NGU Report 2000.17

Ice sheet dynamics on the mid-Norwegian continental shelf based on regional and detailed bathymetric and seismic data

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REPORT

Report no.: 2000.17	ISSN 0800-3416	Grading: Åpen

Title:
Ice sheet dynamics on the mid-Norwegian continental shelf based on regional and detailed bathymetric and seismic data

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County: Norway	Commune:
Map-sheet name (M=1:250.000)	Map-sheet no. and -name (M=1:50.000)
Deposit name and grid-reference:	Number of pages: 54 Price (NOK): Kr. 310,- Map enclosures: 0

Fieldwork carried out:	Date of report: 20.03.2000	Project no.: 2664.31	Person responsible: Bjørn Bergstrøm

Summary:

A regional view of large-scale glacial processes and ice-sheet dynamics on the mid-Norwegian continental shelf during the Weichselian are presented on the basis of a regional digital bathymetric dataset. At times, ice flow was mainly channellised through ice streams located in bathymetric depressions on the shelf areas. Glacial sedimentary processes are discussed with focus on the marine-based part of the Scandinavian ice sheet during the last glaciation (the Weichselian).

Ice sheets that grounded on the shelf edge are thought to have been responsible for depositing complex prograding sequences reaching a maximum thickness of 1500 m on the shelf edge during several glaciations from Late Pliocene time. During interglacials, the shelf areas were sediment starved with little or no clastic sedimentation. Situated above these prograding units, several sediments packages (mainly till of Weichselian age) show a more aggradational pattern.

Keywords: Ice stream	Bathymetry	Mid-Norwegian shelf
Glacial erosion	Ice movement	Glacial troughs
Megaflutes	Till tongue	

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1. ABSTRACT

A regional view of large-scale glacial processes and ice-sheet dynamics on the mid-Norwegian continental shelf during the Weichselian are presented on the basis of a regional digital bathymetric dataset. At times, ice flow was mainly channellised through ice streams located in bathymetric depressions on the shelf areas. Glacial sedimentary processes are discussed with focus on the marine-based part of the Scandinavian ice sheet during the last glaciation (the Weichselian).

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2. INTRODUCTION

A number of studies during the last 30 years have confirmed that the present morphology of the mid-Norwegian continental shelf (Fig. 1) is mainly a result of glacial processes (Holtedahl and Sellevold 1972, Bugge 1980, Rokoengen 1980, Gunleiksrud and Rokoengen 1980, Lien 1983, Rise and Rokoengen 1984, Rise et al. 1984, King et al. 1987, Holtedahl 1993). The stratigraphy and age of the offshore deposits have also shown that glacial processes on the mid-Norwegian continental shelf involved sediment redistribution to a far greater extent and much faster than previously thought (Haflidason et al. 1991, Rokoengen et al. 1995, Henriksen and Vorren 1996, Sættem et al. 1996, Vorren and Laberg 1997, Eidvin et al. 1998, Rokoengen and Frengstad 1999).

Improved regional scale models of ice-sheet are very important in order to understand sediment transport from land to shelf areas, within shelf areas and onto the upper continental slope. Sedimentological, geotechnical and acoustic data from the shelf areas off mid-Norway offer a possibility to constrain such models both qualitatively and quantitatively. Ottesen et al. (in press) presented regional bathymetric data evidencing a highly dynamic ice sheet on the mid-Norwegian shelf. In this report we have extended the data base to include multibeam bathymetry and 3D seismic data sets. This allows us to discuss the glacial sedimentary processes and the dynamics of the large ice sheets on the mid-Norwegian continental shelf in greater detail. We focus on the marine-based part of the Scandinavian ice sheet during the last glaciation (the Weichselian), and especially the behaviour of the ice streams, which are fast moving parts of an ice sheet. The purpose is to improve the understanding of glacial processes on the shelf as a background for Norsk Hydro AS to evaluate sea bed stability in the Ormen Lange area.

3. PREVIOUS INVESTIGATIONS/GEOLOGICAL SETTING

In IKU's regional mapping off mid-Norway during the 1970s and early 1980s, the bedrock surface was divided into 11 units (I to XI from oldest to youngest) with suggested ages ranging from Triassic to Pliocene. Due to basinward subsidence and glacial erosion in the inner part of the shelf, the units subcrop more or less parallel to the coast with decreasing ages westwards (Bugge et al. 1984, Rokoengen et al. 1988, 1995, Sigmond 1992).

Bedrock unit IX (Fig. 2) is found about 50 km west of the crystalline basement as a prominent ridge believed to be dominated by sand and with greater resistance to later glacial erosion than the presumably more clay-rich sediments below and above. From Unit IX and landwards, the Quaternary is fairly thin and the bathymetry, especially between Frøyabanken and Haltenbanken (Fig. 1), reveals varying resistance to erosion of the Mesozoic and Tertiary bedrock units.

A composite seismic profile on the mid-Norwegian shelf (Fig. 2) illustrates the Upper Cenozoic stratigraphy. At the present shelf edge, the extensive and complex wedge reaches a maximum thickness of about 1500 m (Rokoengen et al. 1995). A marked change in depositional pattern is observed above a regional unconformity (below Unit D):
(i) the lower units show complex and strongly prograding sequences.
(ii) the upper units are subhorizontal, exhibiting both progradation and aggradation.

Due to the wide range of ages that has been assigned to these units (Oligocene to Quaternary), they have been interpreted both as glacial and non-glacial by various athors (Rokoengen et al. 1995). Eidvin et al. (1998) analysed six exploration wells on the mid-Norwegian shelf and dated the oldest parts of the sedimentary wedge on the outer continental shelf to Late Pliocene. This was correlated with an expansion of the north European glaciers dated at about 2.6 mill. years by Jansen and Sjøholm (1991). Unit IX was assigned an early Oligocene age (Eidvin et al. 1998).

The succession below the regional unconformity (units L-E, Fig. 2) exhibits large-scale clinoforms prograding towards the northwest gradually building out the shelf . In general, the units are sheet-like with erosional boundaries in the inner part. Most of the sediments below the regional unconformity (units K-E) seem to have been deposited by glacial processes during the Late Pliocene/Pleistocene (Rokoengen et al. 1995, Henriksen and Vorren 1996, Eidvin et al. 1998).

The sediments above the angular unconformity (units D, B, A and U) represent mainly the last interglacial/glacial cycle (Rokoengen et al. 1995, Sættem et al. 1996). The typically irregular base of unit D is interpreted to be the result of strong glacial sculpturing, probably both constructional and erosional, in Late Saalian time. Unit D consists of layered marine (Eemian) and glaciomarine sediments. The three topmost units (B, A and U) are dominated by poorly sorted material representing Weichselian tills from possibly three major glacial advances on the continental shelf. Unit B may represent the first (early) Weichselian glaciation on the shelf, unit A the maximum glaciation and unit U the last glacial advances reaching the shelf edge and the last deglaciation (Rokoengen et al. 1995). King et al. (1987) subdivided units B, A and U into a number of subunits using the till-tongue model. This is elaborated further below.

4. TILL TONGUE STRATIGRAPHY WITH EXAMPLES FROM THE MID-NORWEGIAN CONTINENTAL SHELF.

King et al. (1987) established a seismostratigraphy on the mid-Norwegian shelf based on about 9300 line-kilometer of seismic data, covering the shelf between 65° N and 67°30 N. They mapped Quaternary deposits comprising a more than 400 m thick succession of glacial till interbedded in a complex relationship with stratified glaciomarine sediment (Fig. 3). These so-called till tongue relationships are best developed near the edge of the continental shelf and because of heavy erosion, the model is less applicable in the eastern part of the mid-Norwegian shelf. This is also the case in the Trænadjupet area, where no till tongues are developed in the lower and upper till units, and the middle unit is completely eroded.

King et al. (1987) mapped three major units (Lower, Middle and Upper Till), which were further divided by 25 till tongue occurences. The Lower Till unit is up to 175 m thick and contains 7 till tongues. The Middle Till unit is up to 225 m thick and contains 12 tongues (Fig. 6). The Upper Till is up to 175 m thick and contains 6 tongues. The till tongue model was further developed by King et al. (1991), where they also discussed Alley et al's. (1989) model for deforming basal tills as a possible contributor to the formation of till tongues.

A till tongue consists of a wedge-shaped deposit characterized by seismically incoherent reflections (till), interbedded with stratified glaciomarine sediments. The glaciomarine units spread out at the tip of the wedge, and the uppermost portion gradually terminates in the massive till. The formation of a single till tongue by successive advance and retreat of the grounding line is shown in Fig 3. This regional development of till tounges suggests extensive ice margin fluctuations with likely repeated glacial and glaciomarine recycling during this period. Figs. 4 and 5 illustrate till tongue stratigraphy on the shelf. Fig. 4 shows a seismic section across the Skjoldryggen on the outer shelf edge. The interpretation indicate that the Skjoldryggen is composed of till tongue 22, 23 and 24. Olsen (1997) and Sejrup et al. (1994) has shown that the late glacial maximum comprises two major ice advances onto the shelf, and that both probably reached the shelf edge. These two advances, dated to 22 000 BP and 16 000 BP respectively, may thus be represented by the Middle and Upper Till.

The depocenter of the Lower Till is in the central part of the Trænabanken area, the Gamlem bank area and on the northern flank of the Haltenbanken (Fig. 7). The major depositional center for both the Middle and Upper Till is in the area west of Sklinnadjupet, with the greatest thickness parallel to the shelf margin in the Skjoldryggen area (Fig. 8 and 9). The isopach maps of the Lower, Middle and Upper Till units (Fig. 7-10) illustrate well the prograding nature of the till tongues. Fig. 6 illustrate the general erosive character of the ice depositing the Middle Till in the inner (eastern) shelf areas.

King et al. (1987) interpreted the Lower Till to represent the first major glaciation on the shelf. However, later investigations (Rokoengen et al. 1995, Sættem et al. 1996) have shown that these three till units only represent the last of several glaciations in the area, from the Weichselian and possibly part of the Saalian glaciation.

The two youngest till units near the shelf edge (till tongues 23 and 24 in Unit U) were deposited at about 15 000 and 13 500 y. BP according to 14C AMS-dating of shells (Rokoengen and Frengstad 1999). Along the mid-Norwegian coast, several 14C-dates give ages older than 12 000 y BP, indicating a very rapid deglaciation of the entire shelf area. How these rapid changes in ice-sheet extent and configuration are expressed on the shelf are so far poorly known, but the regional bathymetric dataset (Figs. 11 and 12) now offers possibilities to gain more insight into these processes. In coastal areas of western Norway Larsen et al. (1991) documented rapid shifts in local ice culmination centres during the last deglaciation.

4.1 Other investigation of large scale glacial processes on the mid-Norwegian shelf

Henriksen and Vorren (1996) studied the late Cenozoic sedimentation on the mid-Norwegian shelf (66°N-68°N), and they reported four units named A-D, where the units A and B are the oldest (Fig. 13). Unit A are from well data dated to Miocene (Eidvin and Riis, 1991). From seismic interpretation an Early Pliocene age is indicated for Unit B which is also supported by foraminifera with Miocene affinity in cuttings from well 6610/7-1 (Poole and Vorren 1993). However, an Oligocene age of Unit B has been suggested by Bugge et al. (1984) based on material from drillings on outcrops.

The lithology and the fossil content of Unit C points to a glacigenic origin for these sediments (Eidvin and Riis 1991, Poole and Vorren 1993). Henriksen and Vorren (1996) consider that most of the sediments were originally deposited in an ice-proximal position to a grounded ice sheet. Such a situation is likely to have caused oversteepened slopes and excess pore fluid pressure in the accumulated sediments thereby creating instability and mass-movement down the continental slope (Fig. 14). Henriksen and Vorren (1996) mapped the thickness of all sub-sequences in unit C. They made paleogeographic reconstructions of the northern part of the mid-Norwegian shelf during the Late Pliocene-Early Pleistocene from the earliest (a) to latest (b) phase of outbuilding. The direction of progradation of the shelf edge interpreted from the seismic data and the time isopach maps of the sub-sequences of Unit C shows that the Lofoten area was an important source area during an early phase of the outbuilding (Fig. 15). The source area in the north seems, however, to have decreased in importance during the later stages of the outbuilding (Fig. 16).

5. SEA-BOTTOM MORPHOLOGY RELATED TO ICE-SHEET DYNAMICS

5.1 Bathymetric data base

The Norwegian Hydrographic Service collected single beam echosounder data during the years 1965-1985. The regional bathymetric dataset covers a large part of the Norwegian continental shelf south of 68° N with an average line spacing of 500 m. The data were gridded with a cell size of 200 m and plotted as coloured contour maps and shaded relief maps. The dataset covers the areas from the outer coastal zone with crystalline bedrock to the shelf edge and parts of the continental slope, in certain areas down to 1000 m water depth. The data were collected by an Atlas Pinguin echosounder (100 kHz). The positioning system used was Decca Main Chain with an absolute accuracy commonly better than 100 m, but within some areas not better than 500 m. The relative accuracy (repeatability) is, however, much better and the morphology on maps in scales of 1: 500 000 or less will not be significantly influenced by the inaccuracy.

5.2 Major morphological features

The major morphological features on the mid-Norwegian shelf between the outlet of the Norwegian Trench at about 62° N and the Lofoten Islands at about 67°30'N is shown in several figures (Figs. 11, 12 and 17-25). Between the outlet of the Norwegian Trench and northwards to 64° N, the shelf is rather narrow (60-100 km wide), in contrast to areas further north. In the Skjoldryggen area (Fig. 1), the shelf reaches its greatest width, about 250 km.

The shelf includes bank areas with water depths of 100-300 m north of 63°30'N (Trænabanken, Sklinnabanken, Haltenbanken and Frøyabanken). South of 63°30'N there are several large bank areas with water depths less than 100 m (Buagrunnen and Langgrunna) in addition to Griptarane west of Kristiansund where crystalline rocks crop out at the surface. In the north, Trænabanken and Haltenbanken represent the largest bank areas.

The banks are separated by east-west oriented depressions 350-500 m deep north of 64° N and 150-300 m deep south of 64° N. North of 64° N they are up to 60 km wide, while on the southern half of the shelf, between 62° N and 64° N, they are narrower, generally 10-20 km in width (Fig. 23 and 25).

5.3 The Trænadjupet area

Trænadjupet is the best expressed ice-stream drainage depression in the northern part of the study area (Fig. 17). It is between 40 km and 60 km wide and generally widens towards the shelf edge. The bathymetry shows linear elements parallel to the trough axis, reflecting the flow direction of ice streams. In the eastern part of Trænadjupet, at least two different glacial drainage systems coalesce. Systems from the northeast (Vestfjorden) and southeast join to become one major ice stream following Trænadjupet in a northwesterly direction. The bathymetry indicates that the ice stream from the southeast cuts the system from the northeast. The glacial deposits in the Trænabanken area (till tongues) are cut in the Trænadjupet depression (King et al. 1987). Fig. 18 illustrates the megaflutes of the ice stream. The megaflutes follow the general trend of the trough, and are the result of the fast moving ice stream (Shipp et al. 1999). In the southeastern part of the 3D survey (Fig. 18), the megaflutes are not so obvious. This is due to a cover of lateglacial/Holocene clays (5-30 m) in which high numbers of small pockmarks occur (Fig. 18). These pockmarks are not mapped yet.

In the outlet of Trænadjupet, at the shelf break, multibeam bathymetry (Fig. 20 and 21) show the backwall of the Trænadjupet slide (Laberg et al. in prep.). In the upper slope, up to 5 series of blocks parallel to the shelf break are displaced from the backwall of the slide. Further down the slope, these blocks are more disintegrated, before the primary block structure finally disappears. The individual blocks may reach 25 m in height. Ice scour marks on the shelf extends out to the shelf break. Locally, ice scour marks can be observed also on top of the displaced blocks. Further studies are needed to assess the chronology of ice scour marking and block displacements.

5.4 The Sklinnadjupet-Skjoldryggen system

The Sklinnadjupet is a symmetric, U-shaped trough approximately 30 km wide, up to 470 m deep and 100 km long, presumably mainly eroded by ice streams flowing south of Trænabanken during the last glaciation (Fig. 11 and 23). The eastern part of Sklinnadjupet has acted as a confluence basin for drainage of ice from the onshore areas. The trough is oriented approximately east-west. The form and trend of the western part of Sklinnadjupet indicate that during the latest phase, the Sklinnadjupet ice stream was deflected towards the north, and flowed in a northwesterly direction out to the shelf edge. This is probably because the ice sheet east of Skjoldryggen was frozen to the ground or pinned by a large, supposedly mainly ice-pushed ridge, Skjoldryggen (Sættem et al. 1996). East of Skjoldryggen, several large and small scale glaciotectonic features exist, some of which are comparable to the well-known Horseshoe form (Fig. 21 and 22) described by Sættem (1990).

In the eastern part of the Sklinnadjupet, the bathymetry indicates that confluencing glaciers drained into the depressions (Fig. 23). It appears that the shallow bank areas acted as barriers influencing glacial flow pattern.

The Sklinnadjupet partly parallels another major ice-stream drainage route east of the Haltenbanken area and southwest of Sklinnabanken (Fig. 23). This depression is oriented NW-SE between Haltenbanken and Sklinnabanken and continues westwards towards the Skjoldryggen area.

Skjoldryggen (Fig. 23) has for a long time been interpreted as an end-moraine ridge at the outermost shelf edge (Holtedahl 1993 and references therein). It is almost 200 km long, up to 200 m high and 10 km wide and is by far the largest end moraine on the Norwegian continental shelf. The morphology east of the Skjoldryggen is complex, comprising several depressions and ridges. Sættem et al. (1996) reported glaciotectonic deformation in this area, an interpretation supported by the bathymetric dataset. It seems that the displaced blocks were either transported to and incorporated into the Skjoldryggen moraine ridge, or existed as individual or complex ridges. Sættem et al. (1996) suggested that, following the advance of the ice margin to Skjoldryggen, the ice lobe which deposited the ridge froze to the ground beneath. This pinned the ice, and led to a build up of stress at the ice lobe base which gave rise to glaciotectonic displacement of blocks of frozen sediments. During this period, the ice stream possibly were deflected and passed north of the Skjoldryggen area and out to the shelf edge. Immediately south of Skjoldryggen, a gentle depression may indicate an "old" slide event. This apparently predates the formation of the moraine ridge extending southwards from Skjoldryggen.

