law including Ikka Fjord amongst the three first officially protected areas in West Greenland. Within a longer time frame, it is our hope to see the Ikka tufa columns included into the UNESCO World Heritage list.

Geological setting

Ikka Fjord is a threshold fjord with two distinct parts; a deep outer fjord and, inside a pronounced constriction known by the Danish name 'Snævringen' (the Narrowing), the much shallower inner fjord area of Ikka Bund. The profile in Fig. 2 shows that Ikka Bund is a former

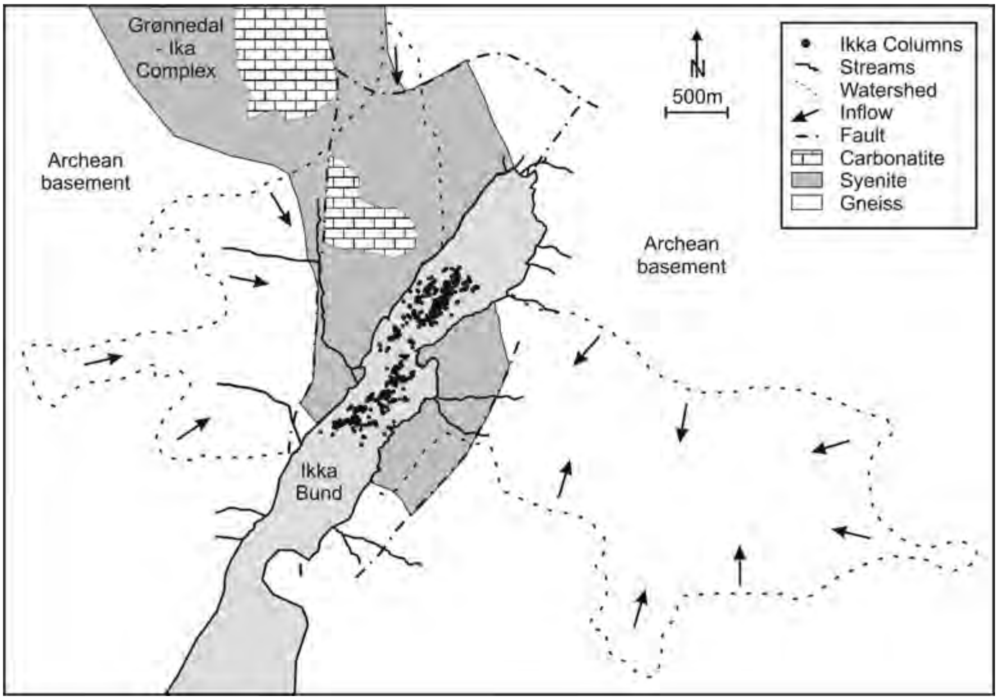

Fig. 3. The local bedrock geology of Ikka Bund demonstrating the juxtaposition of the columns with the outline of the Grønnedal-Ika Complex taken from Emeleus (1964). Also shown are the two catchment areas for Ikka Bund. Note the correspondence between carbonatite outcrops and the western catchment area.

hanging valley on the main body of Ikka Fjord. The constriction of Snævringen acts as a threshold that prevents much of the ice that accumulates in the outer sections of Ikka Fjord from entering Ikka Bund.

Ikka Fjord is flanked by steep, 500 m high mountains, dominated by monotonous Paleoproterozoic (Ketilidian) metasediments and gneisses (Allaart 1976). Alkaline magmas belonging to the rift-related Gardar episode intruded the area 1350 to 1100 Ma ago (Berthelsen 1962; Emeleus & Upton 1976), and one of these intrusions, the 1299±17 Ma Grønnedal-Ika complex (Emeleus 1964; Blaxland *et al.* 1978) cuts Ikka Bund in a NW-SE trending belt into (Fig. 3) (Emeleus 1964; Allaart 1976). The complex is composed of steeply dipping syenite and nepheline syenite arranged in a ring, 8x3 km in size, around a centrally emplaced plug of xenolithic syenite and carbonatite (Emeleus 1964). The intrusion of the carbonatite was a vigorous and forceful event evidenced by the high degree of brecciation in the surrounding rocks. The Grønnedal-Ika Complex was originally ovoid in plan outline but this form has been dramatically disrupted by episodes of faulting and later intrusions of Gardar dykes and sills.

The Grønnedal-Ika Complex was exhumed probably during the Tertiary and further exposed by successions of Quaternary glaciations. During these glacial episodes the Greenland Ice Sheet transgressed the present shoreline of Southwest Greenland extending into the Davis Strait, guided by, and over-deepening, the pre-existing Tertiary topography (Henderson *et al.* 1981). The last great expansion of the Greenland Ice Sheet occurred during the Late Weichselian Sisimiut glaciation when it transgressed the present coastline, reaching its maximum extent by around 14 ka (Kelly 1985; Funder 1989; Weidick 1976). After this the ice retreated and, in the Ivittuut-Nunarssuit region, the ice margin reached the present coastline by 10 ka. The deglaciation of the valleys of the Ivittuut peninsula, including Ikka Fjord itself, was complete by 8 ka (Kelly 1977) and the highest marine levels in the fjord are recorded at 35-55 m (Kelly 1977).

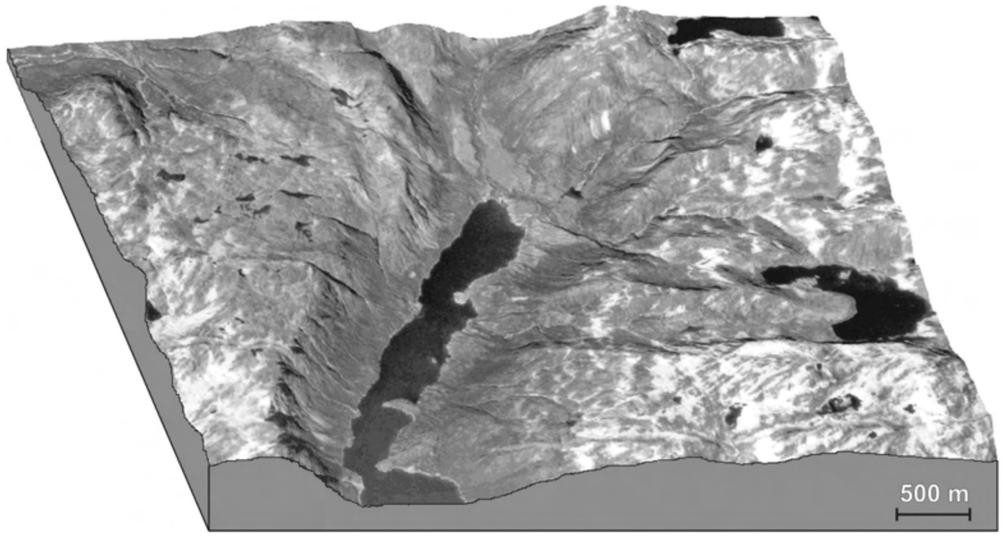

Fig. 4. Aerial photograph draped over a digital elevation model (DEM) of the surrounds to the fjord facing north. Compare Fig. 3 for details on the geology of the area.

The present landscape of the Ikka Fjord region is classified as an area of cirques and plateau remnants (Sugden 1974). The fjord itself is a steep-sided trench cut into a barren, hilly upland plateau with a mean elevation of 500 m above sea level (Fig. 4). Thick fluvioglacial deposits cover the low-level, flat surfaces all around the Ivittuut peninsula including Ikka Bund. Much of this material was deposited as alluvial fans from the surrounding hills; the lower portions of these fans, originally deltaic deposits, are now exposed through the isostatic uplift of the coastline associated with deglaciation. A thick blanket of these fluvioglacial deposits covers the innermost part of Ikka Bund, filling the broad confluence where two higher valleys meet at the northeast end of Ikka Bund (Fig. 4).

The present climate of the Ikka Fjord area is Low Arctic with average winter temperature during the coldest month at –5° C and average summer temperature for the warmest month at 9° C (Funder 1989). The average annual precipitation is between 1000 and 1200 mm (Fristrup 1971). Permafrost is not recorded in this area. Hydrographical observations have been performed in the fjord during the three Danish expeditions between 1995 and 1997 (Buchardt & Kristiansen 1998). The fjord is dominated by marine water with salinities close to 34‰ and summer temperatures at 10 m depth between 1 and 3° C. This water mass probably originates in the East Greenland Current, which bends around the southern tip of Greenland and in the summer influences the fjord systems of Southwest Greenland (Buch 1995). During the summer, the uppermost 2 to 5 m of the fjord water is less saline and warmer than the lower layers with a well-developed halocline. Surface waters are strongly influenced by river discharge and may become almost fresh. From November to May the fjord is covered by sea ice that can attain a thickness of 1.5 m (Rolf Darville, pers. comm. 1995).

Formation of ikaite tufas

The hexahydrate of calcium carbonate is a metastable mineral well-known from carbonate precipitation experiments in the laboratory, where it forms from mixing of supersaturated Ca^{2+} and CO_3^{2-} solutions (Hume & Topley 1926; Brooks *et al.* 1950; Dickens & Brown 1970). The mineral growth is favoured by temperatures close to 0° C and by high phosphate concentrations in the solution, which inhibits the nucleation of calcite and aragonite (Brooks *et al.* 1950; Bischoff *et*

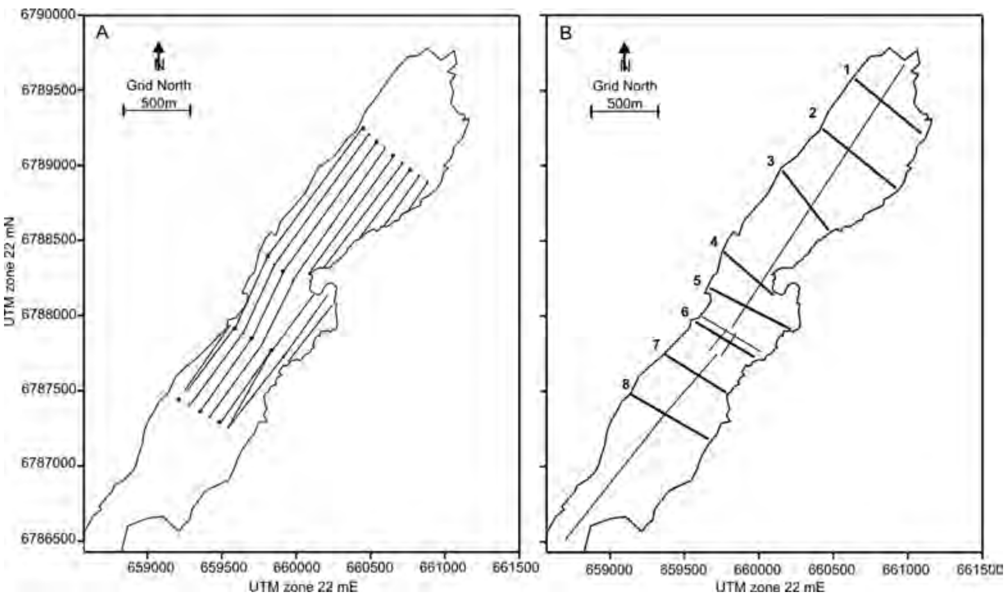

Fig. 5. Track charts for the side-scan sonar (A) and 'pinger' (B) surveys performed in Ikka Bund. Numbers in (B) refer to pinger profiles in Figs 10 and 11.

al. 1993a). If kept at room temperature, the hexahydrate will decompose within hours to calcite and water. The first described natural occurrence was in Ikka Fjord (Pauly 1963a & 1963b), and the mineral has subsequently been identified in many natural cold-water environments, both in the deep ocean (Suess *et al*. 1982; Stein & Smith 1986; Jansen *et al*. 1987), in shallow Arctic waters (Kennedy et al. 1987; Greinert & Derkachev 2004), in lakes (Council & Bennett 1993; Bischoff et al. 1993b), and in cold water springs in Japan (Ito 1996; Ito 1998) and Canada (Omelon *et al.* 2001). Normally, ikaite is found as single crystals or simple crystal aggregates up to several centimetres in length growing in mud. However, precipitation at springs favour much smaller crystal sizes, and tufa textures are formed in association with ikaite at these localities, either as subaerial crusts and mounds or as subaquatic columns. The enigmatic calcitic pseudomorphs known as glendonite and thinolite have been suggested to originate as ikaite crystals (Shearman & Smith 1985; Shearman *et al*. 1989) and may thus have potential as a palaeoclimatological indicator.