The glacial stratigraphy in both Haltenbanken and Trænabanken outlines thick units of Weichselian sediments (Units A, B and U). The 3 till units of King et al. (1987) comprise stacked till tongues with intervening glaciomarine sediments deposited during successive advances and retreats of the ice-sheet grounding line. The Lower Till is thickest in the Trænabanken and Gamlembanken area (Fig. 7), wheras the Middle and Upper Till generally occupy the outer portions of the shelf (Fig. 8 and 9), with the main depocenter in the Skjoldryggen area where a maximum thickness of 400 m in attained (Fig. 10). In the central and inner shelf area an erosional type morphology dominates (Fig. 6).
Studying King et al's (1987) maps of the till tongues in the Middle and Upper Tills, it is evident that it is the till tongues of these two till units that build the arcuate form of the outer shelf margin west of Sklinnadjupet (Fig. 6, 8 and 9). This makes it probable that these till tongues comprise parts of a large trough mouth fan system originating from mass transport out Sklinnadjupet. The surface form of the trough mouth fan system is in a way masked by Skjoldryggen and large scale glaciotectonic forms (large depressions) east of the ridge.

5.5 Ice drainage offshore Trøndelag

The shallow parts of Haltenbanken have probably prevented an active westward flow of the ice sheet in certain periods (Fig. 11). Several SW-NE-trending depressions (including Suladjupet) indicate that ice mainly drained southwestwards, inside of Haltenbanken, before turning westwards across Frøyryggen north of Frøyabanken.

The Suladjupet depression attains a water depth of more than 500 m and is incised 200 – 300 m into the surrounding sea bottom (Fig. 11). The depression was formed by glacial erosion, mainly into the Upper Jurassic/Lower Cretaceous claystone of the Spekk Formation. IKU bedrock unit IX subcrops below a thin Quaternary cover at Frøyryggen (Fig. 2), and it is evident that this sandy unit has been resistant to glacial erosion. Multibeam bathymetry in the Sularyggen/Suladjupet area (Fig. 24) illustrates well the glacial megaflutes and drumlins across the Sularyggen area, probably continuing further west towards the shelf edge. Prograding glacial sequences and a wide erosional depression are seen west of Frøyryggen (Bugge 1980, Bugge et al. 1987, Rokoengen et al. 1995).

5.6 Ice drainage offshore Møre

The continental shelf offshore Møre is narrow (60-100 km wide) compared to the areas further north (Fig. 12 and 25). Several WNW-ESE-trending depressions are separated by shallow bank areas. We believe that these troughs were also drainage routes for ice streams. Outside Smøla, the ice drainage is directed in a southwesterly direction, towards the northern part of the Storegga slide. Another ice stream has passed south of the Griptarane highs towards the northwest, and coalesced with the ice stream off Smøla. Northwest of the Romsdalsfjord, a NW-SE-trending depression (Onadjupet) ends in the Storegga slide area at the shelf break. Northwest of Ålesund, another depression extends almost to the shelf break where it coalesces with the aforementioned ice-stream channel.

Langgrunna is a large bank area that guided ice-stream flow both south and north of the bank (Fig. 12 and 25). Breisundjupet forms a narrow, elongated depression, representing the continuation of the deep Storfjord drainage system onto the open shelf, and ends in the eastern part of Langgrunna. This special extended fjord feature is very uncommon on the shelf and indicates special glacial conditions during its formation; for instance, erosion by very channellised ice flow in an area where the surroundings were covered by frozen based ice could produce such a feature. A possible tectonic origin has also been discussed (Rokoengen 1980).

South of Breisundjupet, an ice-stream drainage route from the east onto the northern part of Måløyplatået can be inferred. Måløyplatået is the southernmost bank area of the mid-Norwegian shelf, located close to the outlet of the Norwegian Trench. Thus, this area probably was influenced by the large Norwegian Trench Ice Stream from time to time (King et al. 1996, Sejrup et al. 1996), as the ice drainage from the mainland either was deflected in a northerly direction and/or partly assimilated by the Norwegian Trench Ice Stream. On Måløyplatået (Fig. 25), arcuate ridges indicate major halts during deglaciation (Rokoengen 1980, Rise and Rokoengen 1984, Rise et al. 1984).

6. ICE SHEET VARIATIONS DURING MID- AND LATE WEICHSELIAN

Knowledge about climatic changes and Scandinavian ice-sheet variations during the last glacial periods have increased significantly during the last 20 years as a result of studies in the deep sea (Veum et al. 1992, Baumann et al. 1995, Frontval et al. 1995), of Greenland ice cores (Grootes et al. 1993, Taylor et al. 1993) and from Quaternary stratigraphy on land (Larsen & Sejrup 1990, Mangerud 1991, Olsen et al. 1996, Olsen 1997, 1998, Sejrup et al. in press). Olsen et al. (1996) and Olsen (1998) have reconstructed the minimum number and size of glacial variations based on till stratigraphy with intervening paleosols from Finnmark, northern Norway, covering the last 300,000 years (Fig. 27), whereas Sejrup et al. (in press) present glaciation curves for southern Fennoscandia through both the last 150 ka (Fig. 28) and through the last 1.5 my (Fig. 29).

Based on more than 100 ^{14}C AMS-datings, Olsen (1997) reported the glacial variations during the last 45 000 years, suggesting the existence of extensive ice-free areas in several intervals (interstadials) alternating with rapid ice-growth periods (Fig. 30).

The occurrences of marine-influenced sediments at high altitudes (above maximum late glacial marine limit) even in the innermost fjordvalleys during the interstadials imply also rapid ice retreat after each ice culmination (Olsen & Grøsfjeld 1999). This gives a glacial model with a predominantly unstable ice sheet, and short intervals of glacial or interstadial character, as well as short time between glacial maxima and minima during the entire period after 45 000 y. BP. The last glacial maximum comprises two major glacial expansion phases, dated at 22 000 y. BP and 16 000 y. BP. Both advances probably reached the outer parts of the shelf and can probably be correlated with the uppermost shelf unit A and unit U, respectively.

7. ICE FLOW OVER THE LAND AREAS, CENTRAL NORWAY

From glacial striation and erratics of various lithologies it has been known for a long time that even (most of) the highest mountains, west of the main water shed in mid-Norway, have been covered by westwards flowing ice at least one time during the last glaciation (the Weichselian). For example, pebble to boulder-sized clasts of a red sandstone occurring in bedrock in Sweden (Fig. 31) are observed on the terrain surface or in different glacial or non-glacial deposits on high mountains, as Hartkjølen in Nord-Trøndelag county, as well as in valleys and coastal areas between Trondheimsfjorden and Ranafjorden (Fig. 31). This indicate clearly westwards directed ice flow and a considerable glacial transport of erosion products from the western part of Central Sweden over the mainland of mid-Norway and to the adjacent shelf in the west. During the intervals with thick and extensive ice, as during the last glacial maximum, the ice divide which separated the east- and westwards moving parts of the ice sheet, was located far east of the national border. A NNE-SSW directed elongated zone indicating the broad ice divide is illustrated on the basis of the easternmost positions of westwards directed glacial striation (Fig. 32). The youngest striations in the coast- and fjord areas of Norway indicate clearly topographically dependent ice flow during deglaciation phases, which often deviates from the ice movement direction during the glacial maximum.

8. ICE-FLOW MODEL

From the present bathymetric dataset (Figs. 1, 11 and 12) and earlier investigations on the Norwegian continental shelf (King et al. 1987, Rise and Rokoengen 1984, Rokoengen et al. 1995, Sættem et al. 1996, Vorren and Laberg 1997) and on data from the land areas in Central and Northern Norway (e.g. Bargel et al. 1999), we have reconstructed a probable flow pattern of the western part of the Scandinavian ice sheet during the Late Weichselian (Fig. 26). In addition we have used investigations from Antarctica as a basis for the model.

Extensive research has been carried out in West Antarctica during recent years in order to understand the ice-sheet dynamics of large, marine-based ice sheets (e.g. Shabtaie and Bentley 1987). The emphasis has been on the large ice streams which drain about 90% of the West Antarctic ice sheet. These ice streams are fast moving parts of ice sheets, normally 300-500 km long, 50-80 km wide and with speeds of 300-700 m/year, whereas the surrounding ice sheet may have a speed of less than 10 m/year (Bindschadler et al. 1996). Generally, the ice streams are located in overdeepened troughs, often eroding several hundred metres below the surrounding sea floor. The glaciological setting of West Antarctica today can partly be compared to the situation on the mid-Norwegian shelf during Late Weichselian time.

Studies on the shelf areas in Antarctica have outlined both prograding and aggrading glacial sequences (e.g. Cooper et al. 1991, Larter and Cuningham 1993), comparable to what we find on the mid-Norwegian shelf. In the Ross Sea, Shipp and Anderson (1997) and Shipp et al. (1999) have described glacial megaflutes and trough forms, both related to paleo-ice streams across the Ross Sea. Domack et al. (1999) mapped the ice sheet expansion to within 150 km of the continental shelf edge in the Western Ross Sea during last glacial maximum. Banks between broad sea-floor troughs were eroded and covered with little or no till and significant subglacial meltwater appears to have been absent in most areas. Glacial marine sediments draped on top of the sea floor are very thin, indicating that grounding-line retreat from the continental shelf edge was rapid, but the timing and details of the retreat phase are hampered by uncertainty in the radiocarbon reservoir correction.

The largest ice stream on the Norwegian shelf followed the Norwegian Trench along the southern and western coast of Norway (Fig. 26), and ended where the ice calved in the Norwegian Sea west of Måløyplatået (King et al. 1996, Sejrup et al. 1996). The idea of an immense Skagerrak glacier flowing along the Norwegian coast was introduced by Helland (1885). For some years this theory was generally accepted, but later became more controversial or was even rejected (Andersen 1964, Holtedahl 1993). Investigations both in the northern North Sea (Rise and Rokoengen 1984) and in the Skagerrak (Rise et al. in: Longva and Thorsnes 1997) however, have demonstrated the ice movements along the trench and proven the existence of the ice stream.
In the Vestfjorden/Trænadjupet area another major ice stream has flowed out to the shelf edge several times (Fig. 17). On the mid-Norwegian shelf, the most evident pathway for a paleo ice stream is Trænadjupet. Draining out Vestfjorden and other areas south of Vestfjorden, the ice sheet confluenced into an ice stream which accelerated and drained out Trænadjupet. Both the large depression clearly visible on the regional bathymetry (Fig. 17) and the extensive flutes shown on the 3D sea bed horizon (Fig. 18), evidence the existence of a paleo ice stream, probably flowing rapidly out Vestfjorden and further out Trænadjupet across the shelf break where it ended up calving into the deep Norwegian Sea. Vorren and Laberg (1997) have reported large fans in front of ice stream gate ways, e.g. the Bear Island TMF and the Storfjorden TMF in the Barents Sea. This is also reported from many other places in the world, among others the Crary Fan in the Weddell Sea, West Antarctica (Kuvaas and Kristoffersen 1991), the Prydz Fan in east Antarctica (Hambrey et al. 1991) and the Norwegian Channel TMF at the outlet of the Norwegian Trench (King et al. 1996). However, at the outlet of the Trænadjupet, no major form show clear evidence of trough mouth fan outbuilding. This may be partly due to the large water depth and a steep continental slope, causing most of the sediments to be deposited deeper down on the continental slope.

On the mid-Norwegian shelf, the location of the ice-stream drainage routes are mainly located between the shallow bank areas, e.g. Trænabanken, Haltenbanken, Frøyabanken and Buagrunnen and Langgrunna.

Grounded ice sheets are thought to have been responsible for depositing the prograding sequences. During the initial advance of the grounded ice, the inner shelf would have been heavily eroded and gently dipping glacial strata were probably deposited on the shelf. Ice streams carved broad depressions across the shelf and carried sediments directly to the continental shelf edge, thereby creating trough-mouth fans (Vorren and Laberg 1997) and sheet-like prograding sequences (King et al. 1987, Cooper et al 1991). During interglacial periods, the shelf areas were starved of sediment and thus received little or no clastic sedimentation.

9. GLACIAL PROCESSES RELATED TO MAJOR BEDROCK STRUCTURES ON- AND OFFSHORE

The present large scale morphology of the Mid-Norwegian shelf reflects to a large extent the morphology defined by the Base Cretaceous morphology (Brekke et al. 1992). Major structures such as the narrow Møre Platform, the wide Trøndelag Platform and the Vestfjorden Basin (with prominent NE-SW fault structures) are evident from this two-way map of the unconformity at the base of the Cretaceous (S of 69°). The Norwegian Trench on the other hand is not reflected in this paleomorphology.

The onshore bedrock geology (Fig. 33) of Norway between 61° and 68°N can be broadly divided into a few major provinces, as shown in the table below. The bedrock provinces broadly correspond to morphologic provinces (Fig. 34) which may have influenced glacial drainage patterns significantly. A general evaluation of expected resistance to erosion and main mineralogical characteristics is included.

Table 1 – Broad scale bedrock and morphologic provinces, expected resistance to erosion and dominant mineralogy.

Bedrock provinces onshore	**Morphologic provinces**	**Resistance to erosion, mineralogy**
Western Gneiss region – Proterozoic gneisses dominated by metamorphosed igneous rocks	”Western Norway High – **WNH**”	High. Mineralogy is dominated by quartz and feldspar
Mid-Norway (Trøndelag) region – Caledonian metamorphosed sedimentary and volcanic rocks	”Mid-Norway saddle – **MNS**”	Low. Mineralogy dominated by chlorite, mica, calc-silicate minerals
Vikna-Grong-Olden Gneiss culmination (**VGOC**) - Proterozoic gneisses dominated by metamorphosed igneous rocks	”Vikna-Grong-Olden culmination – **VGOC**”	High. Mineralogy is dominated by quartz and feldspar
Nordland Caledonian rocks – mixture of Caledonian metamorphosed volcanic and sedimentary rocks and Caledonian intrusions, covering the inland between **VGOC** and the **LGC** (see below)	No particular morphologic expression, apart from high mountain areas towards the east	Variable. Volcanic, and sedimentary rocks dominated by mica and calc-silicate minerals. Intrusions are dominated by quartz and feldspar.
Mo i Rana-Svartisen-Bodø gneiss region - Proterozoic gneisses dominated by metamorphosed igneous rocks, particularly in the Svartisen area and along the coast	”Svartisen dome – **SD**”	High, rocks dominated by quartz, feldspars, variable amounts of hornblende and mica.
Lofoten gneiss culmination (**LGC**) – Proterozoic gneisses dominated by metamorphosed charnockitic/anorthositic and granitic intrusions	Complex morphology, with positive relief in the Lofoten island, and extensively influenced by northwest-trending fault structures defining the Vestfjorden. The Vestfjorden topographic low continues eastwards (**VC** – Vestfjorden Continuation). A similar topographic low goes from Tysfjord ESE to Sweden (Tysfjord Continuation – **TC**). Both the **VC** and the **TC** may have had strong influence on local drainage patterns.	Variable resistance to erosion, depending on tectonic influence. Mineralogy dominated by feldspar and quartz.

The recognition of these major provinces is a first stage towards connecting the glacial drainage patterns offshore with onshore features. It is further important to stress the dynamics of such systems – areas such as the Svartisen dome may act as local glaciation centres at the early stages of glaciations, while at glacial maximum, such topographic highs may deflect the ice streams. Further studies should incorporate existing glacial movement indicators (glacial striae etc) and ice sheet thickness models, and try to establish the main trends of glacial drainage through glacial periods, taking into account the pre-Quaternary architecture of the Mid-Norwegian shelf. Please note that the province names are informal.

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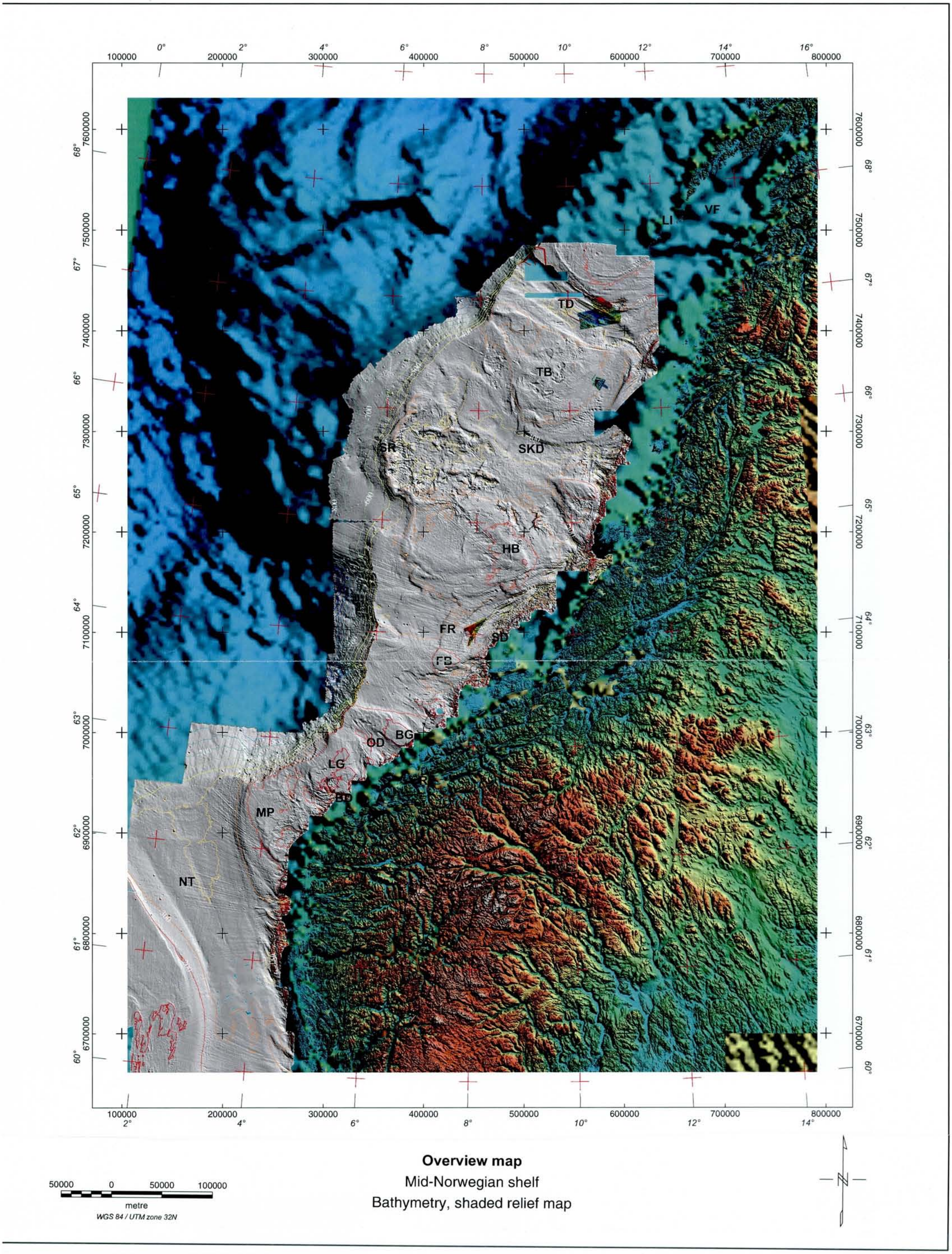