It is generally accepted that ikaite crystals forming the tufa columns in Ikka Fjord are chemical precipitates grown from mixing of alkaline submarine spring water and seawater (Pauly 1963b; Buchardt *et al.* 1997; Buchardt *et al.* 2001). The closelying Grønnedal-Ika Igneous Complex forms the catchment area for local precipitation flowing into Ikka Bund, and part of this precipitation infiltrates the faulted and fractured carbonatitic centre. This water probably dissolves secondary sodium carbonate minerals in fractures such as pirssonite and gaylussite formed from reactions between carbonatite and sodium-rich syenitic rocks and thereby attains its high sodium alkalinity. Likewise, phosphate from the carbonatite dissolves in the water. A high hydraulic head forces the water out under Ikka Fjord, where its forms submarine springs penetrating an impermeable glaciomarine clay layer under the fjord bottom. The stable isotope composition of the spring water (collected from inside the columns, see also Fig. 17) has a signature compatible with precipitation at 500 m elevation thus supporting this generative model. Moreover, the small ^{14}C-activity of newly precipitated ikaite (14-17% modern) indicates a large contribution of

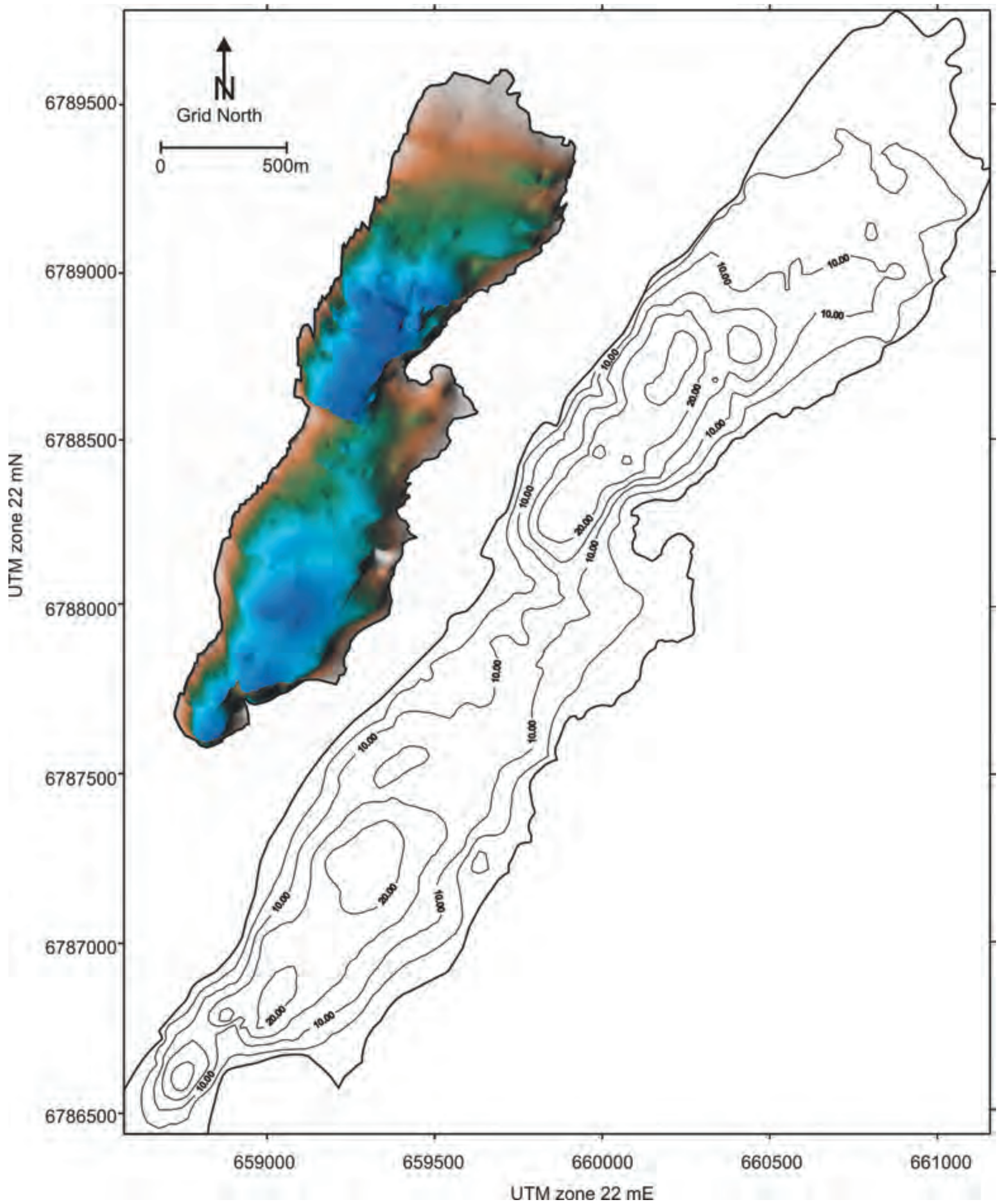

Fig. 6. The bathymetry of Ikka Bund. Contour intervals are 5 m. Offset from the contour map is a coloured, shaded relief model of the bed of Ikka Bund where shallow areas are represented in browns and deeper areas in shades of blue.

"dead" carbon from the Precambrian intrusive carbonatitic rocks (Vous 1998, Buchardt *et al*. 2001). One of the major purposes of the present study was to evaluate the spatial distribution of the tufa structures in relation to general orientations of fractures and dykes in order to obtain a better understanding of the postulated fluid flow systems.

Under normal conditions, calcite or aragonite rather than ikaite would be expected to precipitate, as the solubility of ikaite is one to two orders of magnitude larger than that of calcite and aragonite (Bischoff *et al.* 1993a). However, the low temperatures in the fjord (2-6°C) and the high phosphate content of the spring water favour the precipitation of ikaite over the other carbonate minerals. Columns exposed to seawater for longer periods of time seem either to dissolve or to recrystallize into calcite. An intermediate product of the recrystallization process is the rare mineral monohydro-

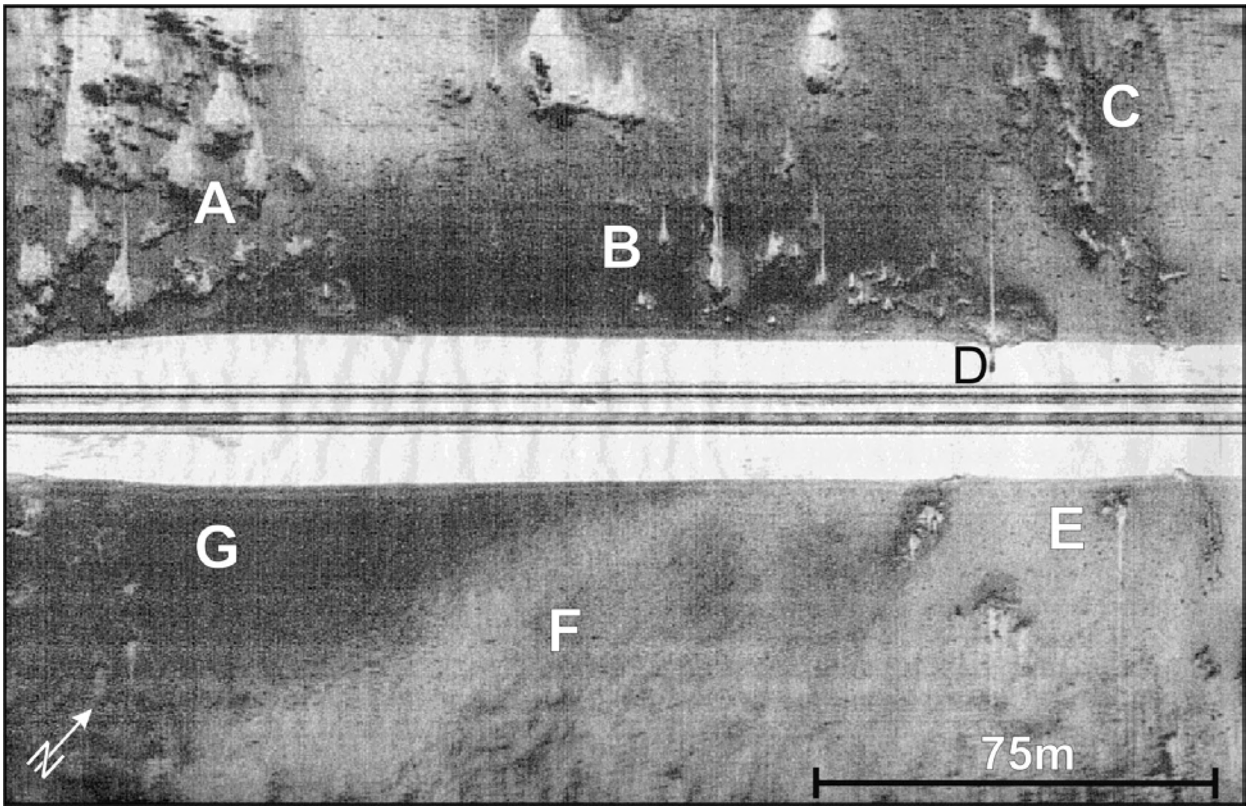

Fig. 7. Example section of the side-scan sonar data acquired in Ikka Bund. The image shows a section of the middle fjord bed with many small and medium sized ikaite columns, with their characteristic long white shadows, poking through recent, muddy bottom sediments. A) Cluster of small ikaite skerry-like mounds formed from more massive, rather than columnar, ikaite growth. B) Cluster of ikaite columns growing directly from a muddy area of fjord bed. C) Ikaite columns growing in a line. D) Ikaite column seen in the water column as the side-scan sonar passed directly overhead. E) Small clusters of ikaite columns. F) Featureless, flat muddy area of fjord bed. G) Dark area of high reflectance is caused by the fjord bed sloping west, back towards the towed sonar fish.

calcite ($CaCO_3 \cdot H_2O$) hitherto known only from freshwater systems (Dahl & Buchardt 2006). Broken and fallen columns are common on the fjord bed and form talus cones surrounding some of the active columns.

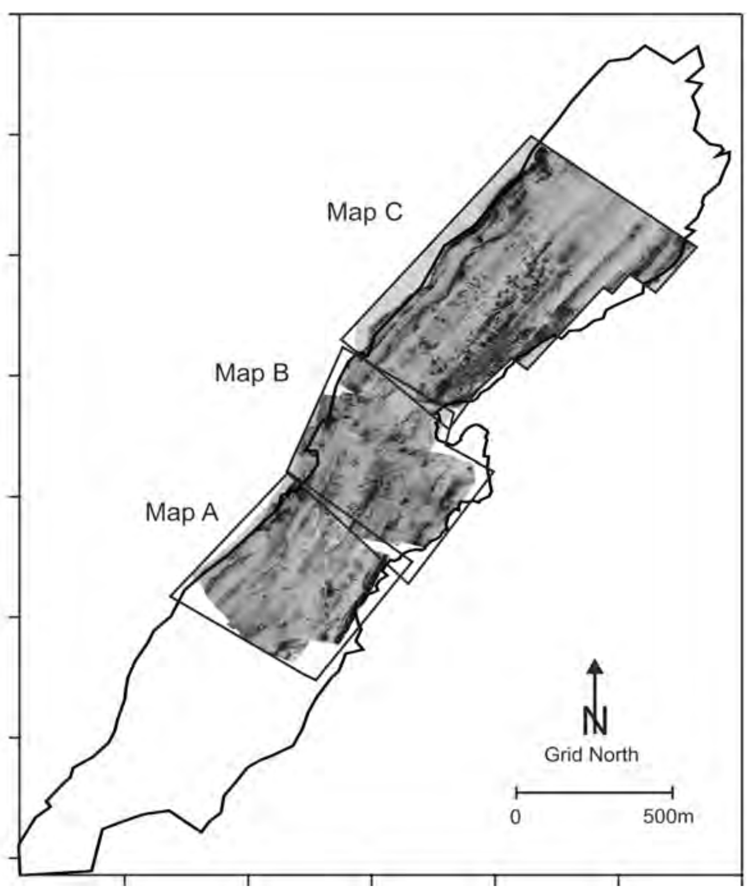

Fig 8. The three blocks of side-scan sonar mosaics produced from the scanned paper records.

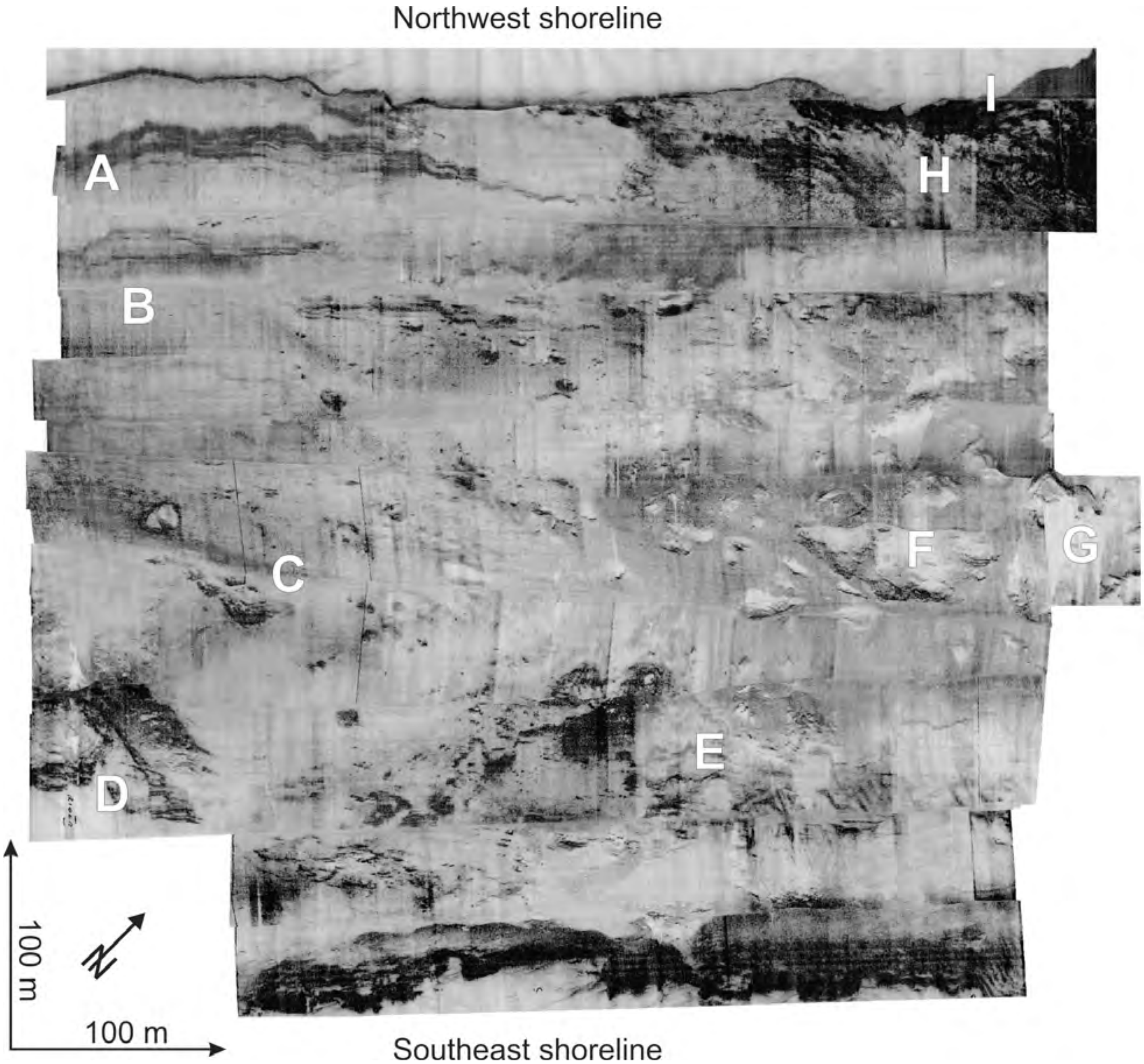

Fig. 9A. Sonar block A. The sonar mosaic reveals the seabed morphology of the outer fjord area of ikaite column development.
A – Fjord-parallel terraces stepping down towards the centre of the fjord.
B – Fjord bed sloping down into the outer basin. Featureless mud-covered bottom.
C – The polished forms of the roche moutonnées are blanketed in mud on the slope down into the outer fjord basin.
D – Small island with a rocky slope descending down northwest into the fjord.
E – Shallow rocky fjord bed. The spaces between the rocky outcrops are filled with sediments.
F – Central zone of roche moutonnées with numerous ikaite columns.
G – Ikaite skerry atop a roche moutonnée. The skerry casts a long shadow towards the southeast shore.
H – Dark, highly reflective surface of the foot of a scree-slope that extends down below the waterline.
I – The northwest shoreline is composed of reworked material from the scree slopes that extend offshore.