Fig. 1. *Shaded relief map covering the mid-Norwegian shelf. 100 m depth contours. LI-Lofoten Islands, VF-Vestfjorden, HB-Haltenbanken, SKD-Sklinnadjupet, TD-Trænadjupet, SD-Suladjupet, FB-Frøyabanken, FR-Frøyryggen, RF-Romsdalsfjorden, SF-Storfjorden, LG-Langgrunna, MP-Måløyplatået, BG-Buagrunnen, BD-Breisundjupet, OD-Onadjupet, NT-Norwegian Trench, TB-Trænabanken, SR-Skjoldryggen.*

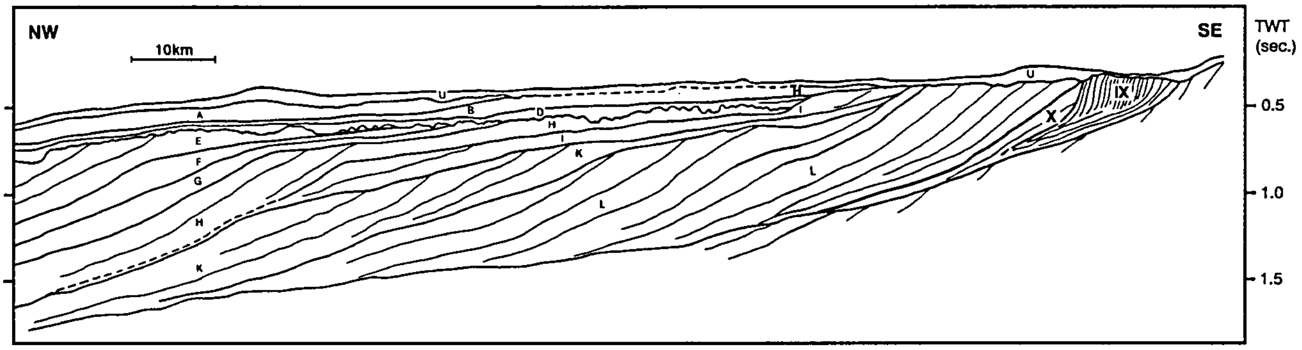


Fig. 2. Composite geoseismic profile showing the Upper Cenozoic stratigraphy across the mid-Norwegian shelf. Modified after Rokoengen et al. (1995). The units K-E represent Upper Pliocene/ Pleistocene sediments, while the units D, B, A and U above the angular unconformity probably represent the last interglacial/glacial cycle. See Fig. 1 for location.

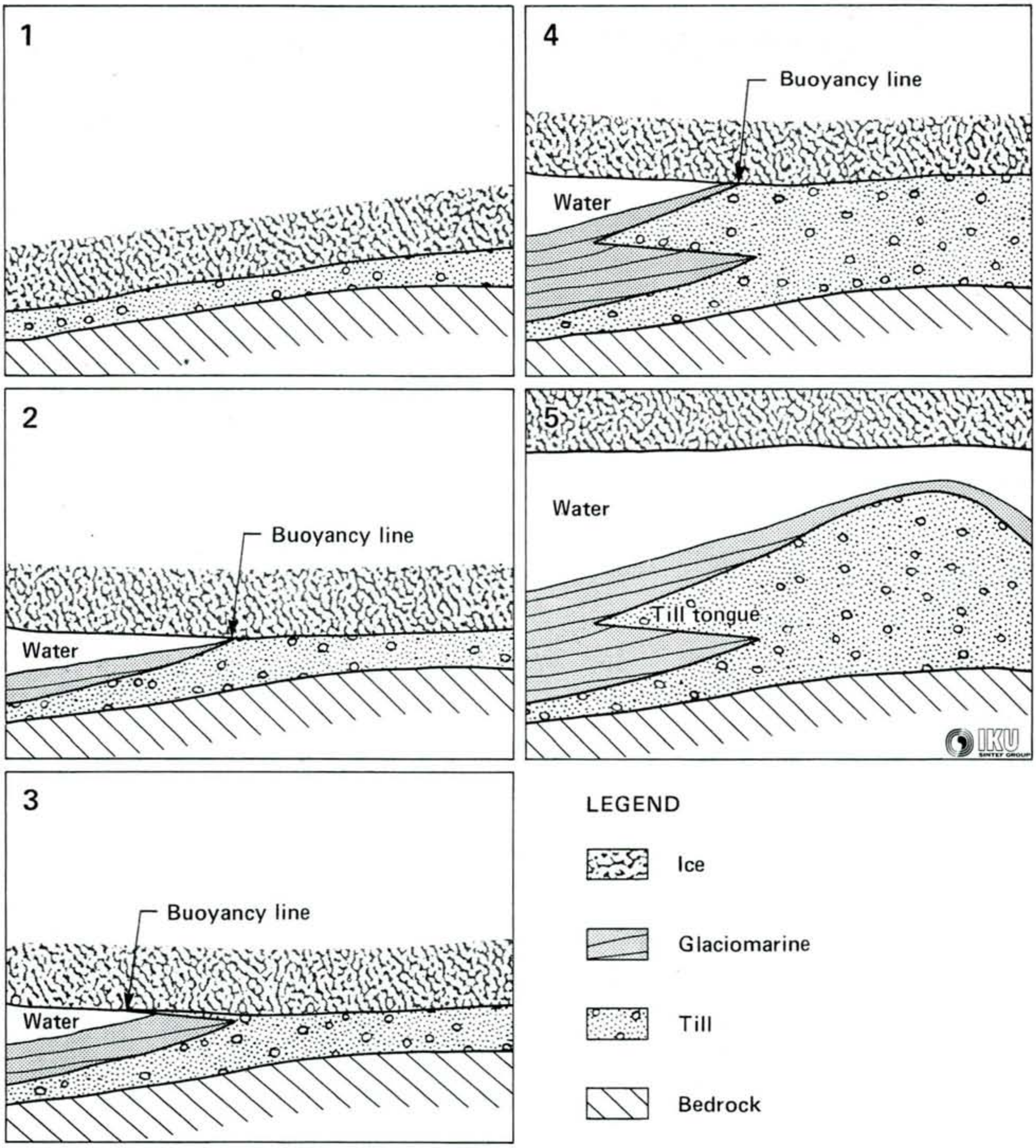


Fig. 3. Diagrammatic model for the development of till tongues. Stage 1: accretion of basal till beneath a thin ice sheet; Stage 2: ice sheet grounded at buoyancy line with accretion of till, and ice shelf with deposition of glaciomarine sediment; Stage 3: migration of buoyancy line seaward with sedimentation pattern shifting accordingly; Stage 4: retreat of buoyancy line and deposition of glaciomarine sediment over till tongue, till core of moraine continues to grow; Stage 5: ice shelf only, accompanied by glaciomarine deposition. (After King and Fader, 1986).

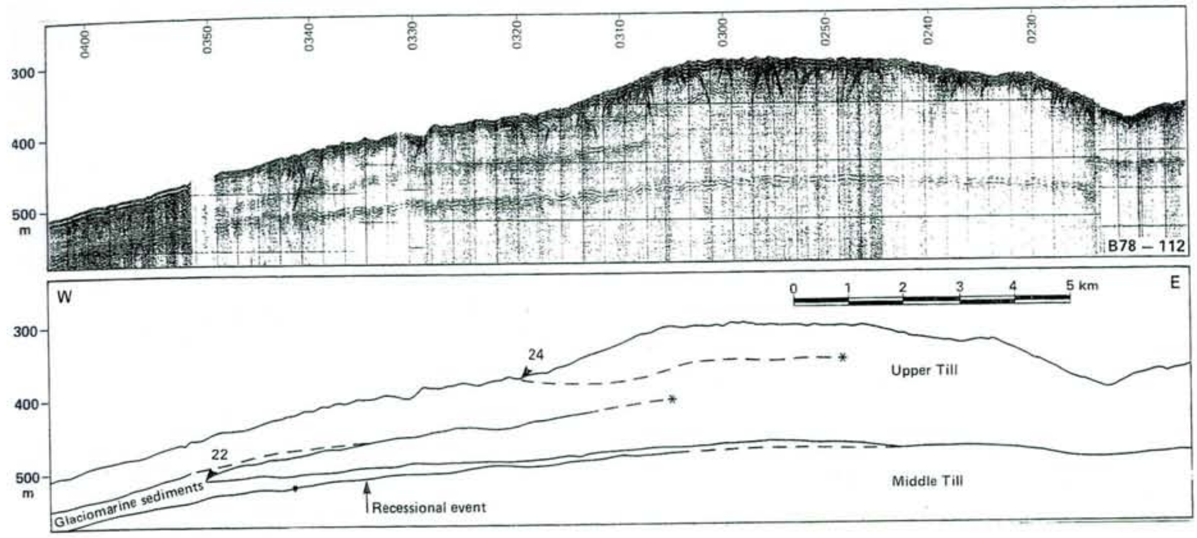


Fig. 4 Skjoldryggen, with interpreted till tongues and glaciomarine sediments. The diagram show the overall morphology, internal stratigraphy, and the relations between Upper and Middle Till. Till tongues are referred to by number, and arrows mark the tip, and star the root of the different till tongues (after King et al. 1987).

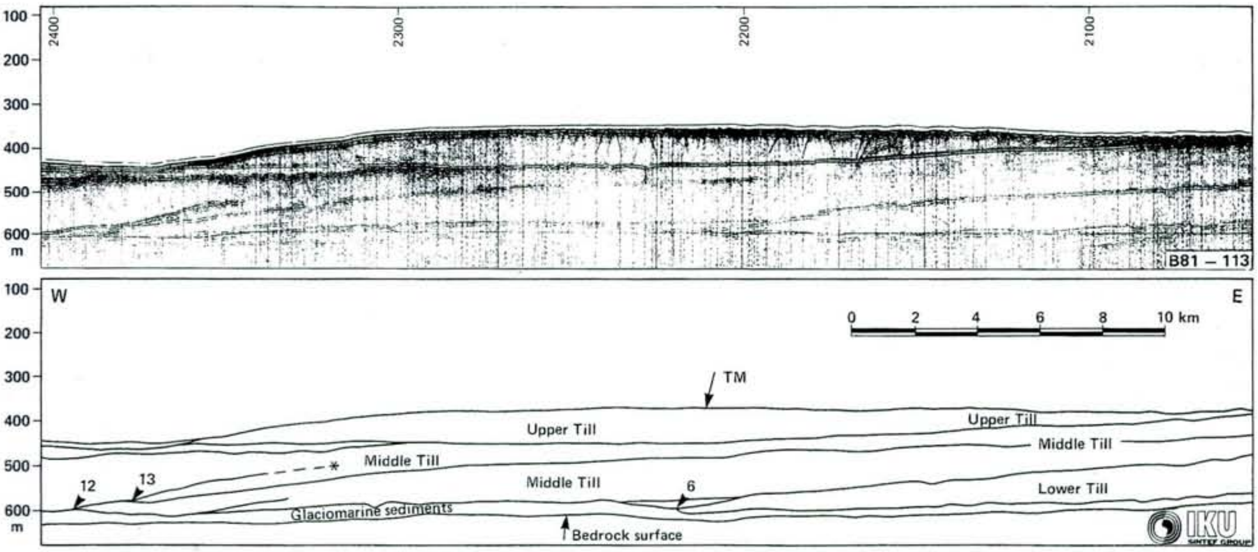


Fig. 5. Tabular, bouyancy line moraine (TM) developed on the surface of the Upper Till. Below are Middle Till, Lower Till and glaciomarine sediment overlying the bedrock surface. (After King et al. 1987).

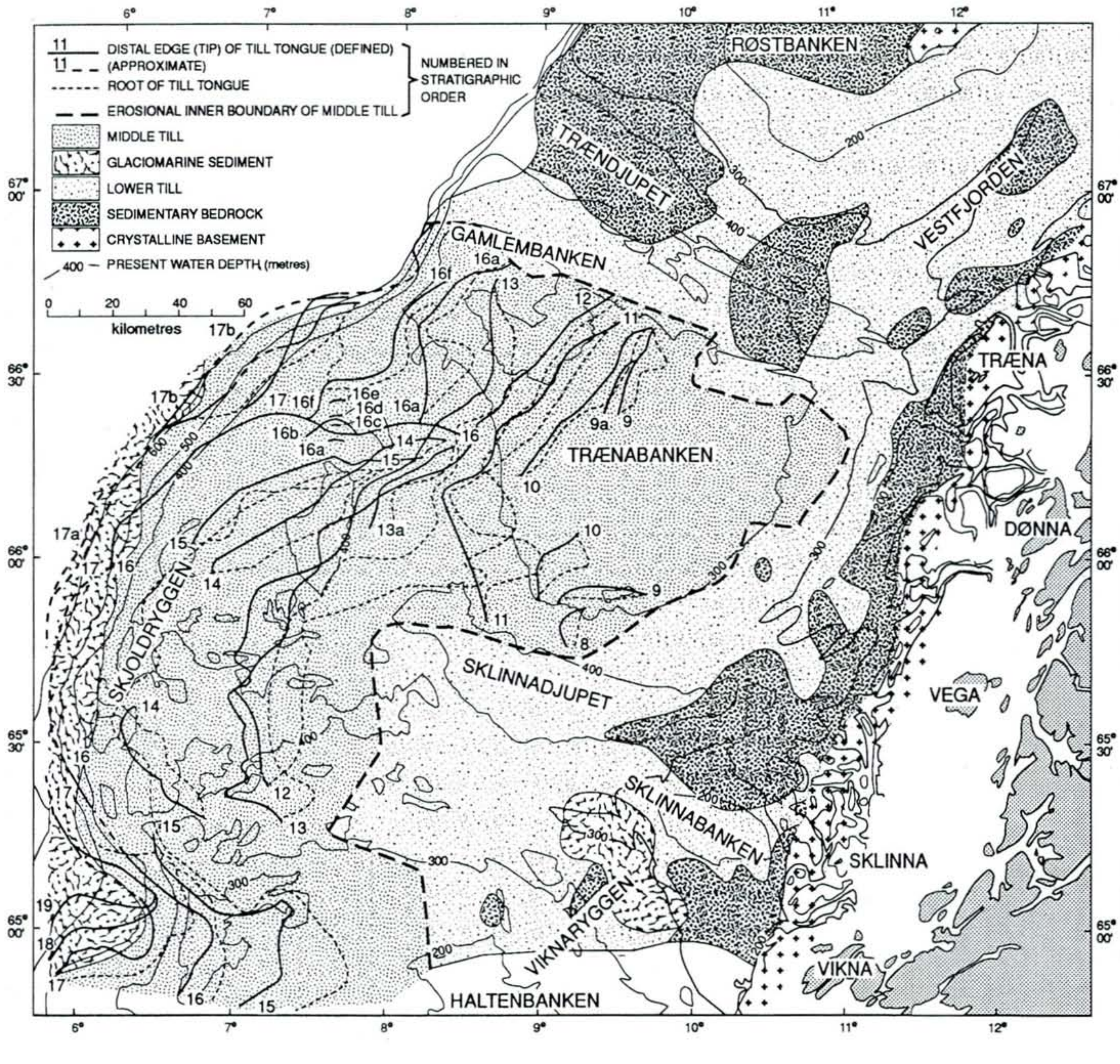


Fig. 6. Simplified map of Middle Till, mid-Norwegian Shelf. From King et al. (1991).