Dating the Ikka columns

Attempts to date the columns by the ^{14}C-method have proved unsuccessful as most of the carbon in the column ikaite is not radioactive. Even the newly formed column tops collected from the cut structures showed less than 15% of modern ^{14}C-activity corresponding to apparent ^{14}C ages of more than 16,000

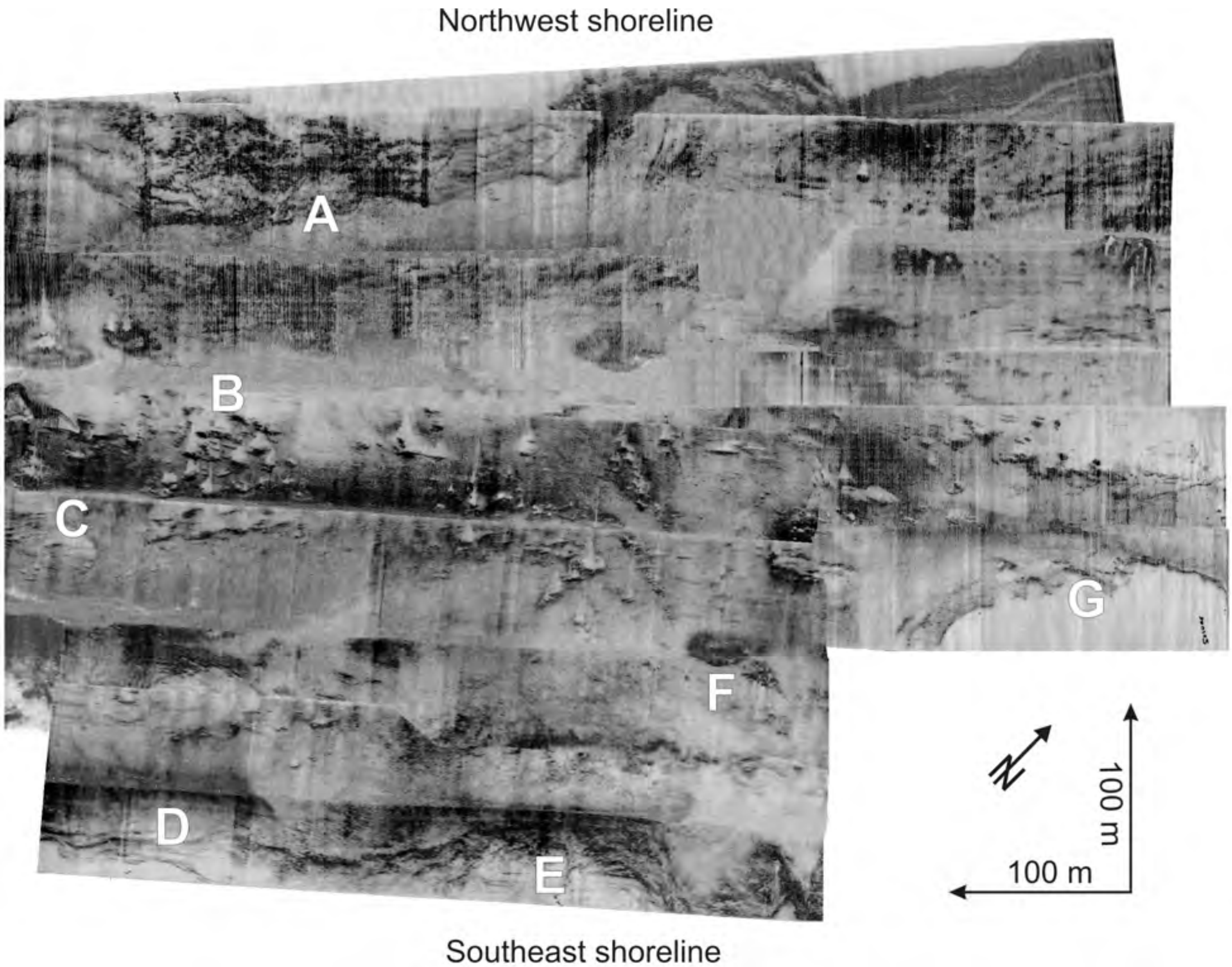

Fig. 9B. Sonar block B. The sonar mosaic reveals the seabed morphology of the seabed morphology of the mid-fjord area of ikaite column development.
A – Slope of coarse material of a submarine outwash fan extending from the mouth of a stream.
B – Ikaite skerries atop roches moutonnées.
C – Central zone of roches moutonnées and ikaite skerries with numerous ikaite columns.
D – Sloping side of the fjord with rock exposures.
E – Outwash fan of stream draining the highland plateau to the southeast. The present channel can be seen.
F – Patch of boulders with several ikaite columns surrounded by mud.
G – Central peninsular that juts out across the middle of the fjord and separates the rocky platform of the shallow outer fjord to the southwest from the sediment-filled, deep inner basin to the northeast.

years (Buchardt & Kristiansen 1998; Vous 1998). The high content of 'dead' carbon in the column carbonates is in accordance with the hypothesis that the carbonate ions have their origin from the dissolution of the Precambrian carbonatite rocks in the Grønnedal-Ika Complex (Buchardt *et al.* 2001). It is thus not possible to give ages for the columns, but the very high growth rates of new columns combined with the metastability of ikaite point to a young age for most of the smaller columns. The fjord was transgressed by seawater following local deglaciation by about 8 thousand years ago (Kelly 1977), defining a maximum age for some of the larger structures such as the Skerry, but the majority of the columns are probably much younger.

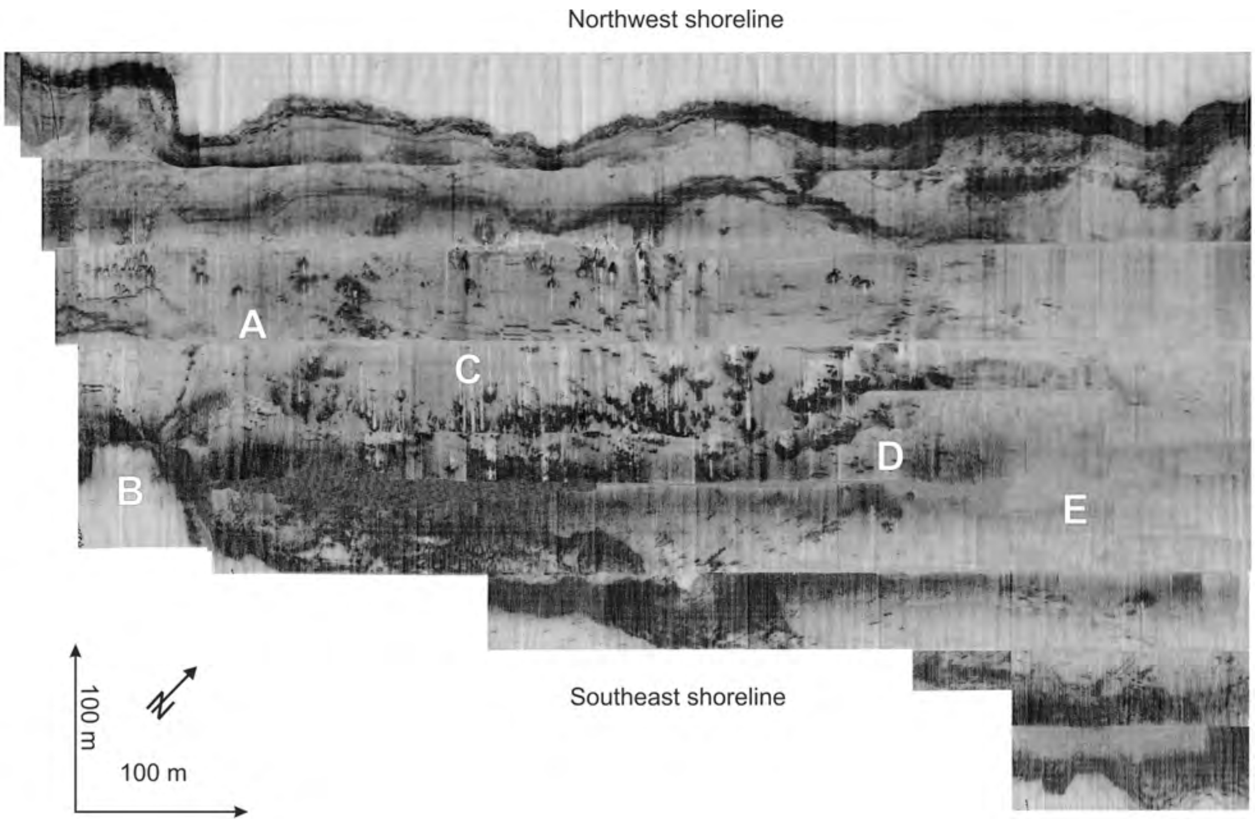

Fig. 9C. Sonar block C. The sonar mosaic reveals the seabed morphology of the inner-fjord area of ikaite column development.
A – Deepest part of the inner basin, a muddy bottom scattered with clusters of ikaite columns.
B – Central peninsular that juts out across the middle of the fjord marking the start of the inner fjord basin. This basin extends northeast until a sudden slope up to the raised inner fjord platform.
C – Line of 'giant' columns extending along the mid-line of the fjord. These tall columns grow from a gently sloping muddy bottom and cast long white 'shadows' across the imagery. Talus cones of mud and column fragments are seen as the circular patches at the foot of each column.
D – Mud covered slope descending into the inner-basin.
E – Raised inner fjord shelf, a featureless muddy plain believed to be reworked fluvioglacial deposits from Ikka Bund.

Mapping the ikaite occurrences in Ikka Fjord

Techniques

Three geophysical techniques were employed to map the locality: an echo sounder survey, a side-scan sonar survey, and a high-resolution seismic 'pinger' survey. This provided the means to map fjord bed features at a scale of 1:1,500. Topographic maps of the Ikka Fjord area at this scale are unavailable and it was therefore necessary to survey the shoreline of the fjord using a total station theodolite to acquire an accurate framework for referencing the geophysical surveys. The surveys were executed along previously chosen traverse lines, defined by buoys and shore markers positioned into the local UTM Zone 22 north grid (WGS84 Spheroid and Datum) using a Differential Global Positioning System (DGPS) (Fig. 5)

Diving investigations of Ikka Bund

The clear, shallow waters of Ikka Bund, although cold, are accessible to divers using compressed air. Each expedition made by the Ikka Project was assisted by

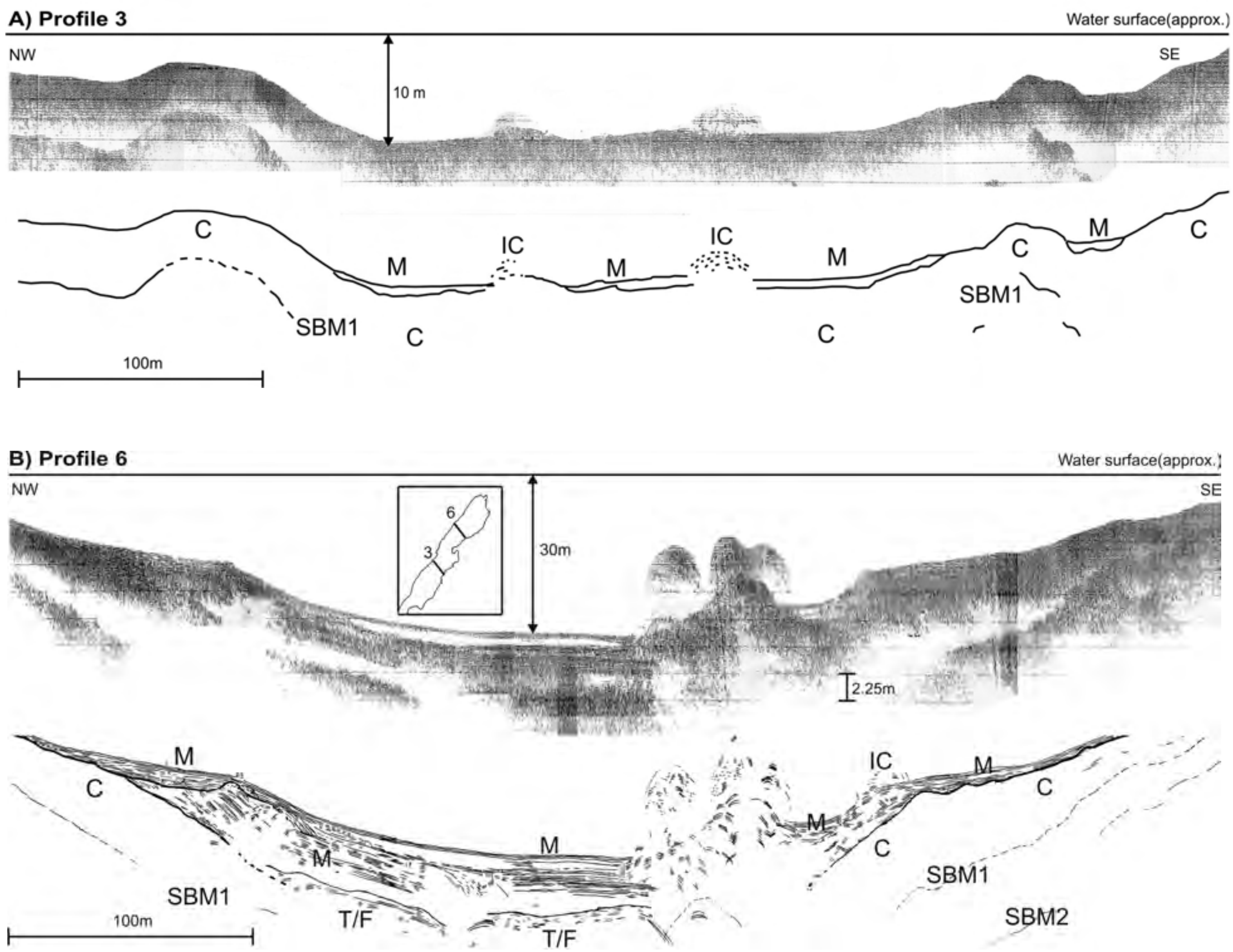

Fig. 10. Examples of the pinger sub-bottom profiles acquired in Ikka Bund. Interpretation of pinger profiles 3 (A) and 6 (B). Profile 3 passes across the shallow rocky platform area that separates the inner and outer basins. Profile 6 passes through the inner basin, the zone of the largest ikaite tufa columns found in Ikka Bund. IC: Ikka column, M: mud, T/F: till/fluvioglacial deposits, C: crystalline bedrock, SBM: Sub-bottom multiple.

divers who were instructed to make direct observations of the locality, to collect geological and biological specimens, to make detailed photographic and video records of the locality and to perform "ground-truthing" of the remote sensing geophysical surveys. Over the course of the three field seasons, the divers have performed in excess of 300 dives in Ikka Bund covering most areas of the fjord bed.

The Ikka columns come close to the surface and are a hazard to craft with draughts deeper than 2 m, so most diving was performed from inflatable boats. Repeated diving of one specific location was greatly assisted through the use of a floating platform that was moored in position. This provided a base from which to undertake experiments and tasks requiring many dives and non-diving scientists who could not have been accommodated on the small inflatables. Dives lasted typically twenty to thirty minutes but on occasion up to an hour depending on the tasks to be performed. The non-diving scientists were able to communicate with the divers through underwater telephones. On a number of occasions the divers used video cameras attached to their masks in conjunction with the tele-

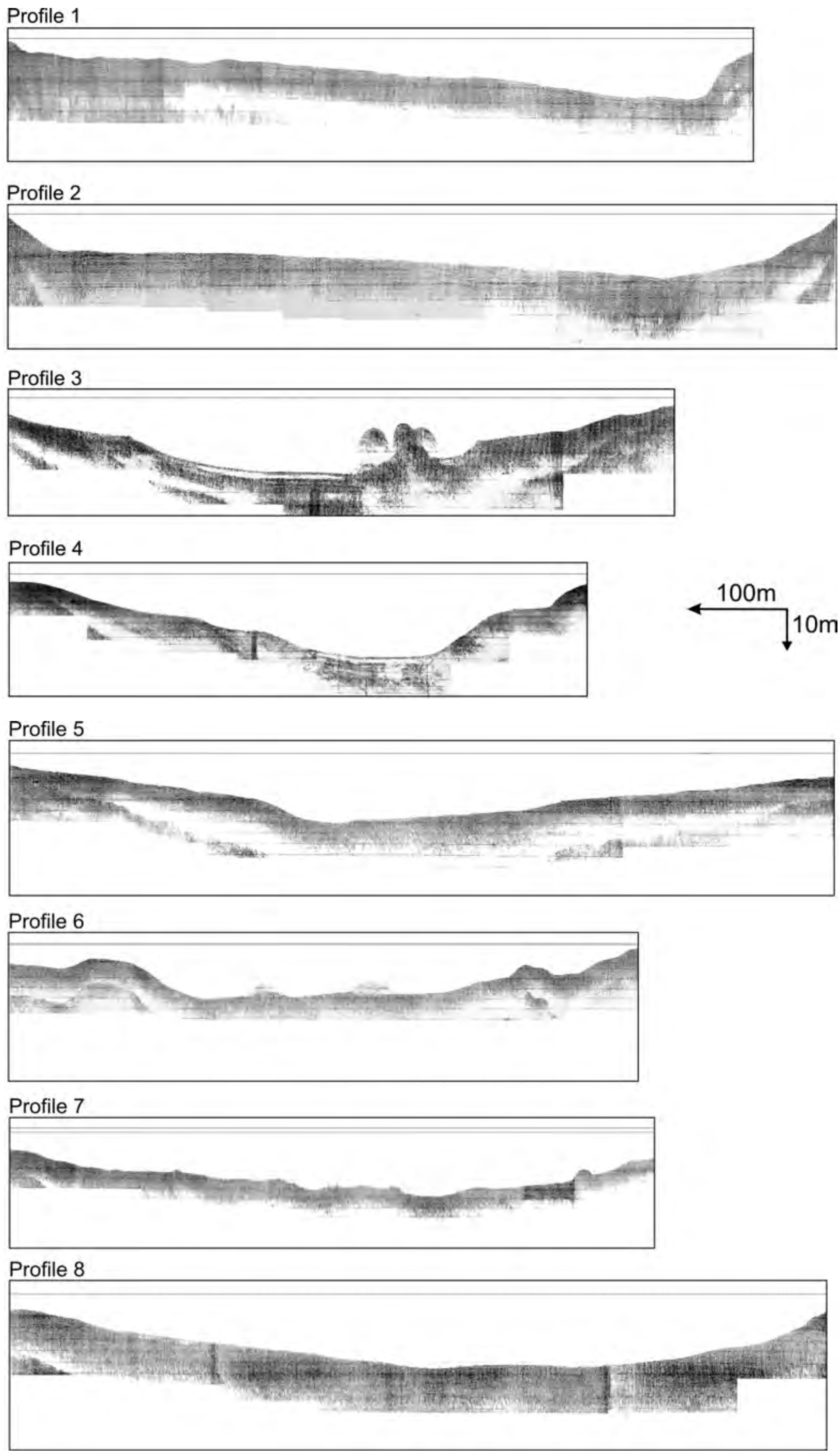

Fig. 11. West to east pinger profiles at regular section along Ikka Bund. The locations of these profiles are shown on Fig. 5.

phones allowing guided instructions from the scientists to be given and videotaped records of their work to be made.

Bathymetric survey of Ikka Bund

The bathymetry of Ikka Bund was mapped using a hybrid of data acquired from the echo sounder, the side-scan sonar and the pinger. In all, 1037 separate depth observations were made and each tidally adjusted to Chart Datum i.e. the level experienced at low water on a mean spring tide (Shufeldt & Dunlap 1981). Ikka Bund experiences a tidal range of up to 3 m.

The contoured bathymetric map (Fig. 6) was produced through the interpolation of a fine grid of depths created from the actual observations made. The interpolation was performed using geostatistical techniques, namely kriging following variogram analysis (Isaaks & Shrivastava 1989), producing a map that represents statistically the best, unbiased estimate of depth for all locations in Ikka Bund.

Side-scan sonar survey

The side-scan sonar survey was made to provide imagery for mapping and analysis of the details of the fjord bed, in particular the positions of the Ikka columns (Fig. 7). The survey was performed along traverse lines that were parallel to the sides of the fjord (Fig. 5) using a Klein Model 400 System, which is a wet-paper 100 kHz analogue side-scan sonar device. Line to line overlap of the sonar imagery was 30% providing total data coverage across the whole survey area.

The rolls of sonar imagery were scanned and mosaiced to create a three-part image of the floor of the fjord over which the columns are found (Figs 8 & 9). These images were georeferenced to the UTM Zone 22-north grid using a polynomial transformation in the GIS package IDRISI (Clark University 1997). Features on the fjord bed including Ikka columns and rock exposures were all mapped directly from the same georeferenced images.

Shallow seismic reflection 'Pinger' survey

The pinger was used to (1) acquire high-resolution seismic reflection profiles across Ikka Bund, (2) to investigate the sub-surface features of the columns, (3) to produce a sediment isopach map and (4) to provide a stratigraphy of the sedimentary fill in the fjord (Figs 10 & 11). The equipment used was an Ocean Research Equipment (ORE) Model 1032 analogue Sub-bottom Profiling System with a maximum vertical resolution of 0.3 m. Data from this system were recorded in the form of profiles on a wet paper depth recorder. Fifteen different traverses were made, profiling both along and across the fjord, concentrated in the area of the Ikka Column Garden (Fig. 5). Eight of these traverses are presented in Fig. 11.

The pinger data were interpreted using a seismic velocity of 1600 ms^{-1} (Milsom 1989), which assumes that the sedimentary fill in the fjord is composed of unconsolidated soft mud and clay with some glacial sand and gravel. These measurements were then used to produce a stratigraphy and a sediment isopach map for the unconsolidated sedimentary fill in the fjord. Attempts at gravity coring to substantiate the stratigraphy were unsuccessful due to technical problems. This meant that the stratigraphy constructed was inferred from seismic character of sediments, supported by; (1) shoreline and diving observations of the sediments lining the fjord bed and (2) the side-scan sonar imagery which showed the locations of bedrock exposures and differing sediment types about the fjord bed.

Results

The environment of Ikka Bund

The bathymetric survey reveals that the waters of Ikka Bund are much shallower than those in the outer regions of Ikka Fjord, having a maximum depth of only 30 m. This is in sharp contrast to the depths of the neighbouring fjords, such as Arsuk Fjord, which in places is over 600 m deep.

The side-scan sonar and pinger surveys have revealed Ikka Bund to be a flat-bottomed trench partially filled with sediments. Two basinal depressions, The Inner and Outer Basin, are separated by a shallow rocky area. This Rocky Platform is only partly covered by a thin veneer of sediments and frequently exposes the local bedrock (Fig. 12). Scree and stream-outwash fan deposits extend out into the fjord at several locations and extensive fluvioglacial deposits cover the bedrock surface at the northeast end of the fjord. The fjord sides are flanked by a series of shore-parallel steps or terraces particularly well developed on the northwest shore. These terraces are interpreted as the reworked toes of scree slopes, interrupted by occasional exposures of bedrock. In the basinal areas, much of the central axis of the fjord consists of a featureless plain covered with mud punctuated by roches moutonnées and Ikka columns.

Ikka columns are common features in the sonar imagery that are easily identified from the long pointed "shadows" they cast across the fjord bed (Figs 7 & 9). The columns are seen to grow on rocky outcrops or directly out from the mud that covers the flat areas of the fjord bed. Talus cones at the bases of the larger columns are imaged as dark circular patches (the appearance of coarse sediments on side-scan sonar imagery) against the surrounding flatter, lighter-toned mud.

The varied nature of the fjord bed means that the cross sectional pinger profiles differ markedly from section to section along the fjord. They do however, have many features in common that are exemplified by profiles 3 and 6 (Fig. 10). Profile 3 was made through the Inner Basin where the waters are relatively deep and tidal current activities are confined to the surface layers. The profile reveals the southeast side of the fjord to be composed of shallowly buried roches moutonnées draped in a thin cover of beach sediments and marine mud. Across the middle part of the profile the fjord was found to be a deep trough filled by an estimated 15 m of sediments, Unit M, interpreted as very soft mud. Underlying Unit M is a strong reflector interpreted as the top of glacial sands, gravel and clays resting on the bedrock itself, which is not seen.

A column, with a talus cone fringing its base, was ensonified directly by the pinger pulse and is imaged in Profile 3 in the water column revealing its location. Two further columns were ensonified by 'side swipe' of the pinger footprint (in the periphery of the ensonified zone) and are imaged as detached parabolic reflections in the water column. Moving up out of the basin towards the northwest of the pinger profile, the fjord bed is again composed of crystalline bedrock, shallowly buried by very soft mud that thins to no more than a veneer close the shoreline.

Profile 6, acquired across the Rocky Platform, serves to demonstrate the contrast between this area of the fjord bed and the Inner Basin. Sediment cover across the Rocky Platform is patchy and

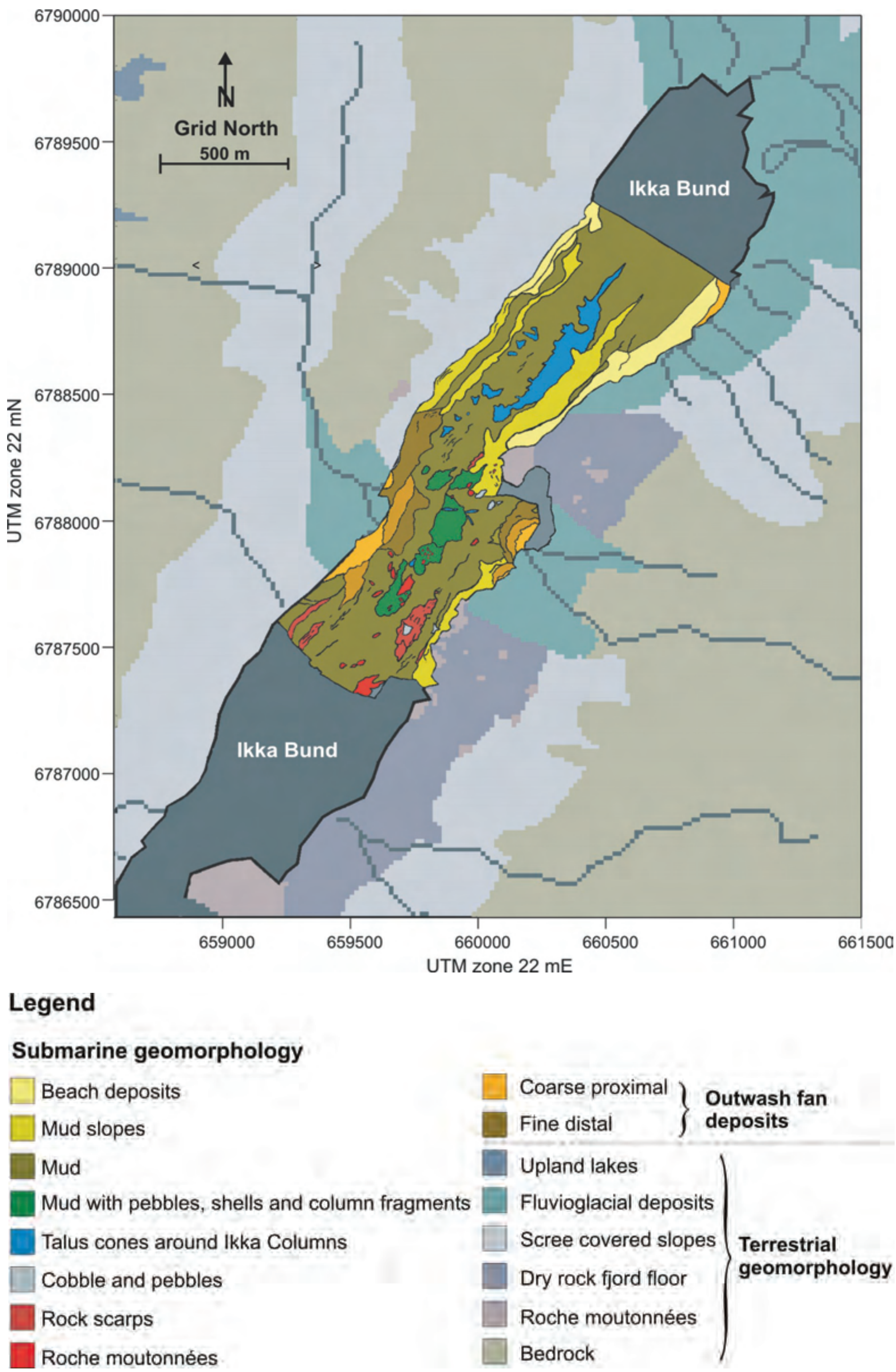

Fig. 12. The mapped geomorphology of Ikka Bund. The Fjord bed sediments and geomorphological features were derived from the side-scan sonar data and visual inspection by divers whilst terrestrial geomorphology derived from the interpretation of the aerial photograph in Fig. 4.