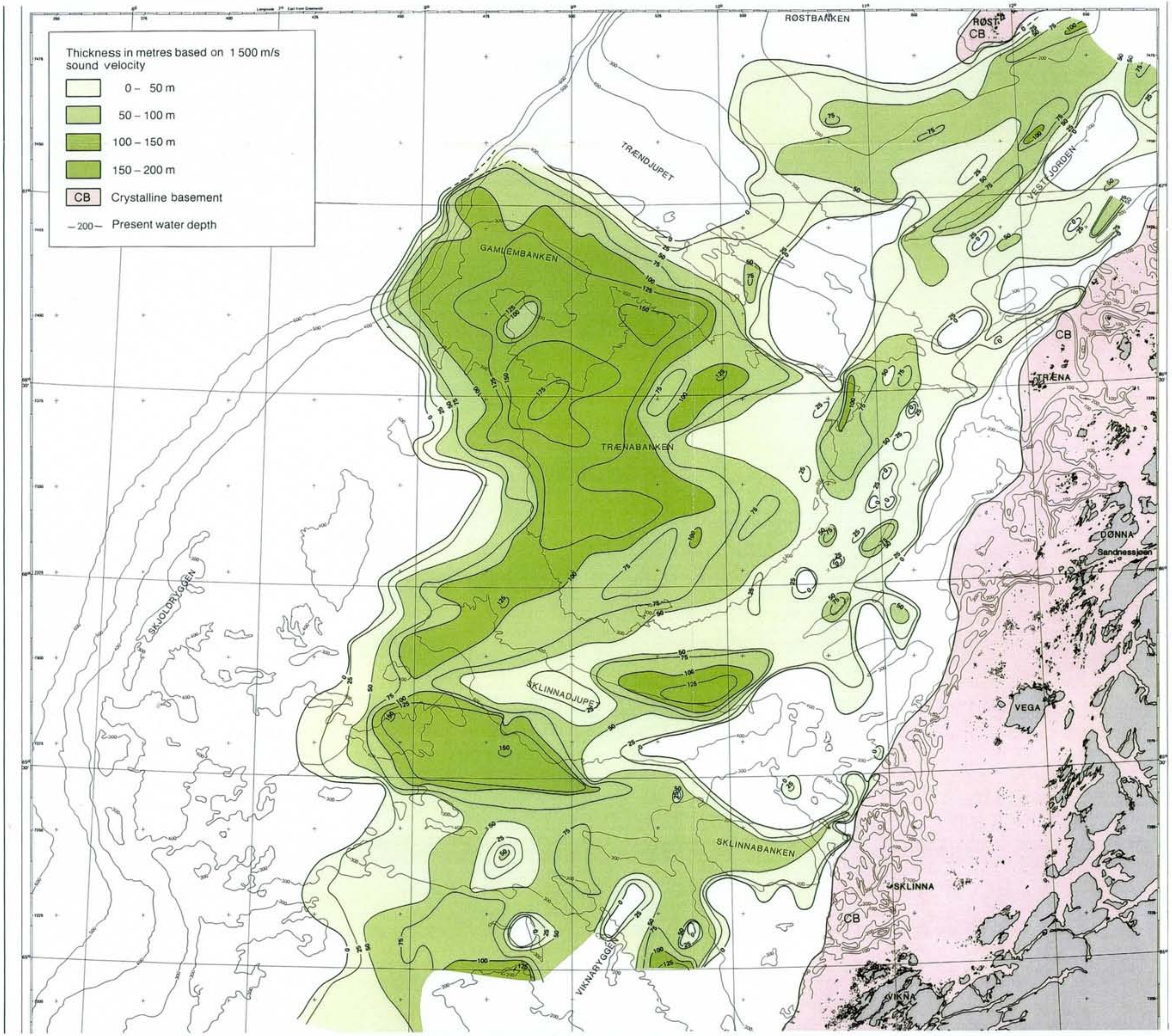


Fig. 7. *Isopach map of Lower Till. Note the complete absence of the Lower Till in the outer shelf (Skjoldryggen) areas. (After King et al. 1987)*

Fig. 8

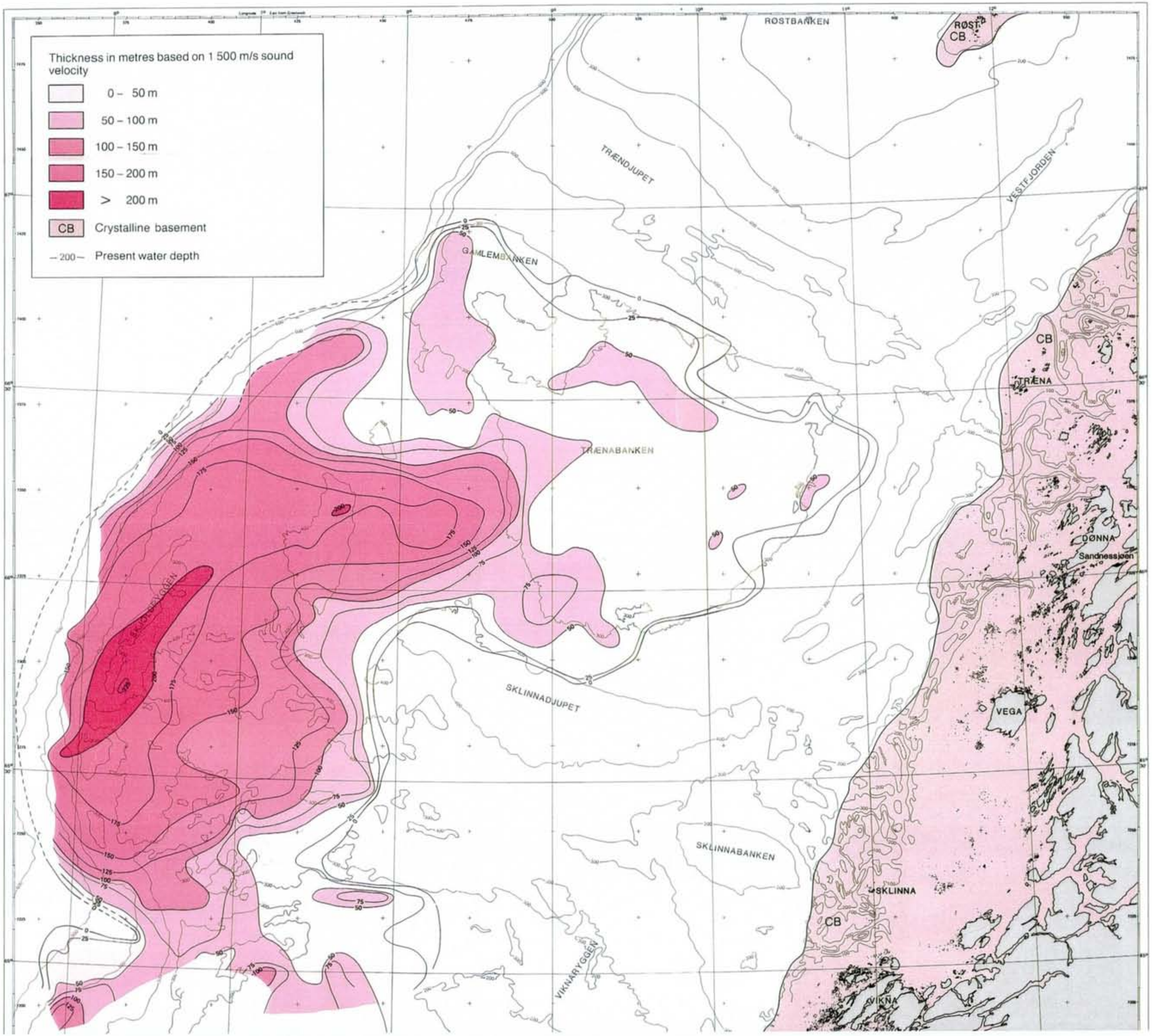


Fig. 8. Isopach map of Middle Till. Note the complete absence of the Middle Till in the Trænadjupet and inner shelf areas (After King et al. 1987)

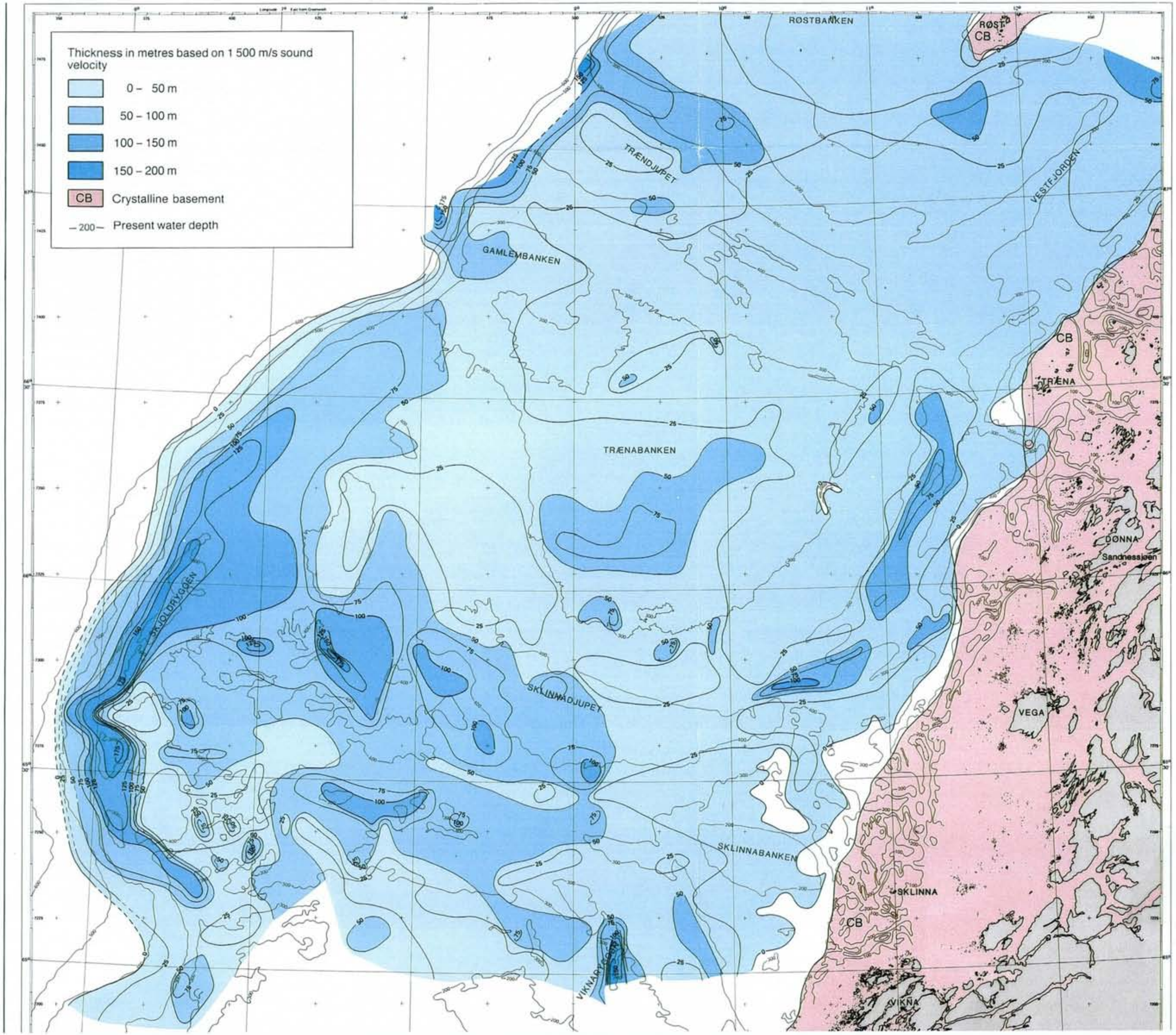


Fig. 9. Isopach map of Upper Till (After King et al. 1987)

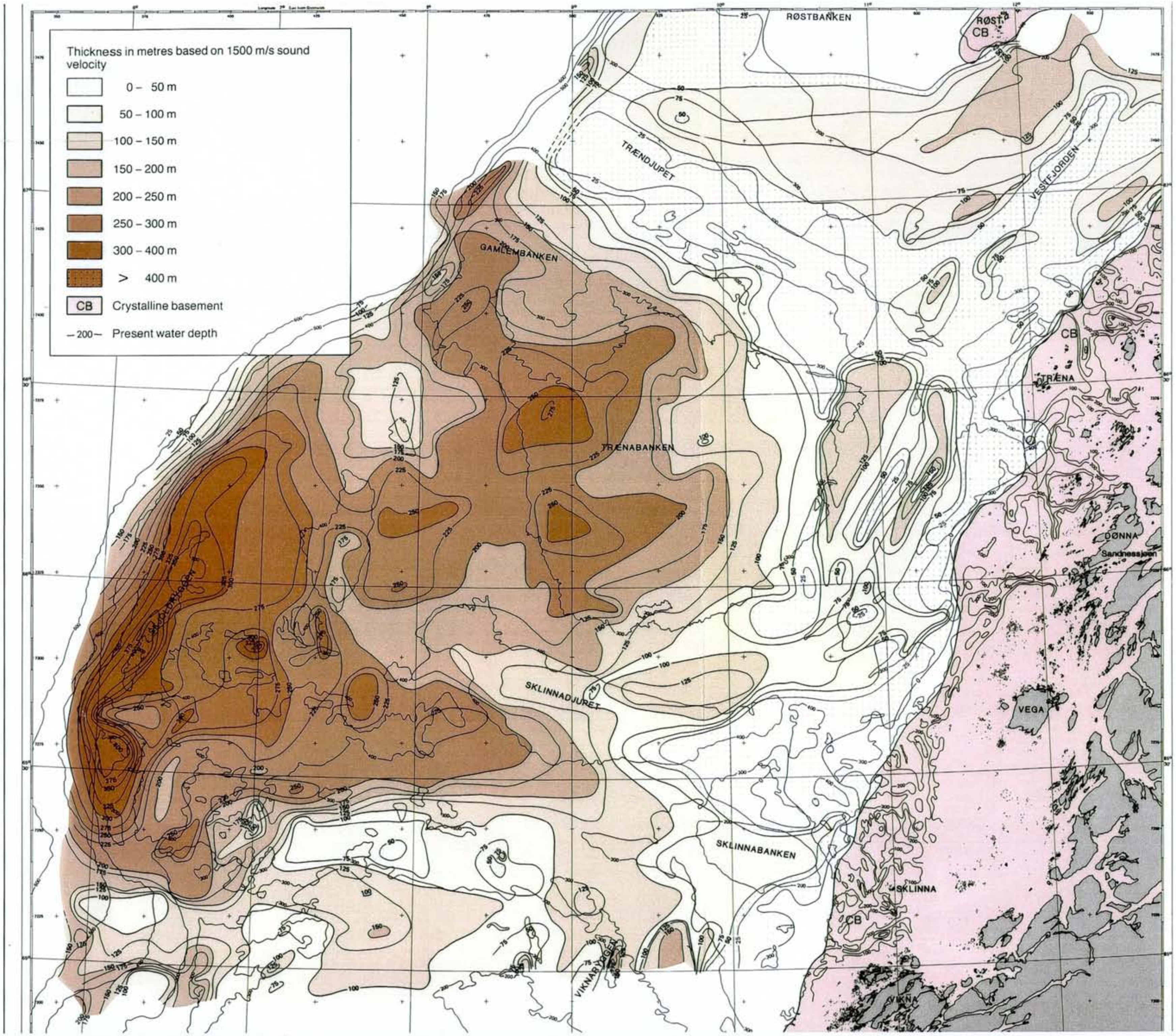


Fig. 10. Total Quaternary thickness (After King et al. 1987)

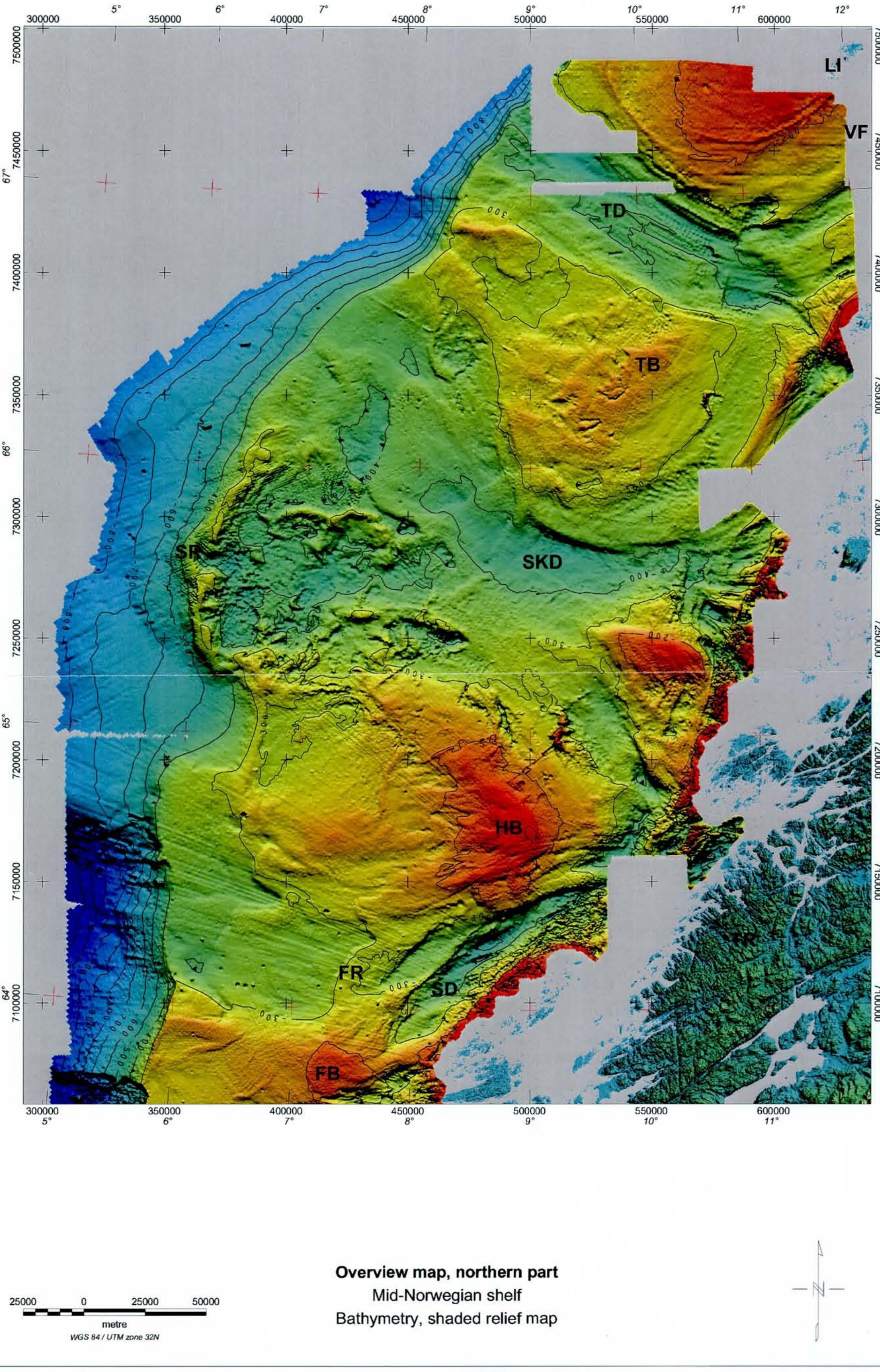
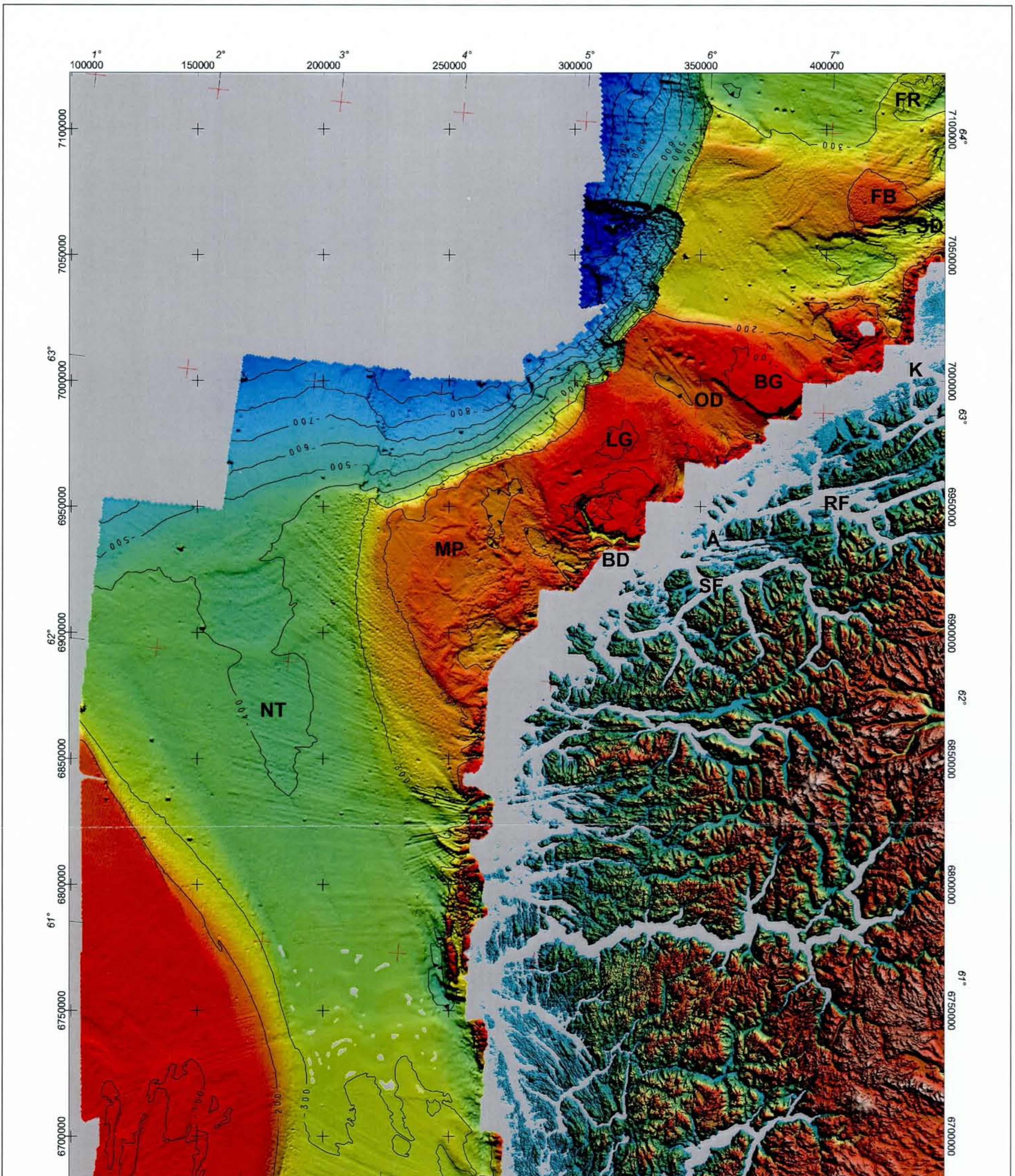