thin, resulting in a highly irregular fjord bed profile with frequent bedrock exposures in the form of roche moutonnées. The pinger energy is only able to effectively penetrate into the sediment veneer and is strongly reflected by the crystalline bedrock.

Glaciomarine clays have been recorded at a few localities along the fjord shoreline and exposures on the fjord bed (Fig. 12). The clay, which is grey and plastic, probably forms a continuous impermeable cover over most of the fjord bottom. A combined sample of several specimens of arctic shells (*Hiatella byssifera, Macoma calcarea*, *Mya eideri* and *Balanus crenatus*) found within the clay were dated through ^{14}C dating and found to be close to 8,400 calibrated ^{14}C years (Vous 1998) reflecting the first marine transgression into the fjord after the deglaciation.

The nature of the tufa deposits in Ikka Bund

Most of the structures in Ikka Bund are columns ranging from a few centimetres to 18 m in height. Actively growing regions of these columns have a fresh white appearance whereas the older areas are buff coloured and invariably colonised by rich communities of sessile marine life that add many other colours to the column surfaces. Calcareous algae belonging to the genera *Lithothamnion* and *Clathromorphum* are abundant as are a number of different species of echinoids, tunicates, sea anemones, tubeworms, bivalves and snails (Düvel 1996, Thorbjørn & Petersen 2003). Some of the patches of fresh ikaite found on the trunks of the columns are presumed to have formed following the release of column water by boring organisms breaching the otherwise impermeable walls of the ikaite structures. Ikaite precipitation immediately followed the release of this column water.

The Ikka columns in Ikka Bund can be classified into four types: columns, fins, mounds and hardgrounds. These morphotypes have been given descriptive names in the spirit of tufa structures named by other authors, in particular King (1878), Dana (1884), Russell (1885), Shearman & Smith (1985) and Benson (1994) (Fig. 13).

Columns

The tufa columns vary in height from finger-sized spikes to great towers, but typically they are between 1-5 m high and 0.2 to 1.0 m wide (Fig. 14). The sides of the columns are parallel or slightly tapering and tend to be rugged in outline with finger-like protuberances of fresh ikaite, algal mounds and eroded pits and crevices. There is a great variety in the ratios of column widths to column heights so that some columns are short and fat whereas others are very tall, slender and needle-like, giving the appearance of being impossibly fragile structures.

Ikka columns terminate in a number of ways ranging from simple blunt or pointed tips, flat crest-like crowns, multiple spires, bulbous knobs and branching horns (Fig. 15A-H). Blunt or pointed tips are the most common forms observed. The rare, crest-like terminations can be up to 1 m across and are seen on the largest columns close to the fjord surface.

Larger columns commonly appear to be created through the amalgamations of clusters of individual columns. One of the largest columns so far seen in Ikka Bund is formed from such an amalgamation, the total structure being approximately 15 m tall and elongated into a fin 5 m wide and less than a metre thick at its tip (Fig. 15G). The top of this column comes to within 1.5 m of the fjord surface at low tide and has a horizontal surface, giving the appearance of being milled flat. Prolific precipitation of fresh ikaite forms a small, fringing crest around its top showing that it is still actively growing. A further 5 m of this composite column are estimated to be buried under a talus cone that shrouds its base. The talus is formed from very soft mud strewn with tufa and algal fragments. This mud is thought to be composed of the eroded remains of the column tips, ground down by winter ice, and the faecal material of the organisms

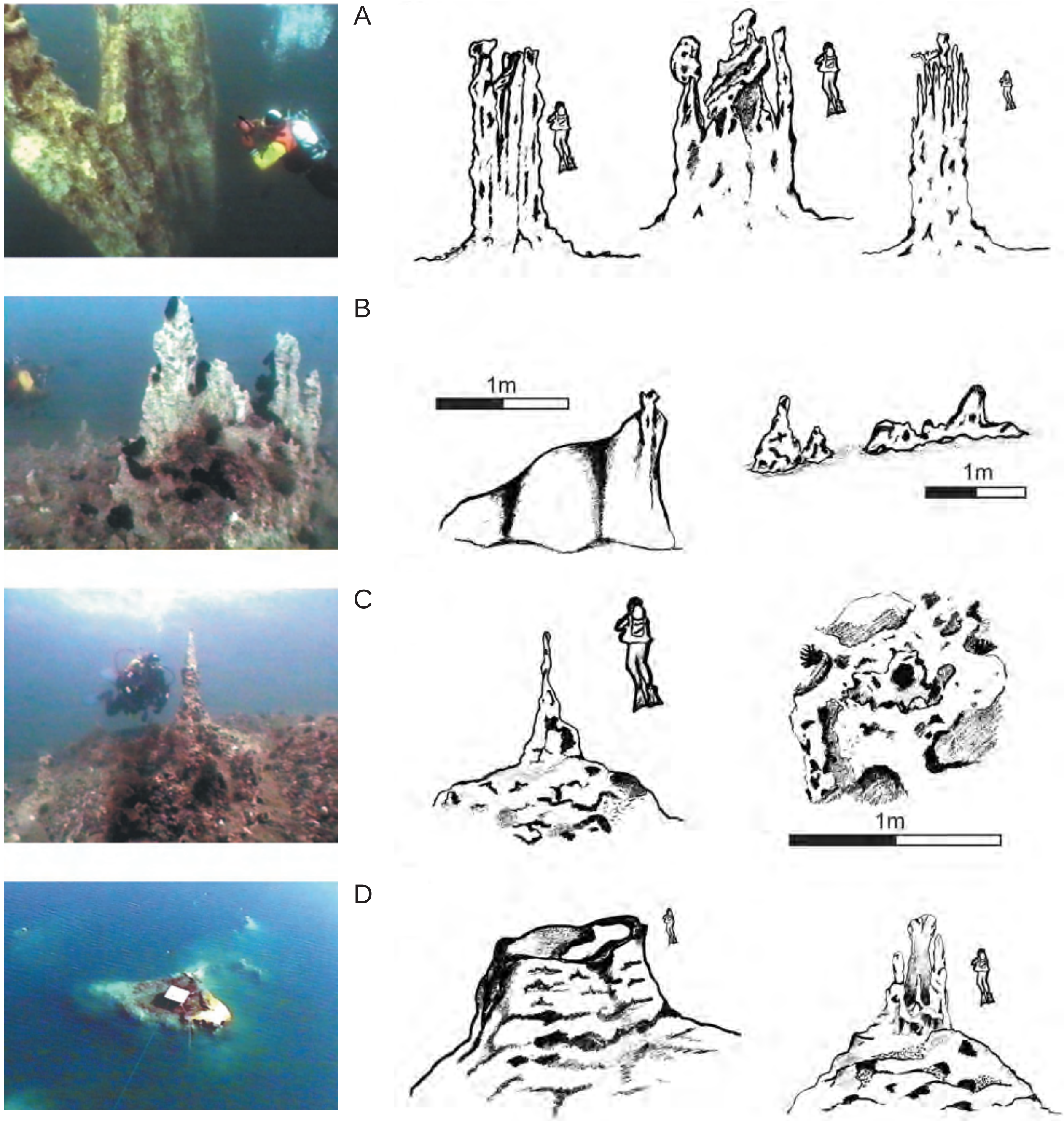

Fig. 13. Ikka tufa classification scheme. Ikka tufa structures in Ikka Bund. A) Columns, sketches show simple column forms with bulbous, crested and multiple spire tip terminations. B) Fins. C) Encrustations, sketches show encrustation around the base of a small column and plan view of area of encrusted fjord bed. D) Mounds, sketches show the skerry (seen from the air in the photo) and a mound crowned with a cluster of small columns. Diver for scale.

grazing the column surfaces. The large tidal range in the fjord means that the tips of the columns are likely to be hammered and abraded repeatedly by the underside of the winter ice.

A characteristic feature of the columns is hollow or very porous interior conduits, which form the piping necessary for spring water flowing within the structures to reach the growth areas at the top of the columns. One column was removed and x-rayed and x-ray pho-

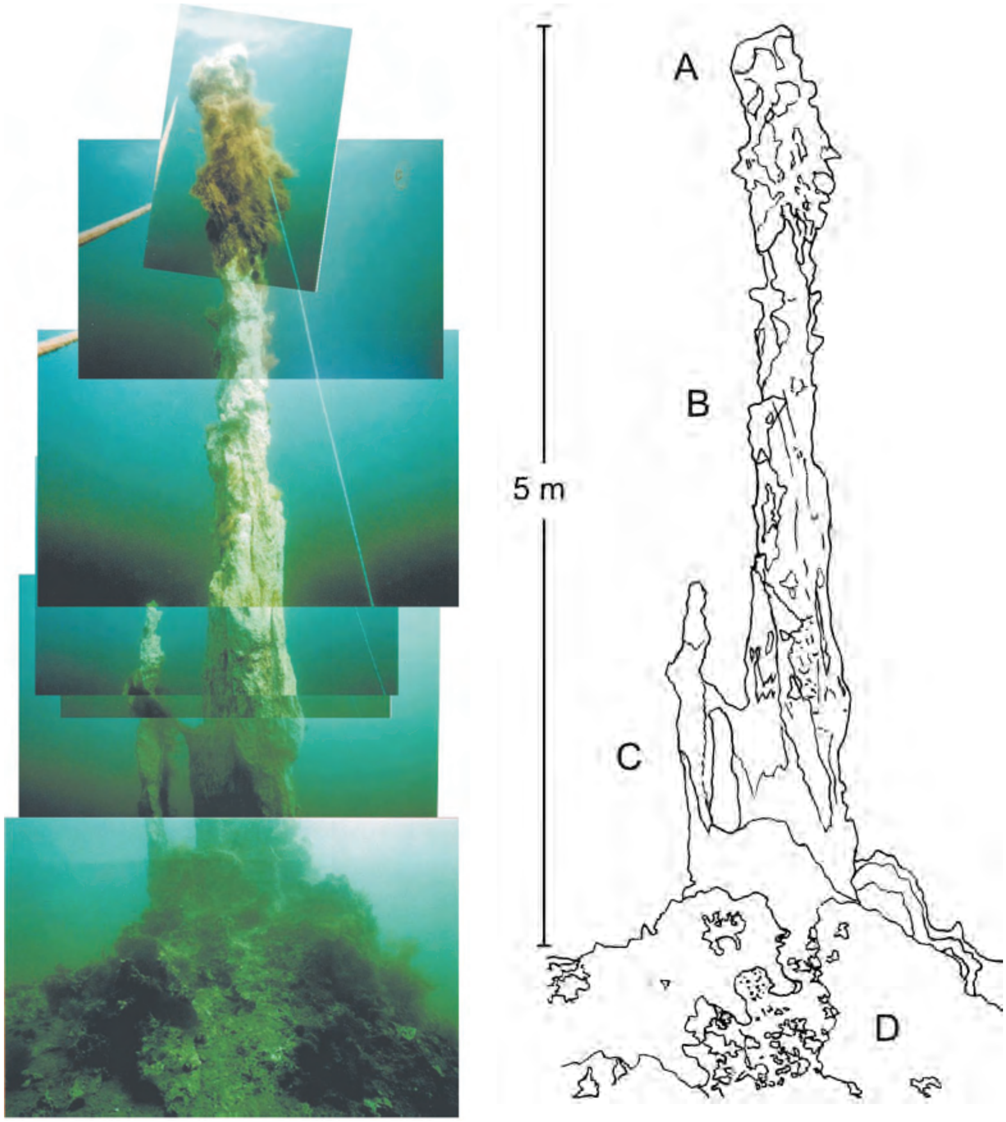

Fig 14. Features of a typical ikaite column. A) Blunt tip of this column is shrouded in brown filamentous algae. Beneath this cover the tip is a blunt stub possibly damaged annually by winter ice since it comes close to the surface of the fjord. B) Shaft of column composed of ikaite almost bare of benthic organisms with the exception of some brown, filamentous algae. C) Base of column protrudes from the talus cone. A second column has begun to grow alongside the main column and is beginning to amalgamate with it through the development of a bridge linking the two near its tip. D) Talus cone formed of mud and strewn with column fragments encrusted with seaweed and calcareous algae, predominantly Lithothamnion. *Photo Uffe Wilken.*

tographs clearly show the permeable conduit in the central part of the section (Fig. 16). When divers drilled the impermeable outer layers of the columns, column water with almost no seawater contamination could be extracted from these permeable conduits. When left undisturbed, these narrow drill holes would seep low density column water out vertically into the seawater and ikaite precipitation would start forming an upturned miniature column (Fig. 17).