Fig. 11. Regional bathymetry. Northern part of the study area. Colour-shaded relief map with 100 m depth contours. LI-Lofoten Islands, VF-Vestfjorden, HB-Haltenbanken, SKD-Sklinnadjupet, TD-Trænadjupet, SD-Suladjupet, FB-Frøyabanken, FR-Frøyryggen, TB-Trænabanken, SR-Skjoldryggen.



Overview map, southern part
Mid-Norwegian shelf
Bathymetry, shaded relief map

Fig. 12. Regional bathymetry. Southern part of the study area. Colour-shaded relief map of the shelf area off Sogn og Fjordane and Møre og Romsdal. 100 m depth contours. SD-Suladjupet, FB-Frøyabanken, FR-Frøyryggen, RF-Romsdalsfjorden, SF-Storfjorden, LG-Langgrunna, MP-Måløyplatået, BG-Buagrunnen, BD-Breisundjupet, OD-Onadjupet, NT-Norwegian Trench, K-Kristiansund, Å-Ålesund.

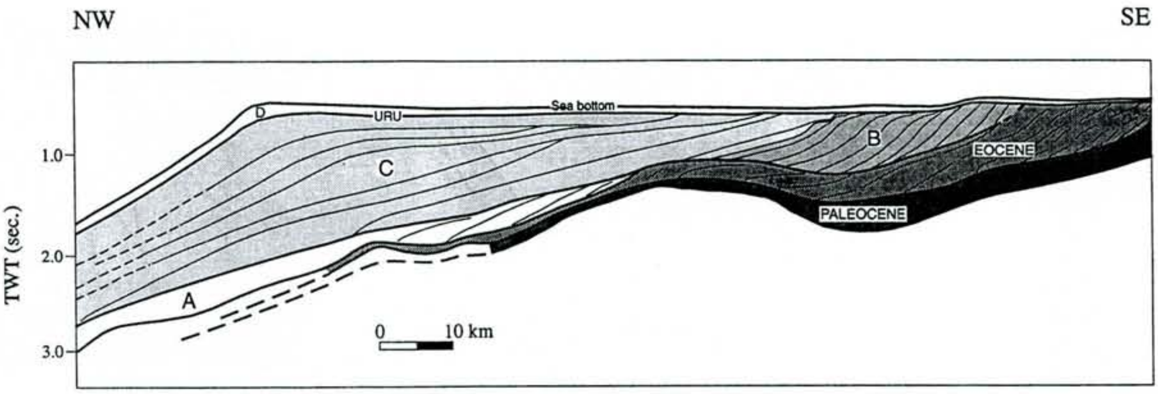


Fig. 13. Schematic cross section of the Cenozoic sedimentary stratigraphy on the mid-Norwegian continental shelf. (After Henriksen and Vorren 1996).

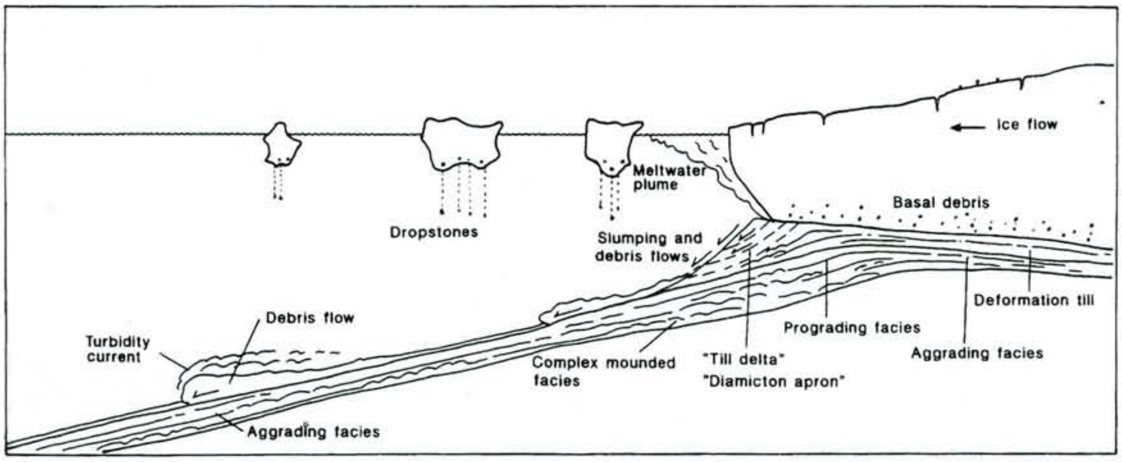


Fig. 14. Ice sheet depositional model for the sequences within unit C on the mid-Norwegian continental shelf. Sediments are eroded and carried from continent and inner shelf areas, principally as basal debris in grounded ice sheets and are deposited on the continental shelf as deformation tills and on the continental slope as marine diamicton. (After Henriksen and Vorren 1996).

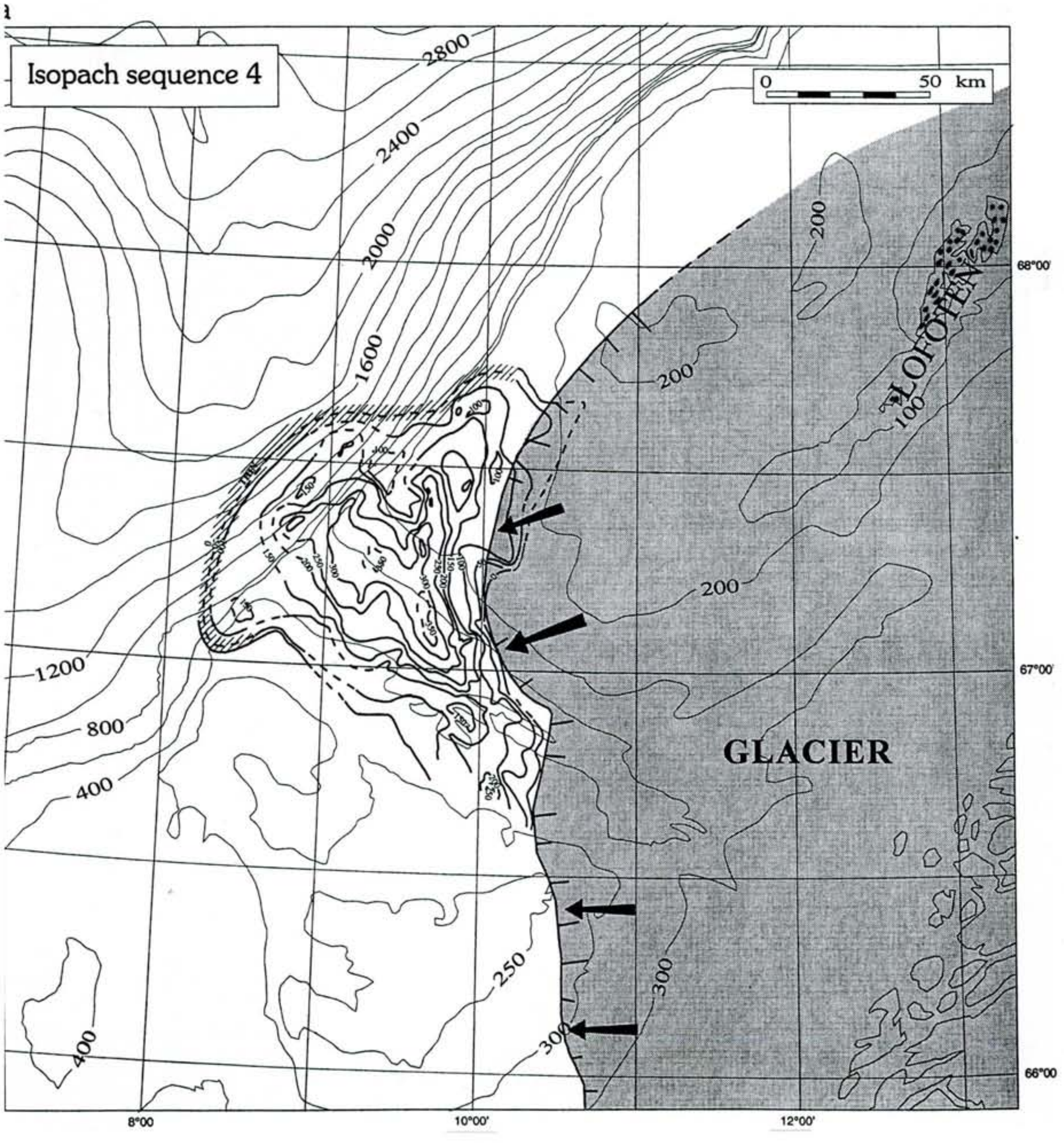


Fig. 15. Paloegeographic reconstructions of the northern part of the mid-Norwegian continental shelf during the Late Pliocene-Early Pleistocene from the earliest phase of the outbuilding. Arrows indicate ice movement and the direction of sediment transport. (After Henriksen and Vorren 1996).

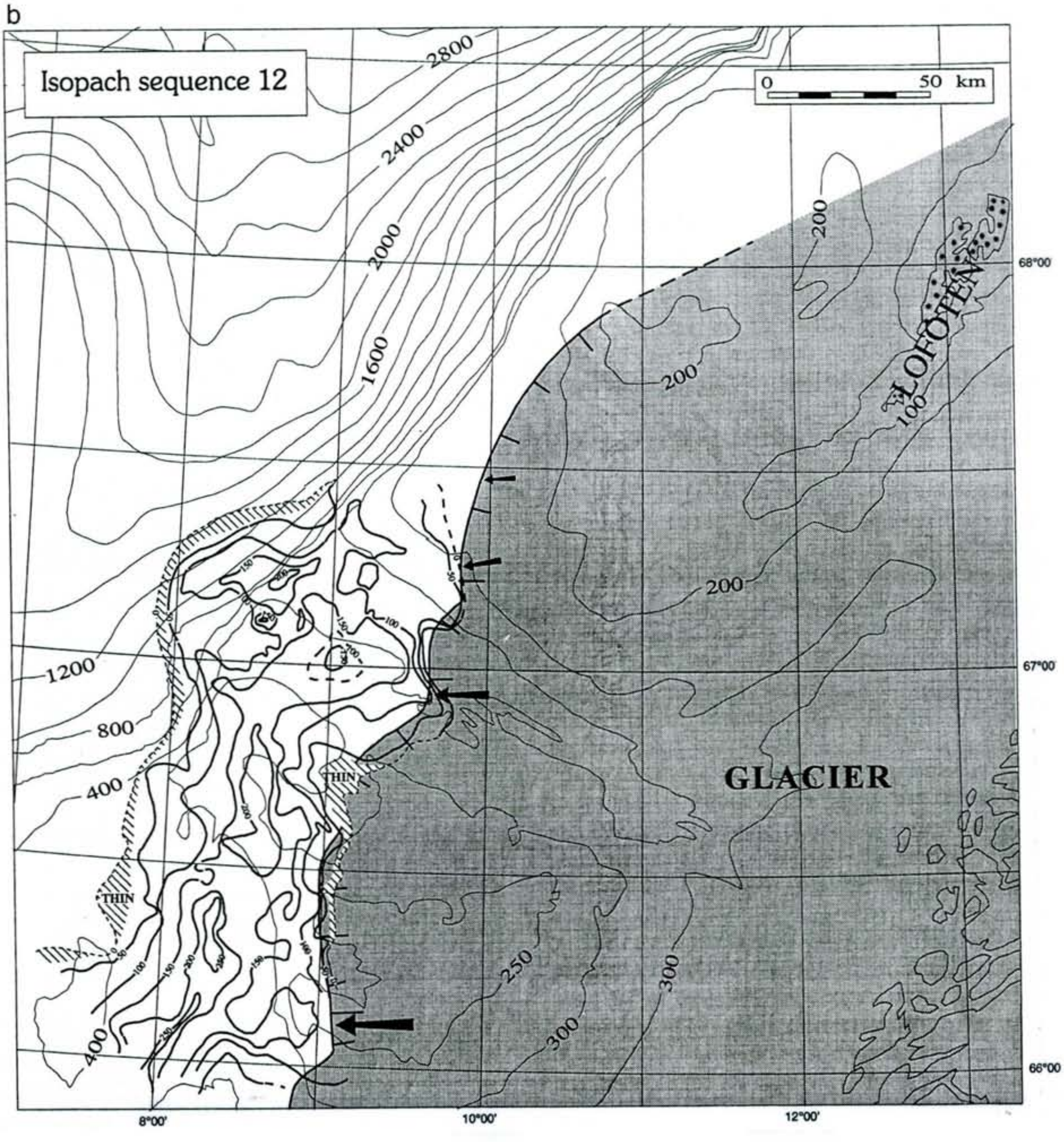


Fig. 16. Paloegeographic reconstructions of the northern part of the mid-Norwegian continental shelf during the Late Pliocene-Early Pleistocene from the latest phase of the outbuilding. Arrows indicate ice movement and the direction of sediment transport. (After Henriksen and Vorren 1996).

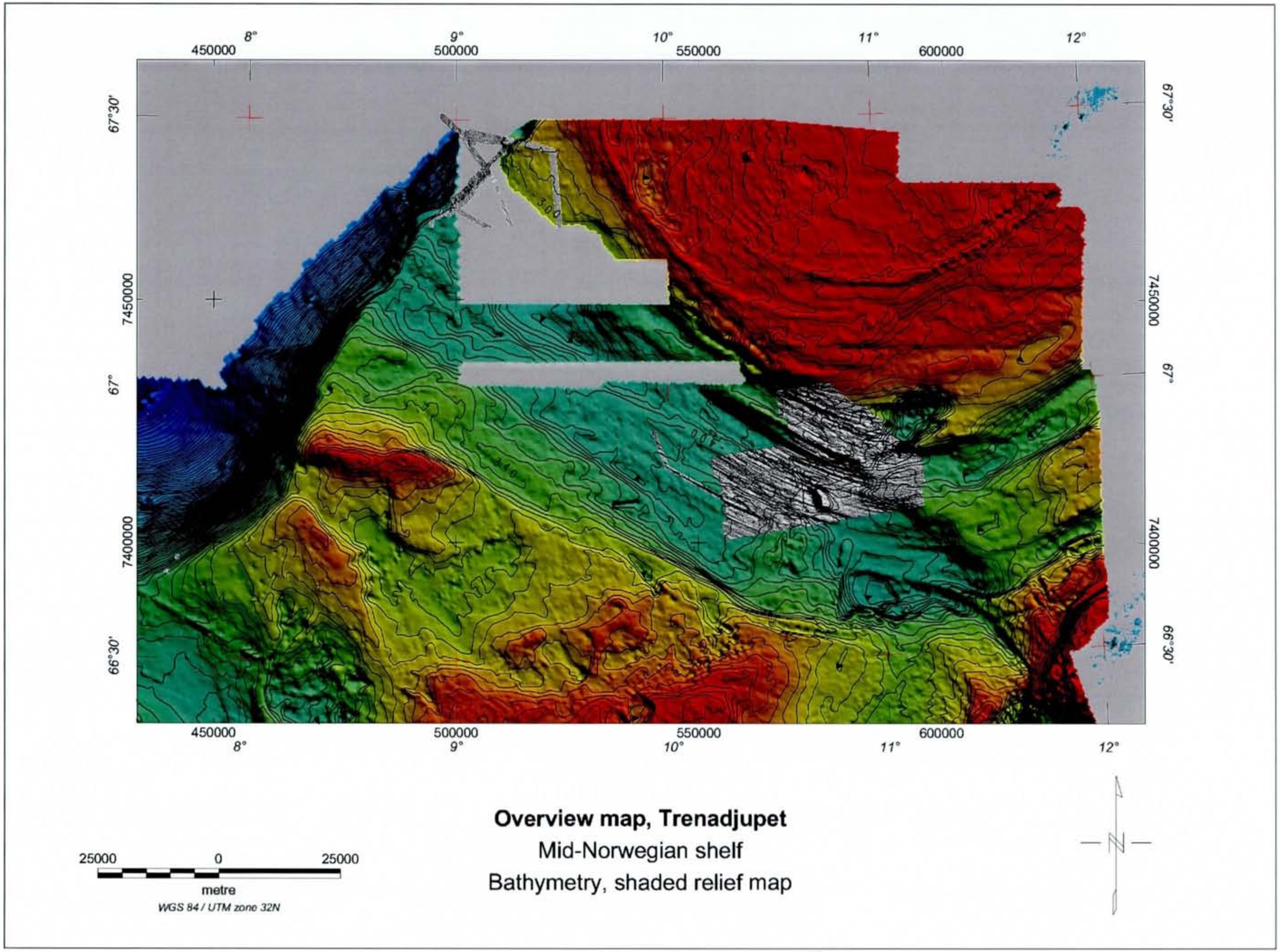


Fig. 17. Trænadjupet. Regional bathymetry identifying ice stream erosion/fluted surface. 10 m depth contours.

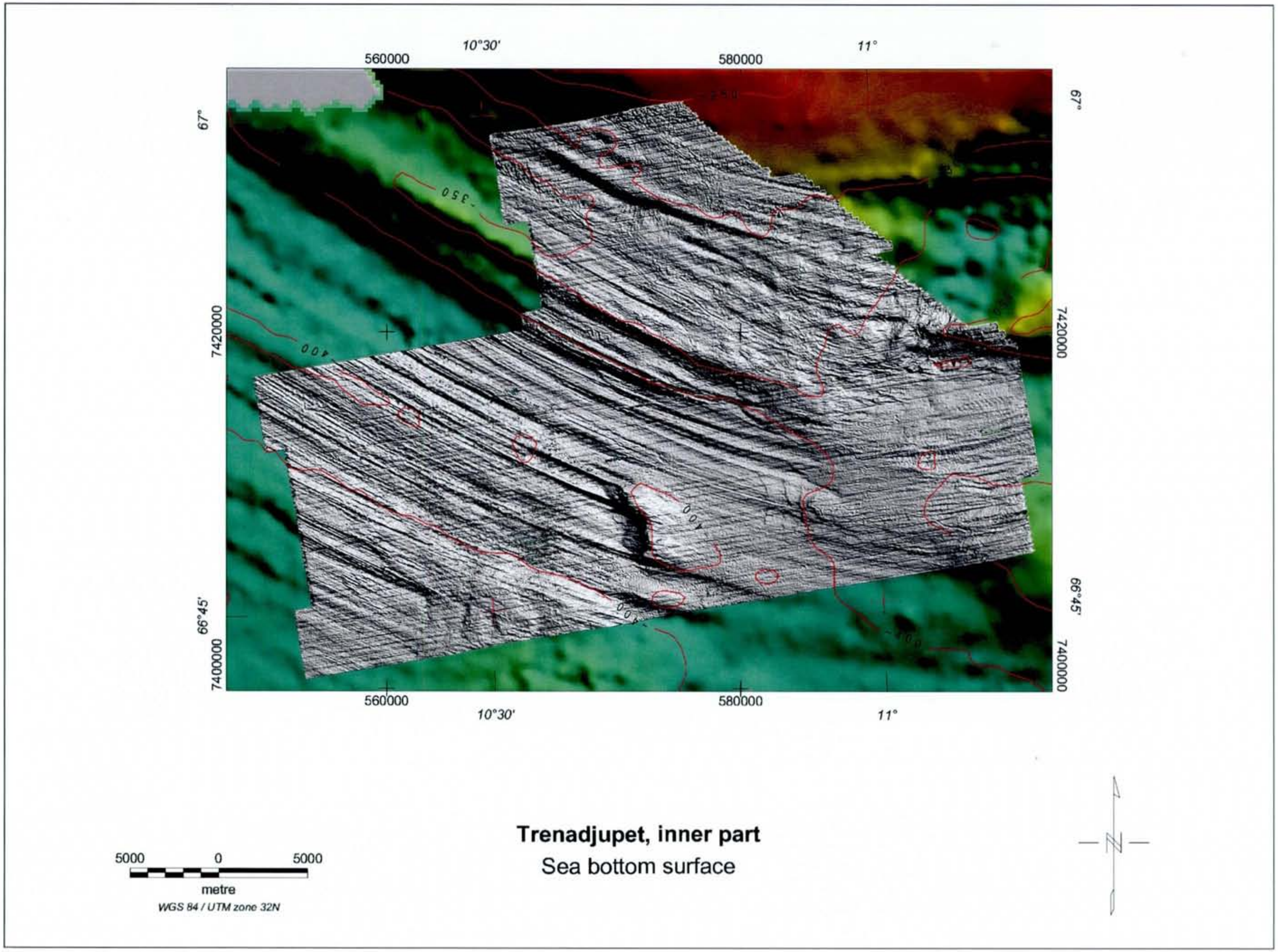


Fig. 18. Trænadjupet. Interpreted sea bottom from 3D-seismic (ST9404). Extensive glacial flutes caused by ice streaming out Trænadjupet. 100 m depth contours from regional bathymetry

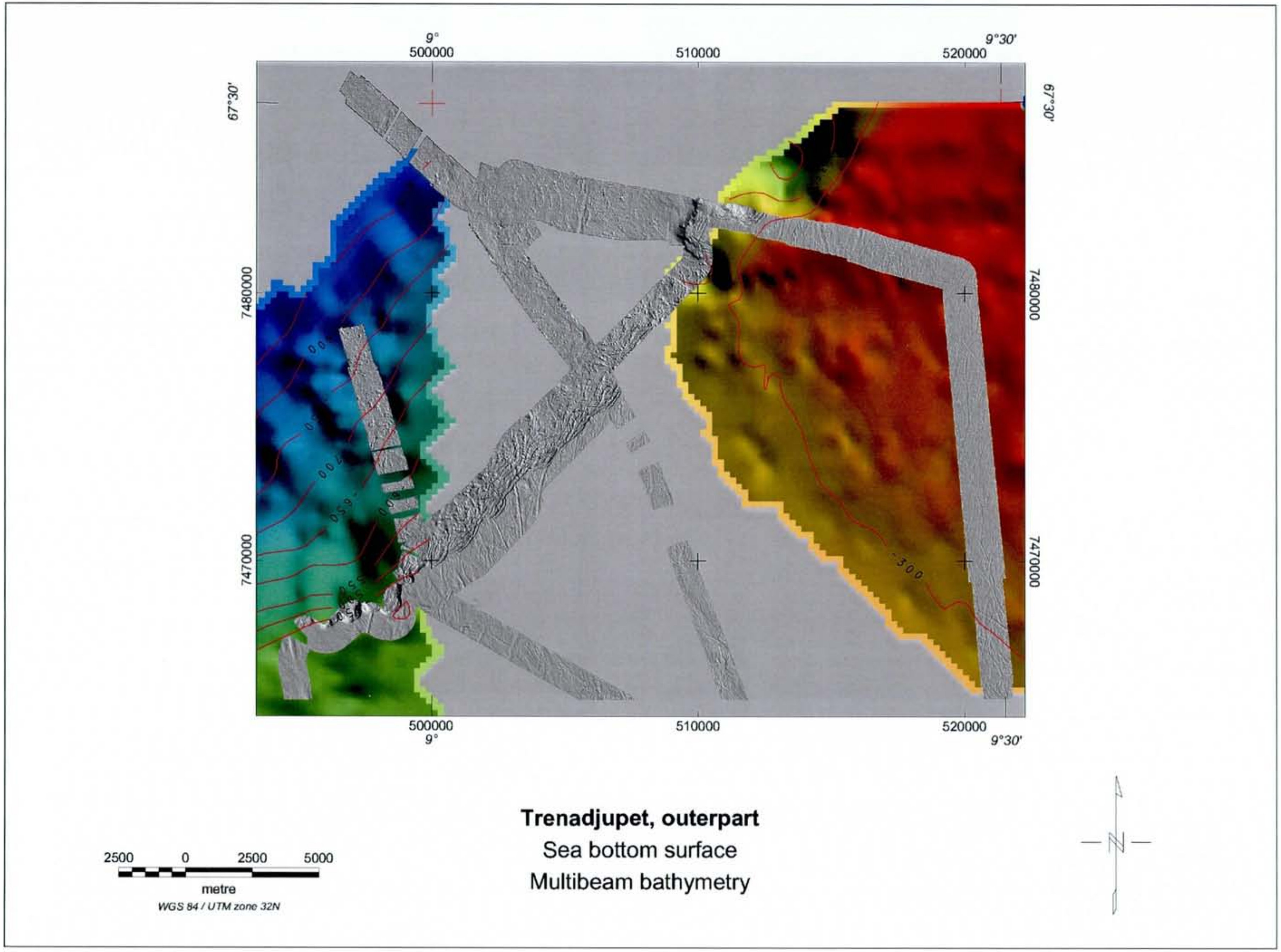


Fig. 19. Trænadjupet – outer part. Detailed and regional bathymetry. The figure outlines the continental margin with the shelf, the shelf break and the upper continental slope. 100 m depth contours in red

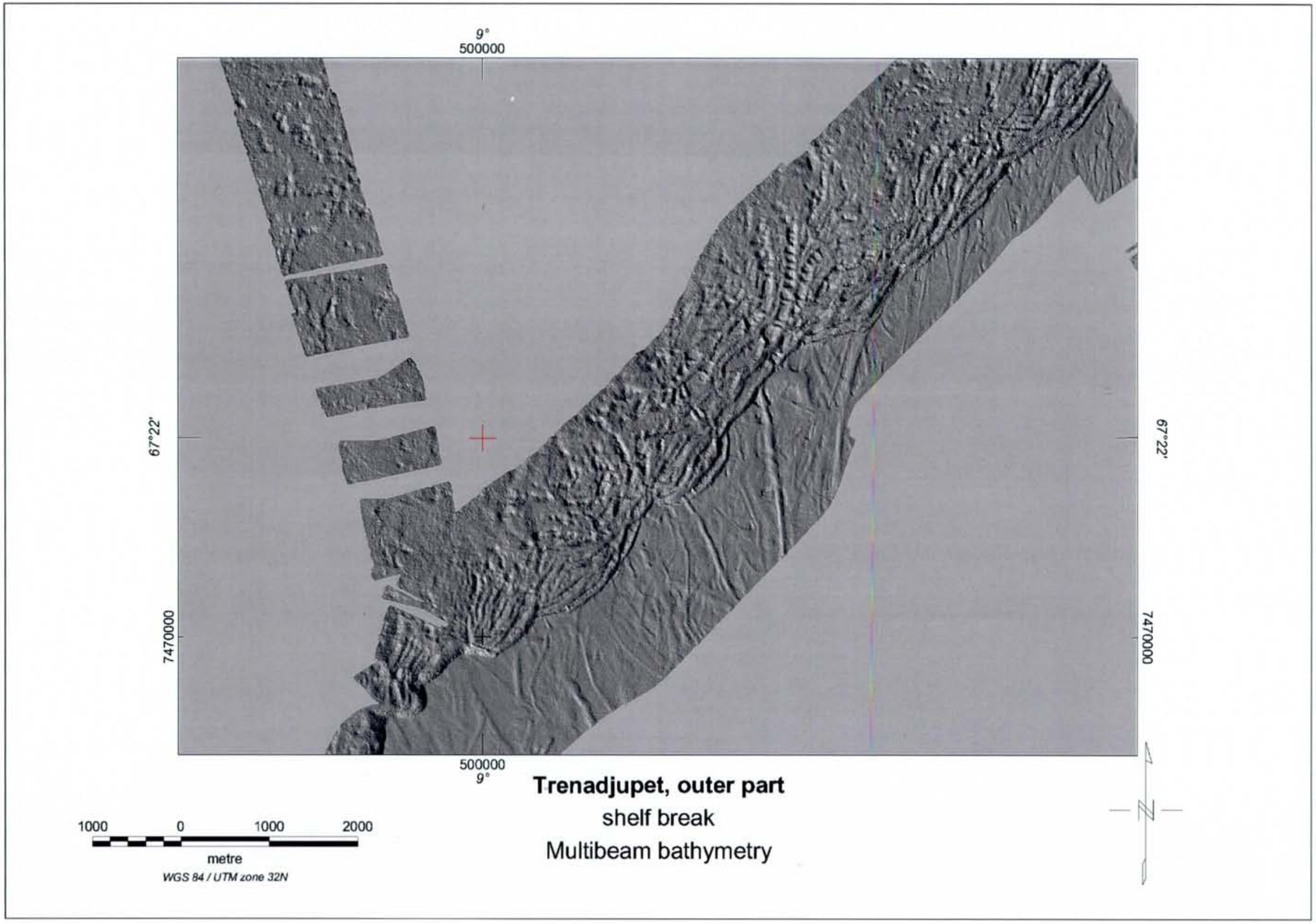


Fig. 20. Trænadjupet. Multibeam bathymetry. Ice scour marks on the outer shelf. Slide deposits along the shelf break/upper slope.

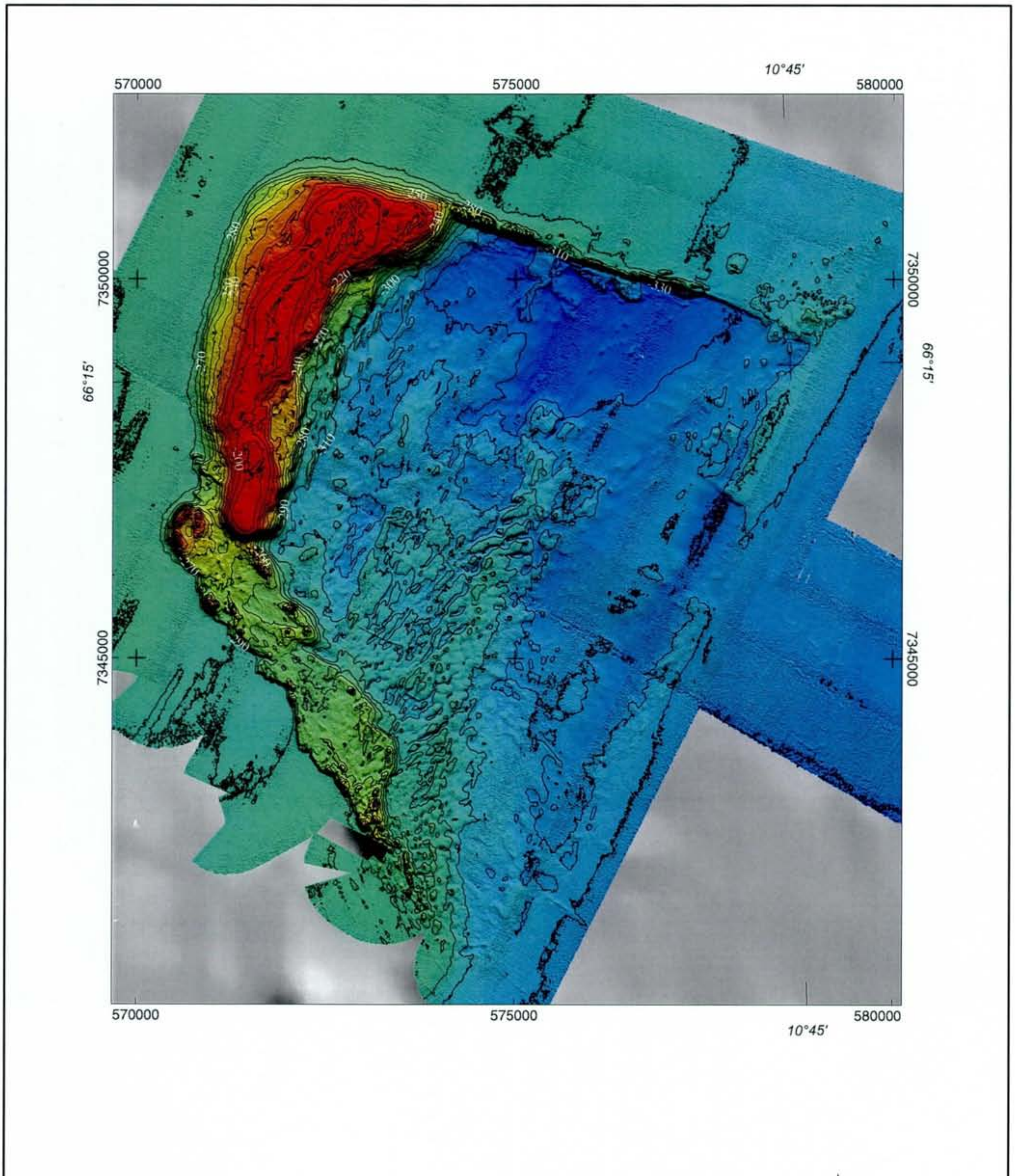


Fig. 21. Inner Trænabank. Horseshoe. Multibeam bathymetry, colour shaded relief map. Glaciotectonic feature/morainic ridge comparable to forms east of the Skjoldryggen area. 10 m depth contours.