Ikka columns are frequently arranged in clusters, of no discernable form, or in lines ranging from a few metres to tens of metres long. The short lines were apparent to the divers; whereas the longer lines are only perceptible in the side scan sonar imagery. Within these lines an elongation of the tufa structures is occasionally seen in the direction of the line suggesting they are formed over a common linear structure such as a linear spring water seep such as joints, faults or carbonatite dykes.

Tufa-fins

Linear arrangements of columns often form fin-like curtains of tufa material. Most fin structures are column amalgamations, but some are 'true-fins' with

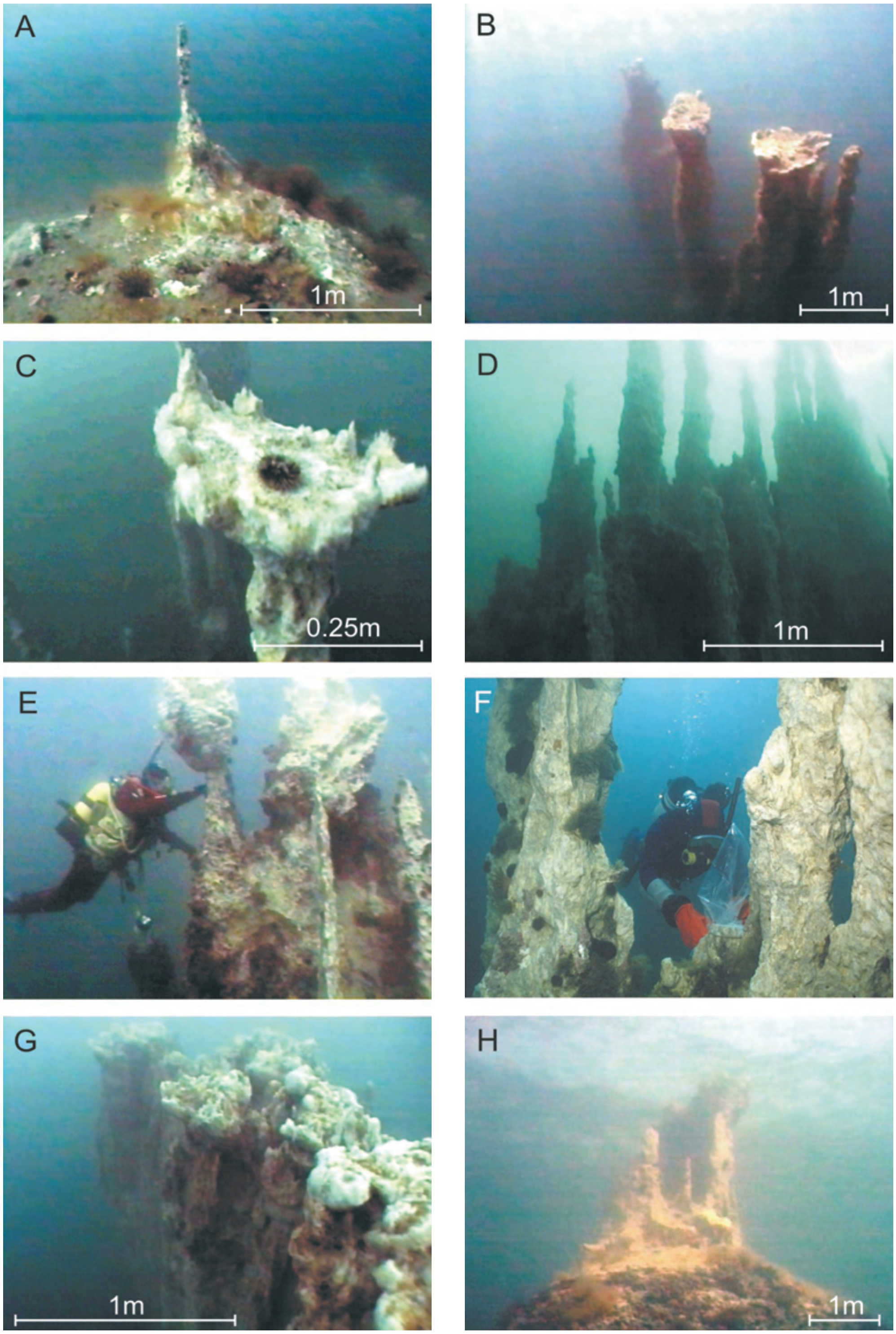

Fig. 15. Examples of ikaite tufa column terminations. A) Simple blunt tip[1)]. B) Giant columns with blunt tips[1)]. C) Hand-like crest[2)]. D) Multiple spires[2)]. E) Bulbous growths[1)]. F) Diver collecting column water from multiple spired column[3)]. G) Fin-like column amalgamation[1)]. H) Mound crowned with columns[4)]. Photos: [1)]Kirsty Brown, [2)]Antony Taylor, [3)]Richard Martin, [4)]Rolf Darville.

smooth sides and sharp ridge-like crests that appear to have formed directly in this way. Many examples of amalgamated column fins have been found in Ikka Bund but the true fins are rare and therefore their description is based on limited observations.

Tufa-fins are small-scale features when compared to the other structures in Ikka Bund, being typically less than 2

Fig. 16. X-ray photo of a small section of an Ikka column illustrating the porous structure. Note traces of a central conduit in the column (arrows). X-ray facility was kindly provided by Doctor Tuxen at Grønnedal Hospital.

m long and 2 m high. Some examples have undulating, 'wave-like' sides but generally 'blade-like' in plan view. Some tufa-fins were seen as parts of linear arrangements of Ikka tufa structures with their long axis running parallel with the linear trend of the group. The existence of tufa fins again suggests the presence of linear springs systems over which some Ikka columns are growing.

Mounds

Towards the seaward limit of the Ikka Column Garden, massive accumulations of Ikka tufa form into mounds. The largest of these mounds is approximately 10 m high and 15 m across and is a prominent feature in Ikka Bund. The top of this mound reaches to within half a metre of the surface at low tide and is a navigation hazard and has therefore been named the Skerry (Fig. 13D). Other mound structures identified in Ikka Bund are much smaller than the Skerry, typically 2-3 m high and 3-5 m across at the base, one of which has a crown of multiple columns several metres high (Fig. 15H). The mounds are easily identifiable features in side-scan sonar imagery and some can also be seen below the waters surface from a boat when conditions are still at low tide.

The Skerry formed the focus of much of the sampling activity in the fjord. It is composed of a variety of calcareous materials, fresh ikaite and ikaite tufa containing mollusc shells, echinoid tests and calcareous algae. The top of the Skerry is partially covered with a white, powdery precipitate, formed of ikaite sand with minor amounts of calcite and monohydrocalcite (Dahl & Buchardt 2006), which settles in hollows on the surface rather like drifting snow. Much of the lower part is thickly encrusted by calcareous algae giving the structure an irregular, rugged appearance. Living on and amongst this mass is an abundance of marine life; sea anemones, echinoids, starfish, sea squirts, brittle stars and fish in a reef community. Around the edges of the Skerry a muddy talus fringe slopes off at a gentle angle, estimated at 3°, into the surrounding muddy fjord bed. Scattered over this talus fringes are the rubbly fragments of broken ikaite tufa and calcareous algae, suggesting that the structure is frequently damaged by winter ice.

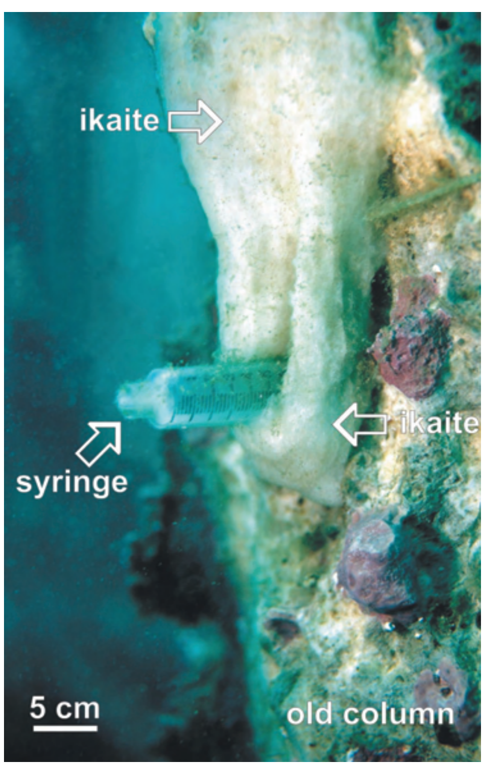

Fig. 17. Formation of new ikaite at a penetration hole in a column wall. The hole was drilled by a diver 13 months previously and secured with a modified syringe for tapping column fluids. Column water has seeped from the column and risen along the outside of the syringe, and new ikaite crystals formed by the mixing of this water with seawater. The lump of new ikaite above the syringe was almost 20 centimetres. Also, the tip of the syringe was found to be blocked by ikaite crystals when the syringe was first revisited the following field season. Photo Richard Martin.

Hardgrounds

Patches of stony fjord bed, notably on the Rocky Platform around the mounds, are cemented into hardgrounds comprising lithified sand, gravel and cobble sediments. Being difficult to identify on the side scan sonar imagery, the description of the hardgrounds is based on the observations of small areas of hardground made during dives. However, the impression was that these small areas represent sections of much larger areas of cemented fjord bed sediments.

Where hardgrounds are encountered the seabed is cemented solid to an as yet undetermined depth so that apparently loose cobble regolith cannot be freed from the mass without a hammer. Between the stones occasional, small, finger-sized columns were growing, giving a spiky appearance to the fjord bed. Around the bases of some of the columns the talus cones are similarly cemented, their hardened surfaces covered in a tufa crust (Fig. 15A). In most cases hardgrounds are now cemented by calcite and monohydrocalcite, presumed to be replacement after ikaite (Dahl & Buchardt 2006). These crusts are colonised by calcareous algae and bryozoans and contain the tests of bivalves that have become cemented into the tufa, adding to the mass of these structures.

Detritus from the Ikka columns

Abrasion of winter ice, iceberg damage including the toppling of columns, and the occasional boat anchors have caused damage to the Ikka columns. As a result many fragments of broken columns have been observed on the floor of the fjord, some as long as 3 m. In most cases, the original ikaite precipitates have been dissolved and only open calcareous frameworks of algae and other encrusting organisms are preserved, but also recrystallized calcite is represented. These column fragments form an important contribution to the bottom sedimentation in the areas most densely populated by tufa structures.

The rate of ikaite precipitation

The divers have observed water seeping from many columns, revealed by the oily-looking slick that results when freshwater and seawater of differing refractive indexes mix underwater. On several occasions, streams of tiny bubbles of gas, close to atmospheric air in composition (Buchardt *et al.* 2001), accompanied this seeping water. If a column was deliberately cut to enhance the seepage flow, this water could be collected for analysis by tying plastic bags over the stumps (Fig. 15F) (Buchardt *et al.* 1996a).

The action of cutting Ikka columns and initiating the seepage of column water (estimated to be between 3 and 18 cm^3 per hour, Buchardt *et al.* 2001) led to the discovery of the impressive rate at which ikaite precipitates. Fresh ikaite was seen to be forming on the stump of a cut column within days of being cut. After three weeks, 3 cm of fresh ikaite growth were measured on the same stump and after 13 months this had grown to 55 cm. This fresh growth was cut and collected once again for geochemical analysis and a growth rate of 45 cm over 12 months was recorded for the same column when revisited again the following year (Fig. 18). From these observations growth rates have been calculated (Buchardt *et al.* 2001) giving an increase in height of 25-50 cm per year, or 1 to 4 cm^3 of ikaite per day, for a column 15 cm in diameter and an estimated porosity of 50%.

Distribution of Ikka tufa structures about the bed of Ikka Bund

The tufa structures in Ikka Bund grow on a variety of substrates and occur either in clusters or as single isolated features. The relationship between the Ikka tufas and the substrate on which they grow is unclear as talus, hardgrounds, algal crusts or dense seaweed masks the root areas of all the columns observed. Therefore observations by divers have not been able to resolve which factors control the spatial patterns

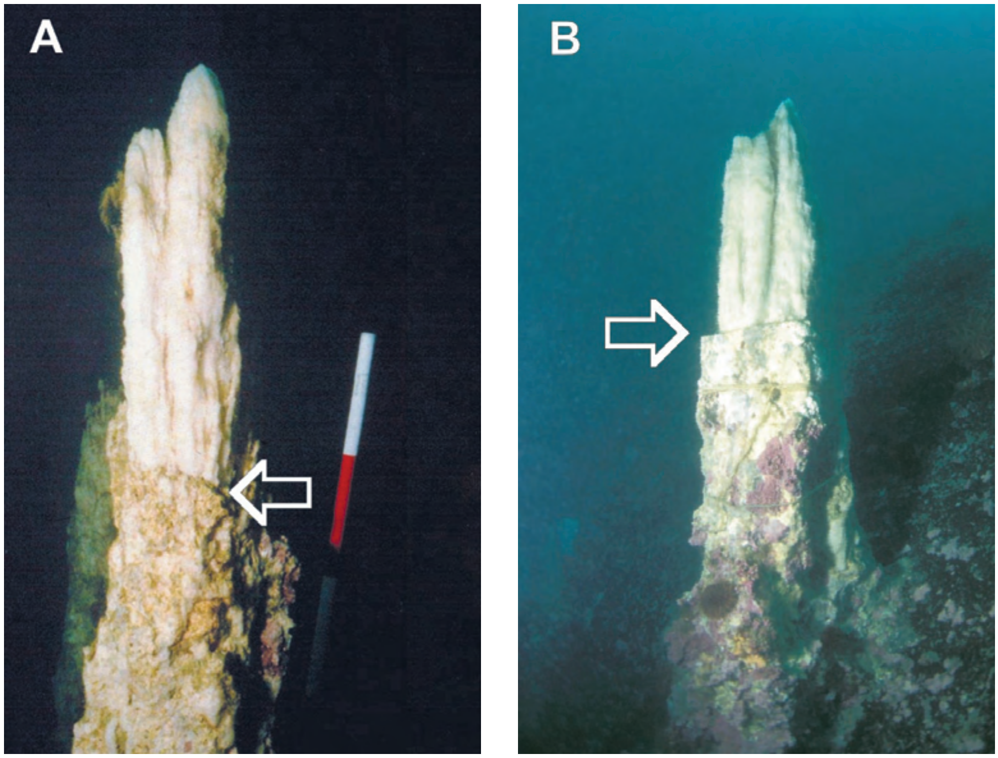

Fig 18. Rapid growth of ikaite above a cut surface (arrowed) that dissected a "mother" column found in about 8 m of water. A) Growth of new column top 55 cm in height observed 13 months (July 1996) after the mother column was cut. B) Growth of a new column top 45 cm in height 12 months (July 1997) after collection of the new top growth shown in A. C) The column seen in B cut by diver four years later (June 2001). The column is now close to one metre tall. Photos Richard Martin and Rolf Darville.

and the distribution of morphological types on the fjord bed. However, the mapping of the Ikka columns from the sonar imagery has revealed the general trends and has enabled the division of the Ikka tufas within the Column Garden into broad areas of morphotypes.