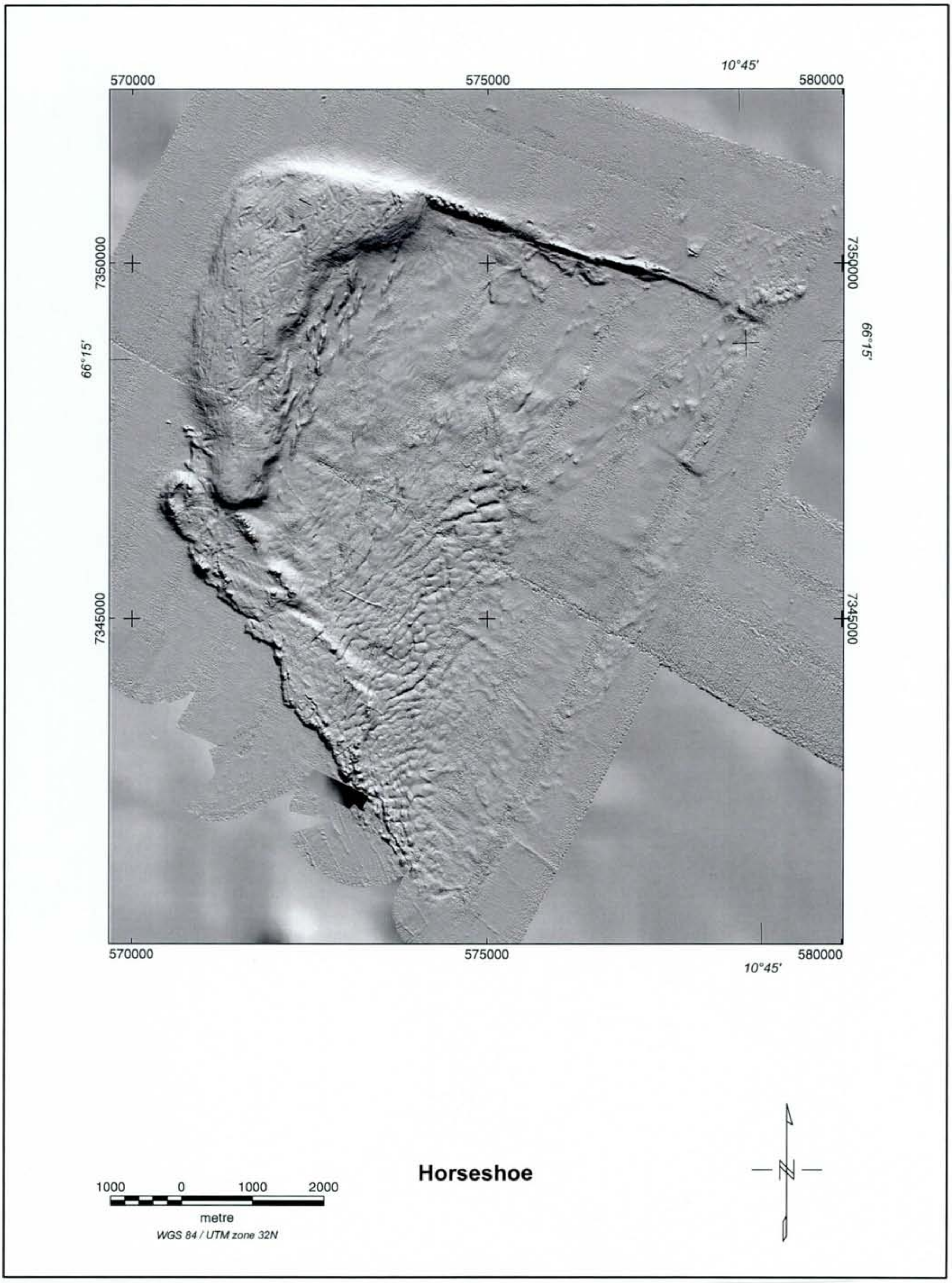


Fig. 22. Inner Trænabank. Horseshoe. Multibeam bathymetry, shaded relief map. Glaciotectonic feature/morainic ridge comparable to forms in the Skjoldryggen area. Note the ice scour marks on top of Hesteskoen

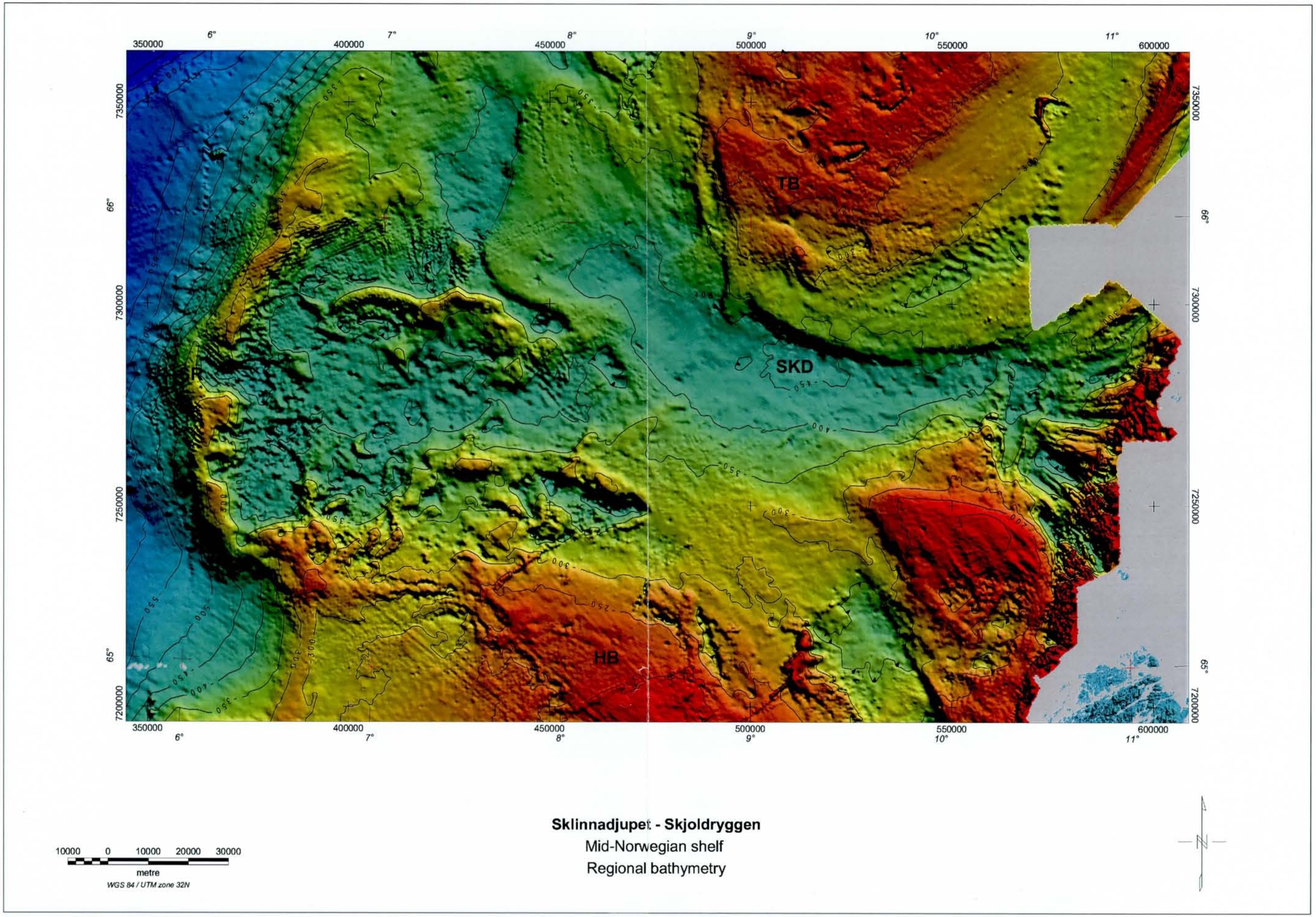


Fig. 23. Sklinnadjupet/Skjoldryggen area. Regional bathymetry identifying ice stream confluencing/erosion in east and glacial mass transport to the outer shelf area (Skjoldryggen area). 50 m depth contours. The border between crystalline and sedimentary rock are seen in the east on the figure

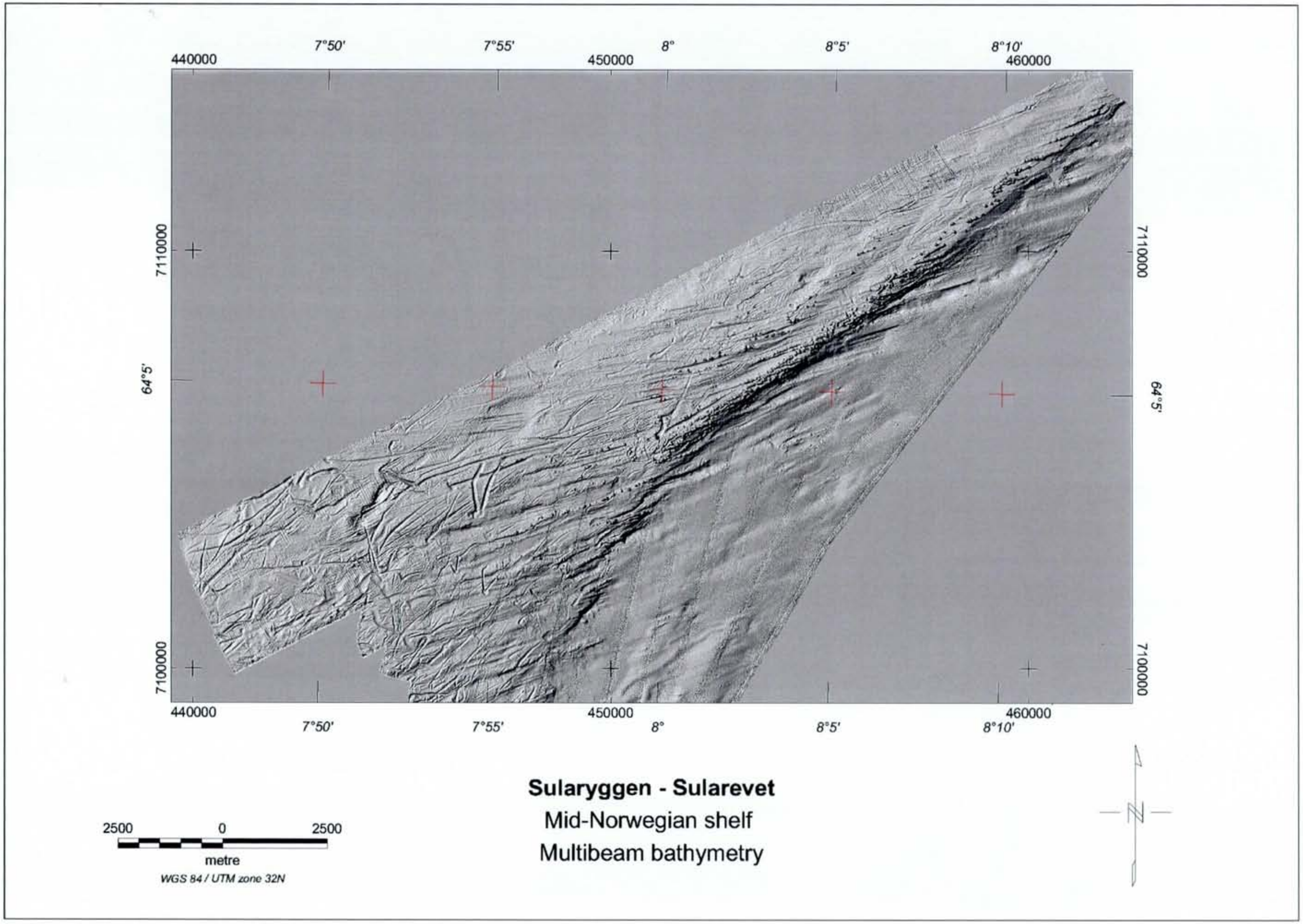


Fig. 24. Sularyggen/Suladjupet. Multibeam bathymetry evidencing large scale glacial erosion across Sularyggen (megaflutes/drumlins). Note the individual coral mounds on top of the Sularyggen (each individual mound is 50-100 m in diameter at the base, and is 10-30 m high).

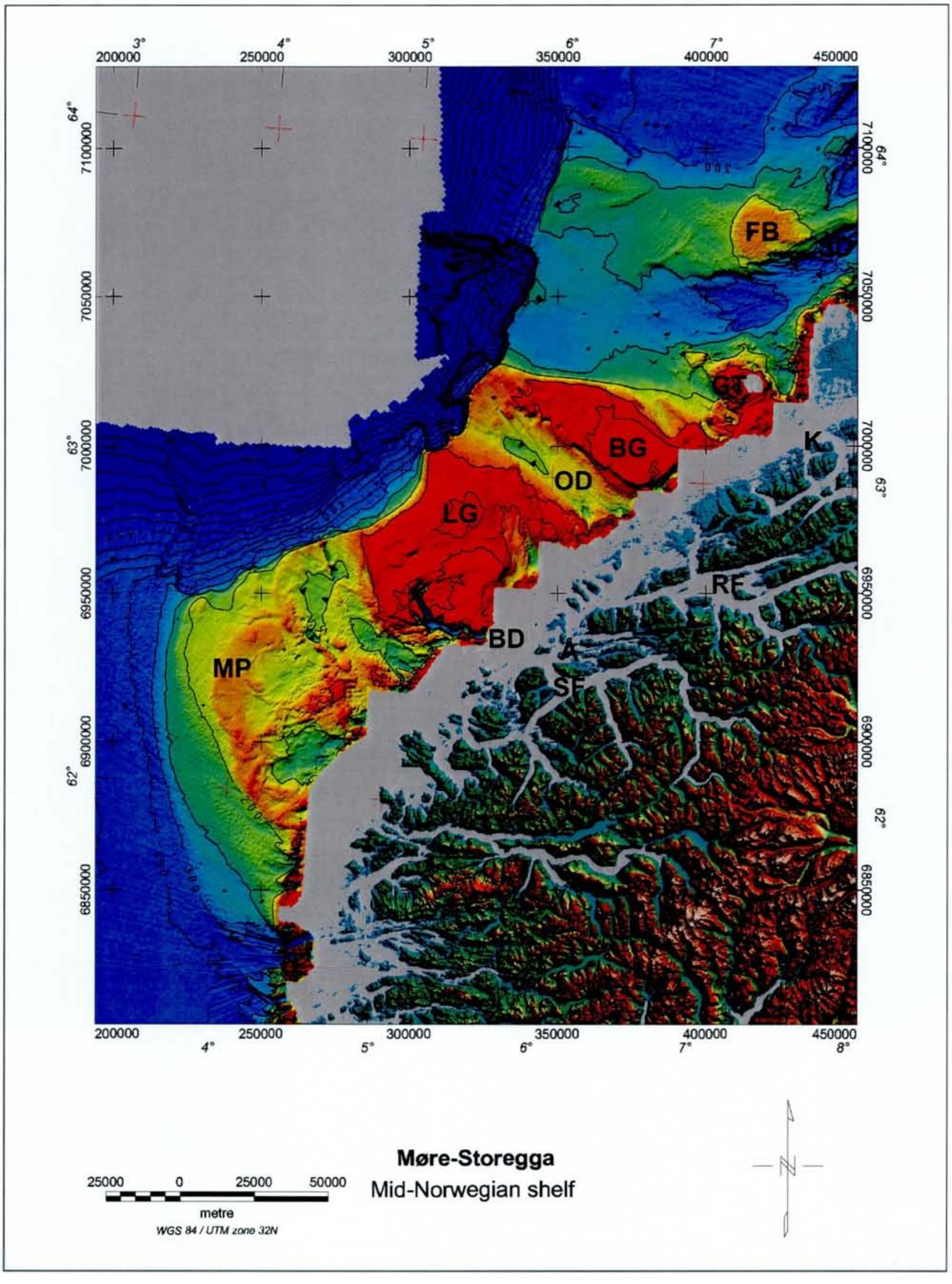


Fig. 25. Regional bathymetry inside Storegga. 50 m depth contours. On Måløyplatået large curved ridges dominate, while further north depressions from land to the shelf break separate shallower bank areas. The depressions are interpreted to have been drainage routes for ice streams during maximum expansion of the Late Weichselian ice sheet. SD-Suladjupet, FB-Frøyabanken, FR-Frøyryggen, RF-Romsdalsfjorden, SF-Storfjorden, LG-Langgrunna, MP-Måløyplatået, BG-Buagrunnen, BD-Breisundjupet, OD-Onadjupet, NT-Norwegian Trench, K-Kristiansund, Å-Ålesund.

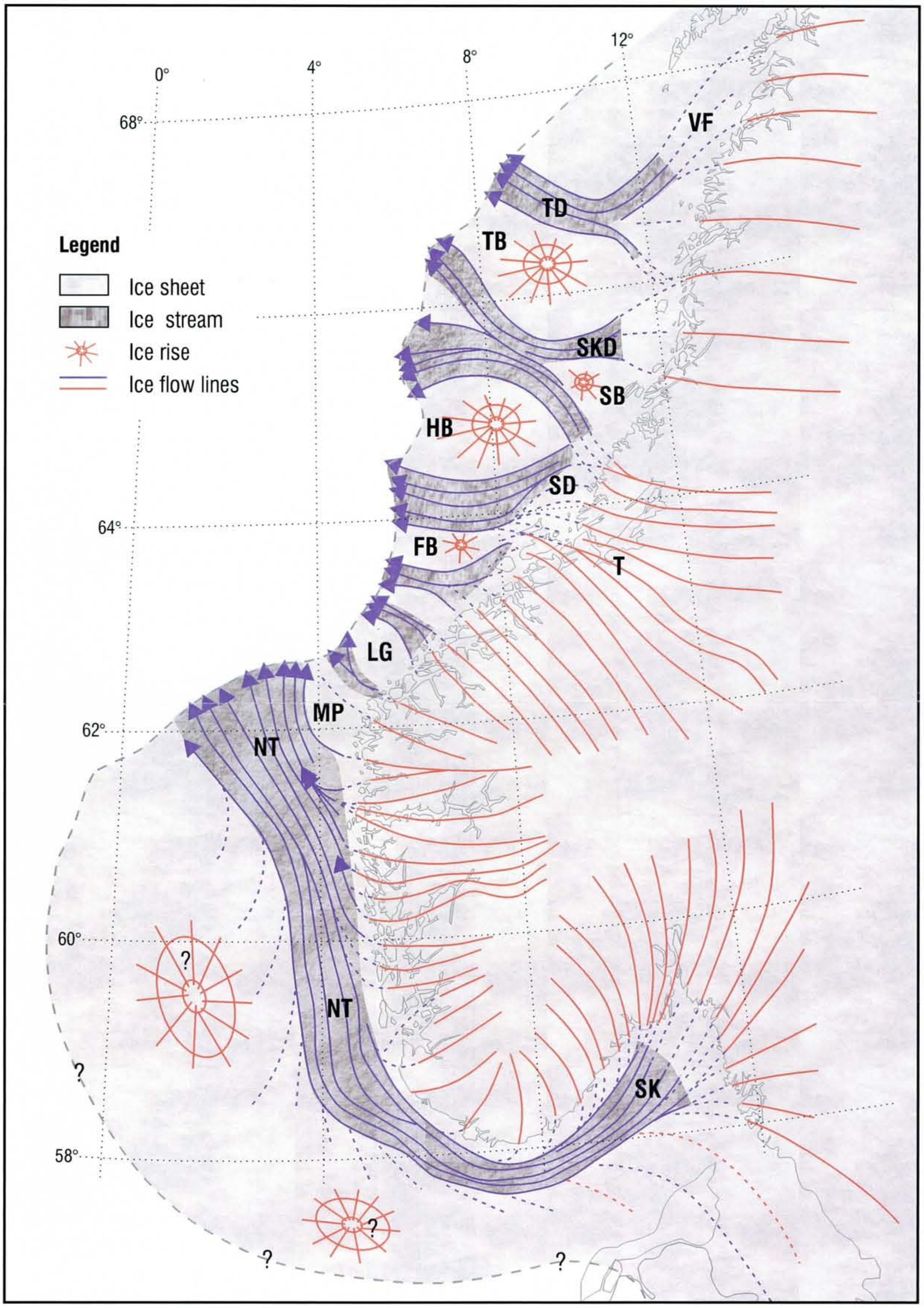


Fig. 26. Interpreted ice-flow model during the Late Weichselian with ice streams flowing along the main offshore depressions/troughs. The largest ice stream was located in the Norwegian Trench. On the mid-Norwegian shelf, the major ice streams followed Trænadjupet, Sklinnadjupet and Suladjupet. The ice streams outside Møre follow smaller depressions perpendicular to the coast. The ice streams seem to originate just west of the crystalline rocks. VF-Vestfjorden, HB-Haltenbanken, SKD-Sklinnadjupet, TD-Trænadjupet, SB-Sklinnabanken, SD-Suladjupet, FB-Frøyabanken, MP-Måløyplatået, NT-Norwegian Trench, TB-Trænabanken, LG-Langgrunna, SK-Skagerrak, T-Trondheim.