The Inner Basin of Ikka Bund

The Inner Basin of Ikka Bund is an elongated steep-sided depression filled with very fine-grained sediments, principally sapropelic mud. The Inner Basin contains the majority of the big columns, which are ordered along a line running parallel to the long axis of the fjord, off-centred towards the southeast. Ikka columns forming along this axis are typically very large and pillar-like, rising from the fjord bed at a depth of 16 to 25 m, to within 2 to 3 m of the surface. The tops of many of these columns terminate in either crest-like crowns or multiple spires and these are the most spectacular structures to be found in Ikka Bund, often clearly visible from the surface. At least 38 of these giant columns have been observed in the Inner Basin. Columns form elsewhere in the Inner Basin, but not in the same numbers and sizes.

Outer area of Ikka Bund

The line of columns seen running through the Inner Basin extends beyond the jutting peninsular that partitions Ikka Bund, down as far as the Skerry. Columns along this axis in this area remain unusually large but are less abundant and are restricted by the shallower water depths (circa 10 m) to heights of around 8 m.

Towards the seaward limit of the Ikka Column Garden, still on the mid-axis of the fjord, ikaite mounds up to 10 to 15 m across and 10 m high can be found apparently to be associated with the central region of the Rocky Platform of Ikka Bund. The largest and most prominent mound, the Skerry described earlier, appears to have developed on a syenite roche moutonnée, which is still visible extending out from under its mass towards the northeast. On the fjord bed surrounding these mounds numerous clusters and individual columns are found, which are mostly smaller examples with blunt tips.

Columns elsewhere in Ikka Bund

Although there are preferred areas for Ikka tufa development, Ikka tufas can occur anywhere around the Ikka Column Garden. A number of reconnaissance dives were made in order to check the interpretation of the sonar imagery. These dives targeted areas where interpretation was difficult or uncertain, areas with different fjord bed substrates and areas with intriguing Ikka column developments. Thus, many of these dives were undertaken away from the main areas of Ikka tufa development allowing observations of other examples of Ikka tufa structures to be made.

As in the main areas of development, Ikka columns in these areas were found occurring in clusters, in lines or in complete isolation and in a whole range of sizes from tiny stumps less than 5 cm tall to great towers. A number of the more isolated columns observed appeared to be more densely covered in seaweed and filamentous algae and had visibly much less fresh ikaite growth suggesting that their rates of growth are much slower.

Investigations outside Ikka Bund

Numerous transects by echo-sounder from our expedition vessel as well as several exploratory dives have not succeeded in identifying any column structures in Ikka Fjord outside Ikka Bund beyond the outcrop of the Grønnedal-Ika Complex. Lowered salinities close to the fjord bottom at more than 100 m depth in the outer Ikka Fjord did however suggest the presence of freshwater springs in the Ketilidian gneisses in this part of the fjord. Columns have not been noted anywhere in Greenland outside Ikka Fjord.

Discussion

Ikka columns

Geochemical analysis of the column water sampled inside the submarine columns identifies it to be highly alkaline freshwater comparable to groundwater of the sodium bicarbonate type with a conductivity corresponding to that of 9-10‰ salinity. Buchardt *et al.* (2001) explained the ikaite precipitation from mixing of the alkaline spring water and seawater. The high supersaturation in the mixing zone, the elevated levels of dissolved phosphate in the spring water and the cold physical environment favour the precipitation of ikaite over calcite and aragonite (Bischoff *et al.* 1993a & b).

The Ikka column structures can be viewed as purely physiochemical, non-biological precipitates where the discharge rate and chemical composition of the submarine springs are the main factors controlling the shape and size of the columns. The fact that the highly soluble ikaite mineral persists as a major column constituent, even in older columns, suggests that some other substance shields the individual ikaite crystals from the aggressive seawater environment. Scanning electron microscopy investigations at low temperatures (cryo-SEM) have identified extensive biofilms around and between the individual crystals of ikaite (Fig. 19). The biofilms are associated with sessile diatoms but probably also form from bacterial activity. It is suggested that these biofilms act as impermeable membranes around the ikaite crystals and thereby add to the lifetime of the crystals and the column structures. Another significant biological input to these structures is the encrustation by calcareous algae of the types

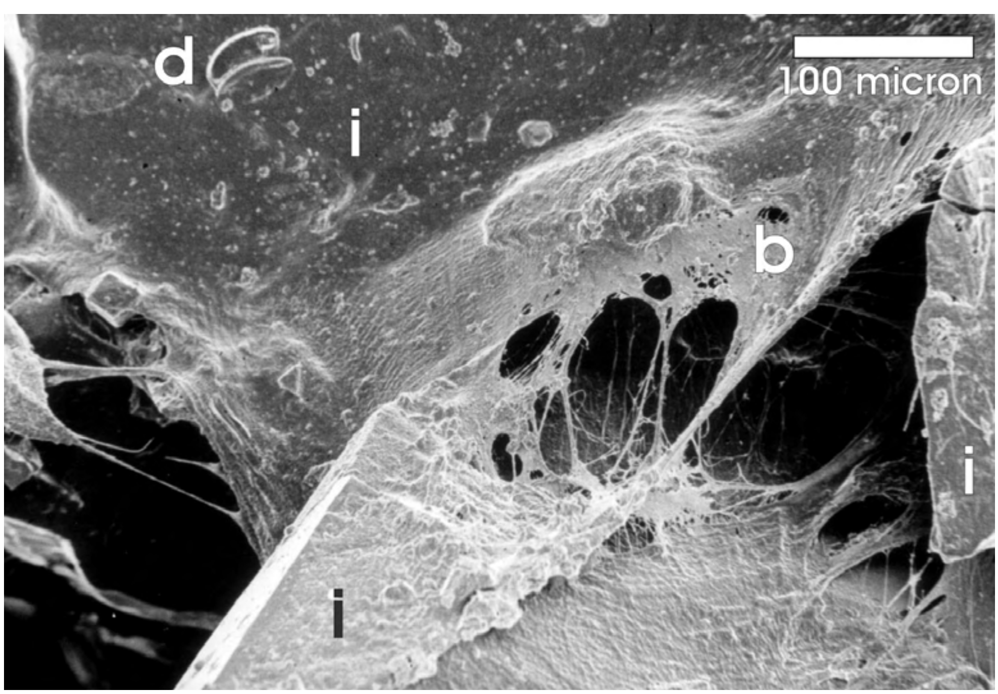

Fig 19. Bio-films enveloping ikaite crystals are revealed by this scanning electron microphoto taken at low temperatures (cryo-SEM). The photo illustrates the partly disrupted biofilms around and between the individual crystals of ikaite. The biofilms are associated with sessile diatoms but probably also originate from bacterial activity. Ordinary SEM photos of ikaite crystals have never revealed traces of biofilms. i: ikaite crystals, b: biofilm, d: diatoms. Photo O.B. Lyshede.

Lithothamnion and *Clathromorphum* (Düvel 1996). Once developed, these encrustations act to stabilize the often-fragile, primary ikaite structures.

Pipes and hardgrounds

The variety of shapes seen amongst the Ikka tufa structures can be explained as modifications to two basic types: pipes and hardgrounds. The tufa structures observed in Ikka Bund are mostly columnar because the ikaite from which they initially formed precipitates from spring water that rises buoyantly under gravity through the denser seawater (with a salinity of up to 34‰). Once formed, the columns act as conduits for the spring water and promote further upward growth at the columns tips. Fins, columns and mounds can all be formed through modifications to the basic pipe form, simple columns becoming fins and mounds, principally by the process of column amalgamation. The elaborate tip structures are mostly formed close to the surface of the fjord where a thermocline/halocline persists throughout the summer and ice damages and abrades the columns during the winter. The moment the buoyancy of the rising spring water is lost, for example at the halocline, vertical growth will cease and flattened tip structures and spreading crown-shaped crests will form.

Column amalgamations have been observed in several stages of development. New columns growing adjacent to existing columns from the same root base eventually coalesce with their neighbours (Fig. 14C). Damage to the sides of a column by boring organisms or mechanical damage by ice or falling debris, initiates the development of new ikaite growth at the point of damage. As these protuberances grow they may then coalesce with the parent or a neighbouring column forming the bridges or bulbous masses seen among trunks or tips. Column amalgamations are distinctive in form having a corrugated appearance, each of the corrugations corresponding with the outlines of previously separated columns. Column amalgamations are often fin-like in plan view suggesting that new columns growing alongside existing columns are forming along a preferred direction.

True Ikka tufa fins are distinct from column amalgamations by having smooth sides. The gentle curvilinear form of these fins suggests that they are growing from fractures of similar plan form. However, of the examples seen, the exact relationship between their roots and the fjord bed is hidden from view by algal encrustation and talus sediments.

Hardgrounds represent a totally distinct type of Ikka tufa morphology when compared to the tufa columns. Some hardgrounds have a fresh appearance, with numerous, vertical, finger-sized stubs of ikaite that may represent the first stages of pipe development. Others are discoloured, encrusted with algae, and may be the remains of columns that have either been toppled or eroded down to their roots. It should also be noted that the grazing actions of echinoids and chitons, and the boring of molluscs would accelerate the process of columns erosion. The mechanism of formation of the ikaite hardgrounds is unclear and the depth to which cementation has occurred needs further investigation. It is suggested that hardgrounds form in areas of very slow spring water seepage from buried fractures into permeable sand, gravel and cobble sediments that are not conducive to the funnelling of spring water into a single conduit.

Spatial distribution of the Ikka columns

The existence of fins and linear arrangements of clusters of columns suggests that the spring systems over which they

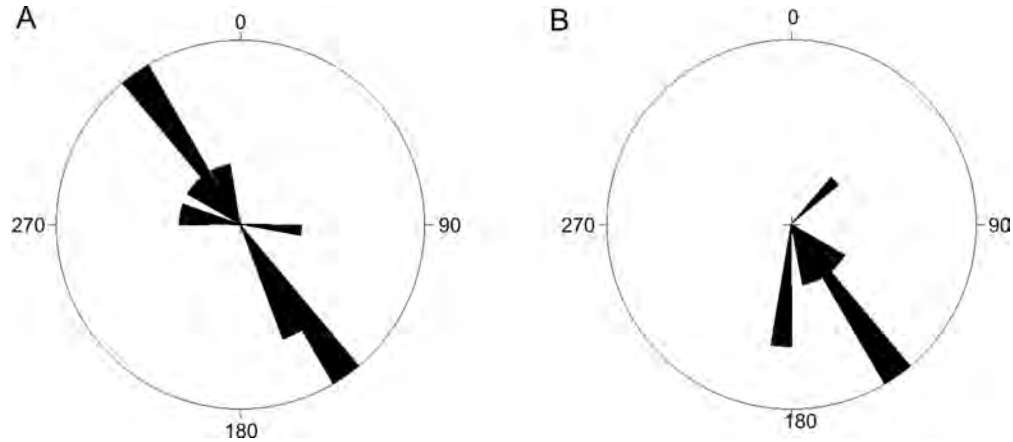

Fig. 20. Rose diagrams of the orientations of fifteen carbonatite dykes (A) and ten fin-like amalgamations of ikaite columns (B). The similarity in the orientations of the dykes and lines of columns, together with the proximity of the two within the Ikka Column Garden demonstrates a plausible relationship between the two.

are growing are linear in form such as joints or dykes or the sharp interface between the sides of roche moutonnées and soft clay sediments abutting against them. The orientations of a swarm of carbonatite dykes, exposed on the shoreline and seen to run under the fjord, were measured and compared with the orientations measured for column fins and amalgamations. The number of observations was limited due to available samples, but do suggest a relationship (Fig. 20). The carbonatite dykes are deeply weathered compared with the gneisses into which they are intruded and are therefore seen well below the rock surface (Fig. 21). The carbonatite seen in these exposures showed signs of dissolution, forming fluid conduits that may be feeding groundwater to the submarine springs and Ikka columns under the Fjord bed.

From observations made during the fieldwork a hypothesis was established that the non-random distribution of the Ikka columns is due to a number of controls, namely: 1) Ikka column development are restricted to the boundaries of the Grønnedal-Ika Complex, 2) Ikka columns require a stable physiochemical environment and therefore do not form where freshwater is discharged from surface streams, 3) Ikka column development is modulated by the thickness of the sedimentary fill in Ikka Bund, and 4) Ikka column development is concentrated around erosional bedrock forms on the fjord bed.

In order to assess the validity of these assertions a GIS (Geographical Information System) model of the geological environment of Ikka Bund was constructed using the GIS package IDRISI (Clark University 1997). The GIS model of Ikka Bund was assembled from the following data coverage:

1) The distribution of columns about the bed of Ikka Bund mapped from the side-scan sonar imagery,
2)The surrounding bedrock geology as mapped by Emeleus (1964),
3) The thickness of the unconsolidated sediments accumulated in Ikka Bund mapped from the pinger data,
4) The locations of streams and stream outwash deposits entering the fjord, from published sources and aerial photographs,
5) The locations of bedrock exposures about the bed of Ikka Bund also mapped from side-scan sonar imagery

The model was then interrogated to investigate the spatial distribution of Ikka columns about Ikka Bund with respect to the postulated controls. The principle means of testing was to extract the distances between the columns and the postulated controls and then examine the proximity relationships statistically using histograms. Whilst this form of spatial relationship testing does not fully substantiate the hypotheses it does provide some evidence to support the arguments.

Relationship to the Grønnedal-Ika Complex

The Grønnedal-Ika Complex is ideally situated to supply the necessary carbonate-bicarbonate-phosphate spring waters for Ikka column formation and it was predicted that there is a strong relationship between the outline of the complex and the Ikka Column Garden. This was tested by plotting the locations of the Ikka columns against the mapped outcrop of the Grønnedal-Ika Complex using the GIS (Fig. 3). The results show that the Ikka Column Garden is contained wholly within the outline of the Grønnedal-Ika Complex, stopping abruptly at its contact with the gneiss country rock into which it is intruded.

This relationship was tested further by using the GIS to compute the predicted watershed surrounding the Ikka Column Garden. In this way it was examined if the springs over which the Ikka columns form are likely to be supplied from groundwater soaking through the Grønnedal-Ika Complex. Plotting the columns against the GIS-derived watershed shows that the eastern part of the carbonatite core of the Grønnedal-Ika Complex lies completely within the hydrological catchment area of the Ikka Column Garden. These findings support the geochemical argument presented by Buchardt *et al.* (2001), and link the Ikka tufa structures and the Grønnedal-Ika Complex.

Relationship to stream activity

An important geochemical prerequisite to ikaite formation is the mixing of column water with seawater. This means that ikaite formation does not occur in the mouths of streams where the physiochemical environment is hostile. The freshwater running into Ikka Bund from streams tends not to mix with the seawater in the fjord for some distance; rather it floats out over the surface of the fjord buoyed by its higher temperature and lower salinity. However, freshwater is likely to also be entering the fjord as subsurface inflow through the large accumulations of coarse sediments washed into the fjord around the stream mouths. Furthermore, these sediments are likely to be churned during storms eroding any

Fig. 21. Carbonatite dykes in Ikka Bund area. Top photograph shows the deep open fissures left by the deep weathering of the carbonatite dykes on the northwest shore. Bottom photograph shows a section of a small carbonatite dyke that contains two conduits formed through karstic dissolution. Photo Paul Seaman.

ikaite crystals that might have been precipitated.

The distance of every Ikka column to every stream mouth was derived from the GIS and the results revealed that Ikka columns do not form within the vicinity of the stream mouths. In fact, significant amounts of Ikka tufa do not develop within 150 m from stream mouths, a finding supported by direct observations made in the field.

Relationship to sediment accumulation

It is generally believed that clay and mud can form aquicludes that make an effective seal to groundwater. It was therefore postulated that the sediments covering the bed of the fjord, which in places are up to 18 m thick, seal the bedrock and prevent the development of Ikka columns. To investigate whether the thickness of sediments affects the development of Ikka columns, the sediment thickness at each column location was extracted from the isopach layer in the GIS model. No evidence of correlation between sediment thickness and Ikka column development could be found, and it was therefore concluded that growth of columns is not generally hindered by sediment thickness.

Relationship to bedrock erosional forms

Roche moutonnées are common features around the shoreline of Ikka Bund and many have been mapped across the fjord bed from the sonar imagery. Numerous mounds and columns were observed by divers to be growing around or over roche moutonnées and it was therefore postulated that these Ikka columns were growing out from springs seeping from thin gaps formed where the fjord bed sediments abut against roche moutonnées. Other observations suggested that some of the Ikka columns might be growing from springs issuing directly from fissures in the bedrock exposures themselves. If either, or both, of these mechanisms control the distribution of Ikka columns, then Ikka column development should coincide with bedrock exposures on the fjord bed. The GIS was used to find the shortest distances between each Ikka column and roche moutonnées and to examine this relationship (Fig. 22).

No clear relationship between bedrock exposures and Ikka columns were found. In the Inner Basin, diver observations generally supported this finding with Ikka columns seen developing in areas where bedrock exposures are scarce or non-existent. However, in the outer fjord area there are significant numbers of roches moutonnées and Ikka columns in close proximity and the situation is less clear. The sonar imagery for this area shows that columns are not exclusively developed on roche moutonnées and that many columns do in fact develop directly from flat muddy areas far from roches moutonnées.

The strong linear and parallel trends seen in the distribution of the Ikka tufas, support the suggestion that some Ikka tufas must be growing from linear structures in the bedrock such as faults, joints or carbonatite dykes. Complexity of the sedimentological, structural, hydrogeological and geomorphological conditions in the fjord means that this basic relationship is likely to be complicated and masked by these other factors.

Are we likely to find other examples?

Columnar tufas, morphologically similar to Ikka columns, are known in and around the shores of Mono Lake, California (Bischoff 1993a; Council & Bennett 1993), and in the waters of Lake Van, Turkey (Kempe *et al.* 1991). In both Mono Lake and Lake Van, spring water rich in calcium ions mixes with highly alkaline lake waters precipitating calcium carbonate minerals. There are a

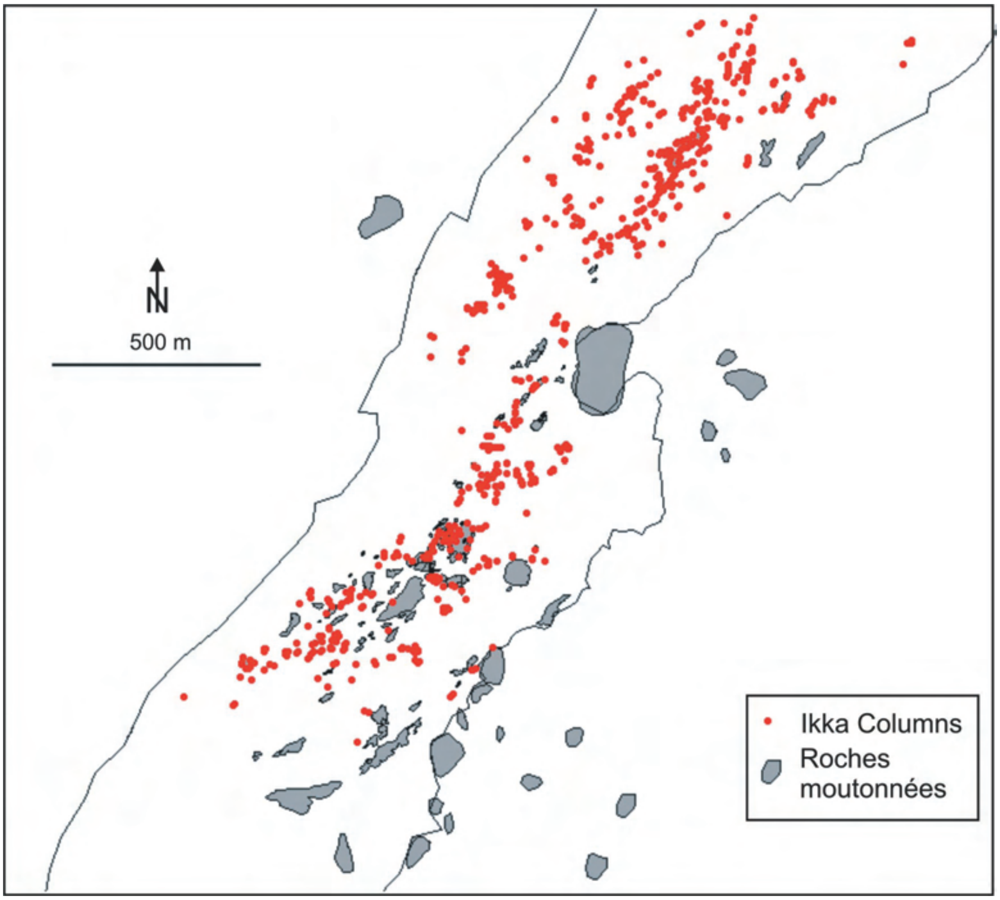

Fig. 22. The distribution of ikaite columns in Ikka Bund with relation to roches moutonnées in the Ikka Column Garden.

number of features in common between these tufas and the Ikka columns, their association with submarine seeps and the mixing of two water types, the requirement for special physiochemical conditions and the density difference between the seep water and that of the water body into which it seeps giving rise to columnar deposits.

However, there are also major differences between these other precipitates and the Ikka tufas, principally in their chemistry of formation. In Lake Van, and probably to some extent in Mono Lake, the carbonate minerals are precipitated predominantly by microbial action. This is not so in Ikka Bund, where the growth rates of the columns is far beyond that at which the microbial activity can influence it. Meiofauna and -flora have been found existing in the pore spaces between fresh ikaite crystals covering the actively growing parts of the Ikka columns, but these exist in a niche environment formed by the columns and are controlled by the precipitation rather than vice versa (Kristiansen & Kristiansen 1999; Sørensen & Kristiansen 2000).

Are the Ikka columns unique?

Laboratory studies show that the physical and chemical conditions under which ikaite will form are quite specific (Brooks *et al.* 1950; Marland 1975). A number of factors coincide at the head of Ikka Fjord in Ikka Bund to create the perfect environment for Ikka column development. Firstly, the existence of an impermeable clay layer in the sediment pile at the bottom of the fjord is a precondition for the establishment of an artesic submarine spring system feeding the Ikka tufa structures. This glaciomarine clay layer is a result of the melting of the local glacier at the end of the last glaciation and the contemporaneous marine flooding of the fjord.

Secondly, ikaite has been shown to form by the aqueous mixing of carbonate and/or bicarbonate ions with calcium ions in the presence of an inhibitor to calcite formation in a cold-water environment. Buchardt *et al.* (2001) have suggested that dissolution of minerals in the carbonatitic Grønnedal-Ika Complex is the source for the peculiar carbonate-, bicarbonate-, and phosphate-rich groundwater that reaches the fjord via the submarine springs. The special chemistry of the Grønnedal-Ika Complex is thus the major prerequisite for the Ikka structures. Thirdly, if Ikka Bund had been more open to the sea then icebergs, similar to those that circulate freely in the outer parts of Ikka Fjord, would very likely topple the fragile Ikka columns. Large icebergs are presently excluded from Ikka Bund by the shallow threshold formed by the narrow entrance at Snævringen.

Finally, had Ikka Bund been deeper, Ikka columns might have formed but are unlikely to have been discovered. Being readily visible from a small boat on a calm day, the Ikka Column Garden was known to early settlers in Greenland, some of who lived in Ikka Bund (Krogh 1982), and is reportedly mentioned in Inuit legends (Rink 1866). Furthermore, had the sea level in the fjord been lower or the threshold to Ikka Bund higher then the area of Ikka Bund would have be flooded with freshwater from the local rivers and the chemical conditions for ikaite formation would not have been met. Perhaps most significantly of all is that the development of Ikka columns in Ikka Bund is likely to be only a short-lived geological phenomenon. When the coincidence of all these prerequisite geological parameters are taken into account it seems highly likely that the Ikka Column Garden of Ikka Bund is a unique phenomenon.

Conclusions

The data obtained through the geophysical investigations and the observations made by divers have revealed a great number and variety of submarine tufa structures about the bed of Ikka Bund. A total of 657 columns were mapped from the side-scan sonar data, however, the resolution of this device means that only columns in excess of 1 m were clearly discernable and so could be mapped, many smaller columns and structures are also known to exist from the direct observations made. The mass of tufaceous materials found include columns, mounds, and hardgrounds, all forming over submarine springs fed by groundwater returning to base level after passage through the Grønnedal-Ika Igneous Complex. Most numerous among the Ikka tufa structures are the columns, which are pipe structures forming conduits for the buoyantly ascending spring water. We include three forms, single columns, fins and column amalgamations into this type. Mounds are major structures, which are probably the oldest tufa features in the fjord and form over very active springs. Hardgrounds probably represent areas of slow and diffuse spring water effluence, but more research is needed into the whole area of ikaite hardground formation.

The relatively thin sedimentary cover in the fjord forms an imperfect seal to groundwater seeping from fissures in the underlying crystalline bedrock creating the submarine springs. The chemistry of the spring water has previously been related to dissolution of secondary calcareous minerals in the Grønnedal-Ika Complex (Buchardt *et al.* 2001). The distribution of the Ikka tufa reflects a number of controlling factors, the strongest of these being the outcrop of the Grønnedal-Ika Complex that defines the limits of the deposits. Within the Ikka Column Garden the locations of streams, deltas, structures in the underlying bedrock, carbonatite dykes and roches moutonnées exert finer controls over the clustering and distribution of columns, but not bottom sediment types or thickness.

It is difficult to be sure when these remarkable columns formed. In term of age, they can't be older than the last ice age some 8 000 years ago. Such prolific carbonate deposition is extremely rare in arctic waters and the Ikka Column Garden is one of the few contemporary examples, and one that may soon be lost if global warming upsets the delicate environment of the Fjord. The Ikka Column Garden is a unique and beautiful natural phenomenon worthy of studying and preserving as a natural heritage site. Furthermore, as the Ikka columns make highly visible features that are easily mapped by side-scan sonar imagery, mapping them produces a unique appreciation of the distribution of springs about the bed of a shallow fjord. This provides us with the potential to study the spatial patterning of submarine seepage and to quantitatively determine of how much water is entering the sea via submarine springs in such an environment.

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MONOGRAPHS ON GREENLAND

Growing over submarine springs in Ikka Fjord, giant stalagmite-like tufa structures are formed from the rare carbonate mineral ikaite. In many instances they form trunk-like columns and fragile spires, in others they grow into massive reef-like accumulations. They can reach 18 m in height and are encrusted in colourful marine life. GIS analyses have shown that the distribution of tufa columns is linked to the outcrop of the ineous Grønnedal-Ika Complex, the proximity to stream mouths and bedrock exposures on the floor of Ikka Bund. Field observations have also shown that carbonatite dykes passing under the fjord are influencing Ikka column developments.

Presented here is a synthesis of the PhD research conducted by Paul Seaman and supervised by Bjørn Buchardt, University of Copenhagen, and Mike Rosenbaum, Imperial College, London.

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