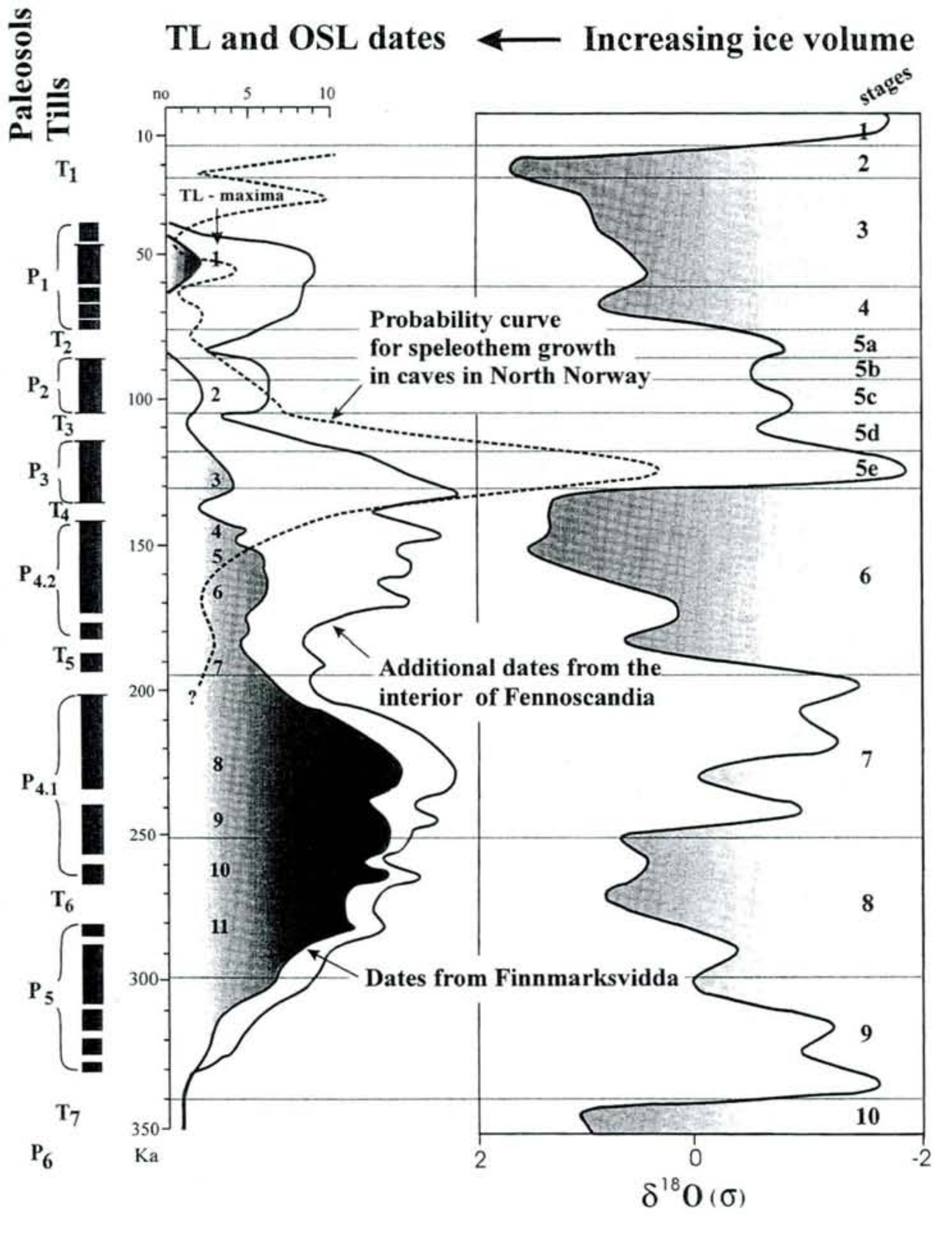


Fig. 27. *Inferred ages of the Pleistocene paleosols in Finnmark, North Norway, based on luminescence (TL and OSL) dating of ice-free intervals, comparison with speleothem dates from caves in Nordland, North Norway, and with a generalised North Atlantic deep sea oxygen isotope record. After Olsen (1998).*

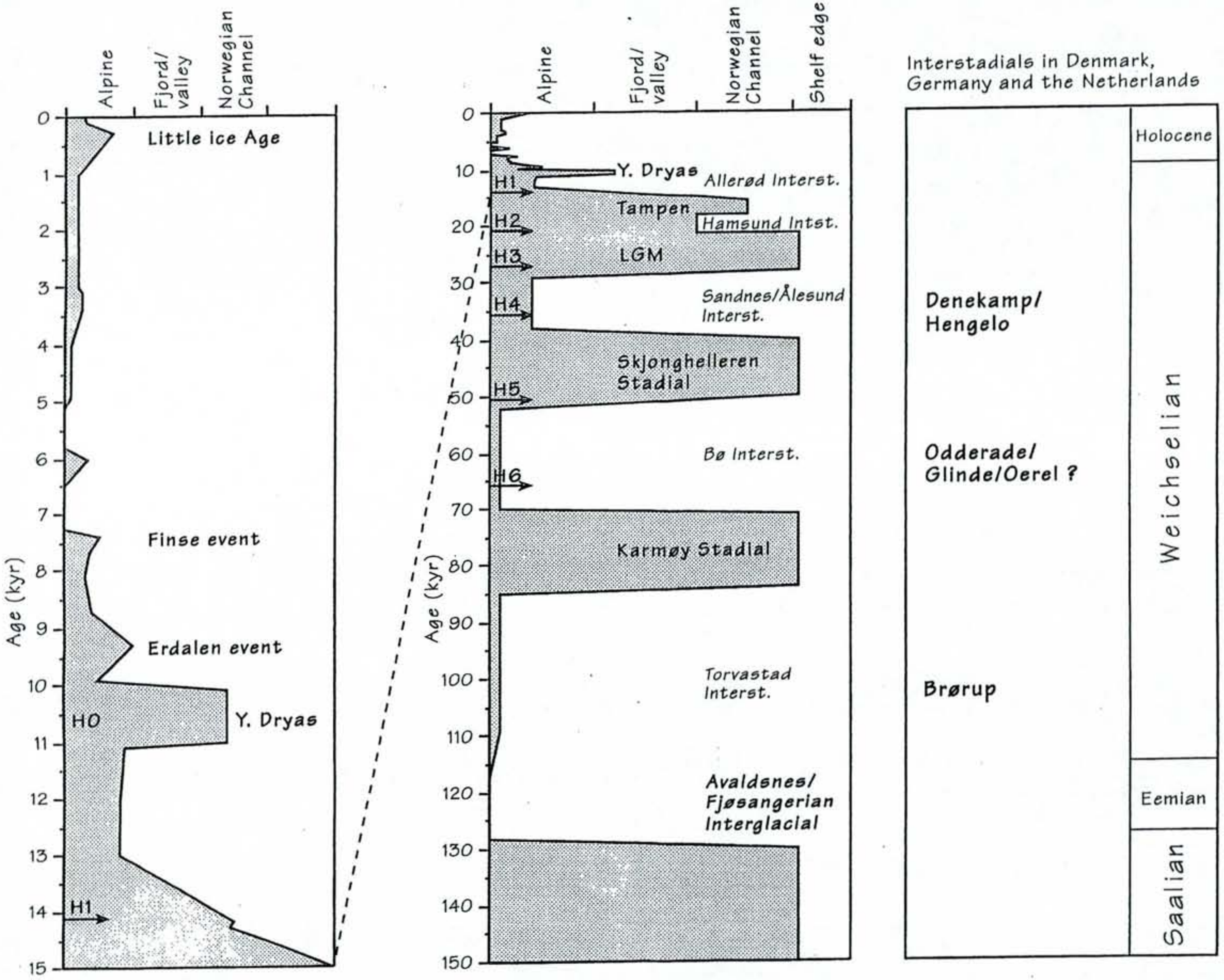


Fig. 28. Glaciation curve for the south-western Fennoscandian region covering the last 150 ka as deduced from evidence from the North Sea and western Norway. (After Sejrup et al., in press). As little information is available on the length of the Weichselian interstadials and stadials beyond the range of radiocarbon, this part of the curve only indicate roughly possible timing of these events.

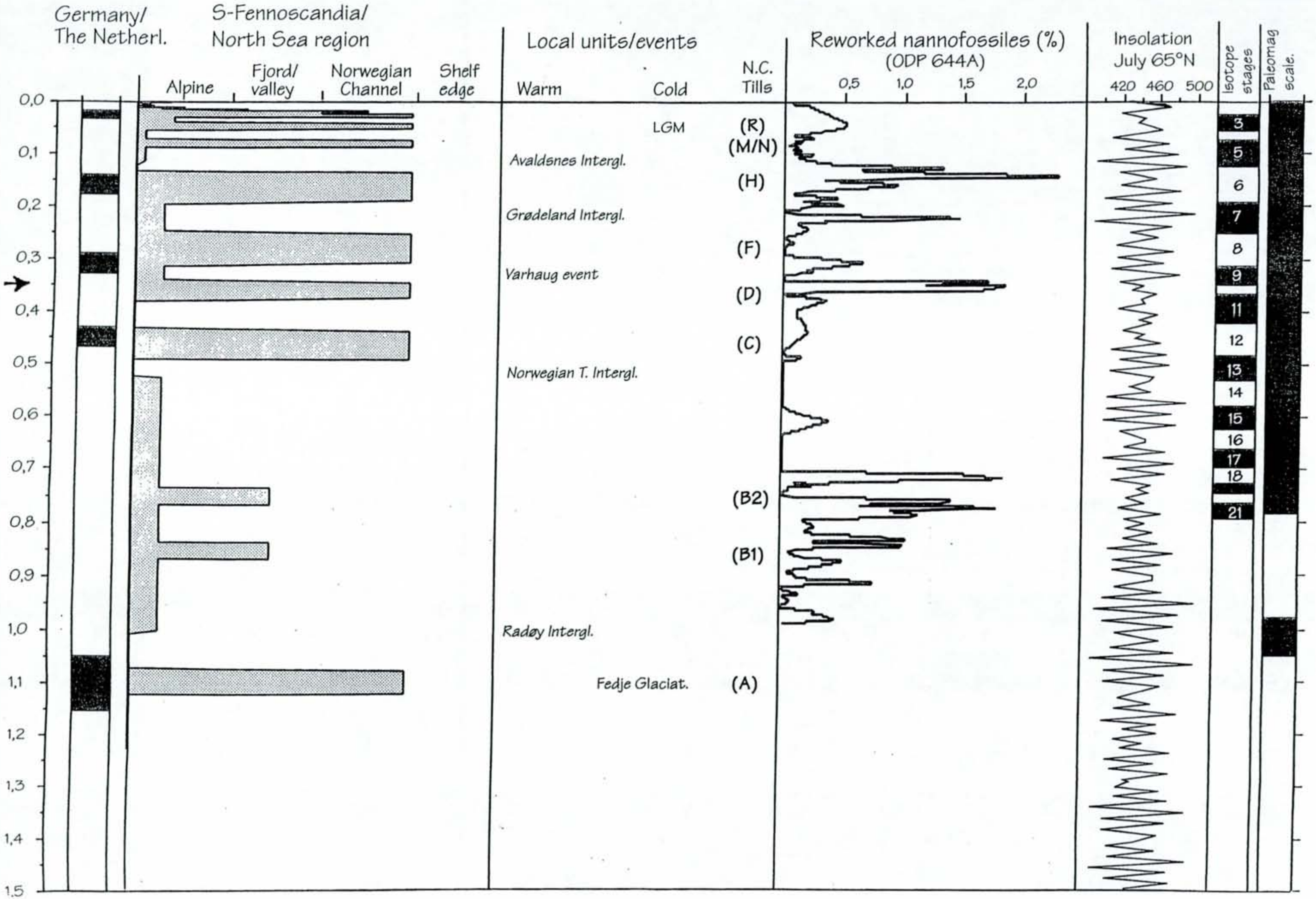


Fig. 29. *Glaciation curve for southern Fennoscandia through the last 1.5 my. (After Sejrup et al. in press). The amount of reworked nannofossils in core ODP 644A from the Vøring Plateau are from Henrich and Baumann (1994). Glacial events in Germany/The Netherlands are modified from Mangerud et al. (1996).*

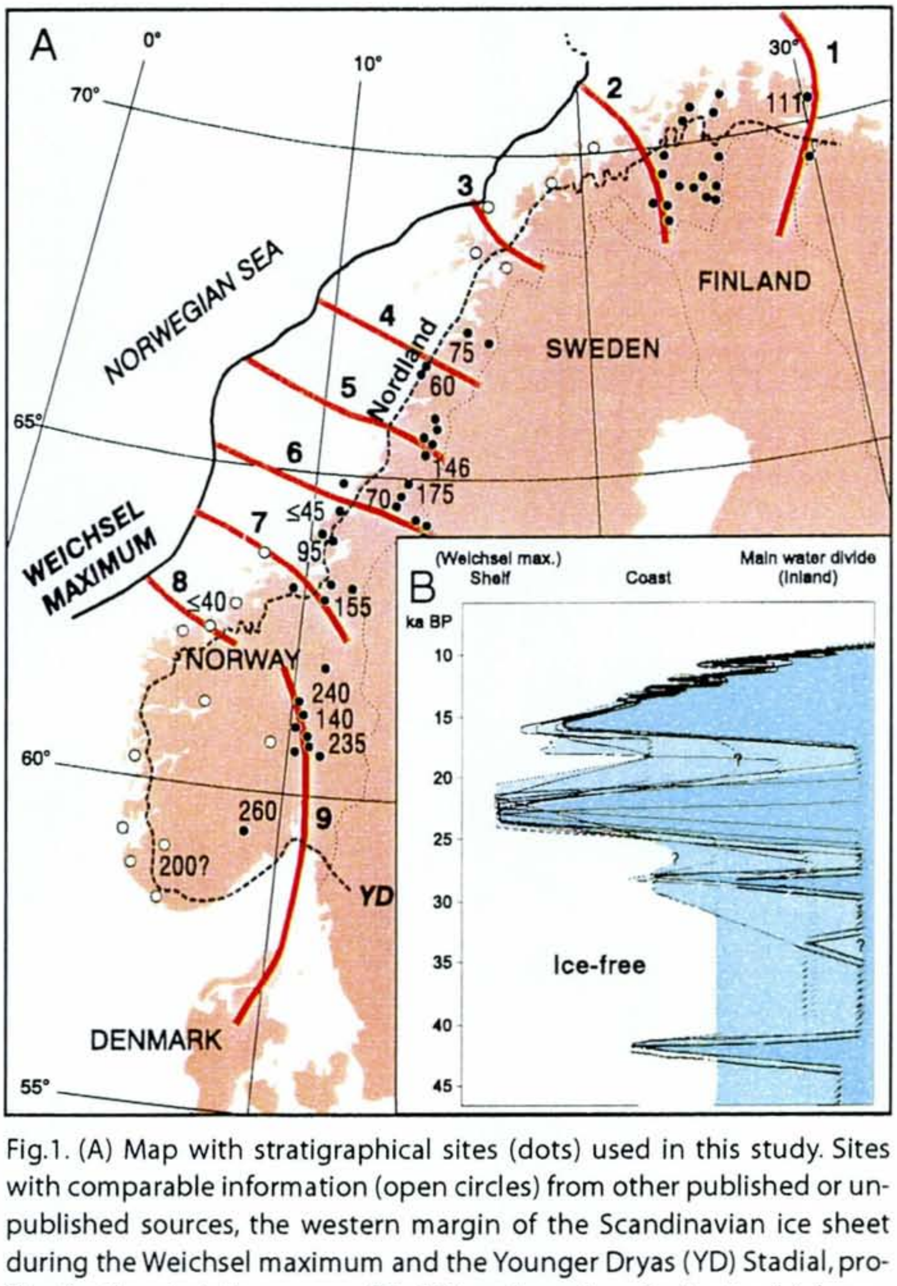


Fig.1. (A) Map with stratigraphical sites (dots) used in this study. Sites with comparable information (open circles) from other published or unpublished sources, the western margin of the Scandinavian ice sheet during the Weichsel maximum and the Younger Dryas (YD) Stadial, profiles for the glaciation curves (Fig.1B), and numbers indicating high sea-levels (m a.s.l.) during the period 15-40 ka BP are also shown.

(B) Composite glaciation curve for Norway during the last glaciation (c. 10-40 ka BP). The curves constructed along each of the nine profiles shown in Fig.1A are all plotted on the same diagram with all profile lines defined to be of equal length. Ice-covered areas are shown with light blue-bluish green colour.

Fig. 30. Time-distance diagrams from Central Norway. Norwegian mainland - continental shelf edge (from Olsen 1997).

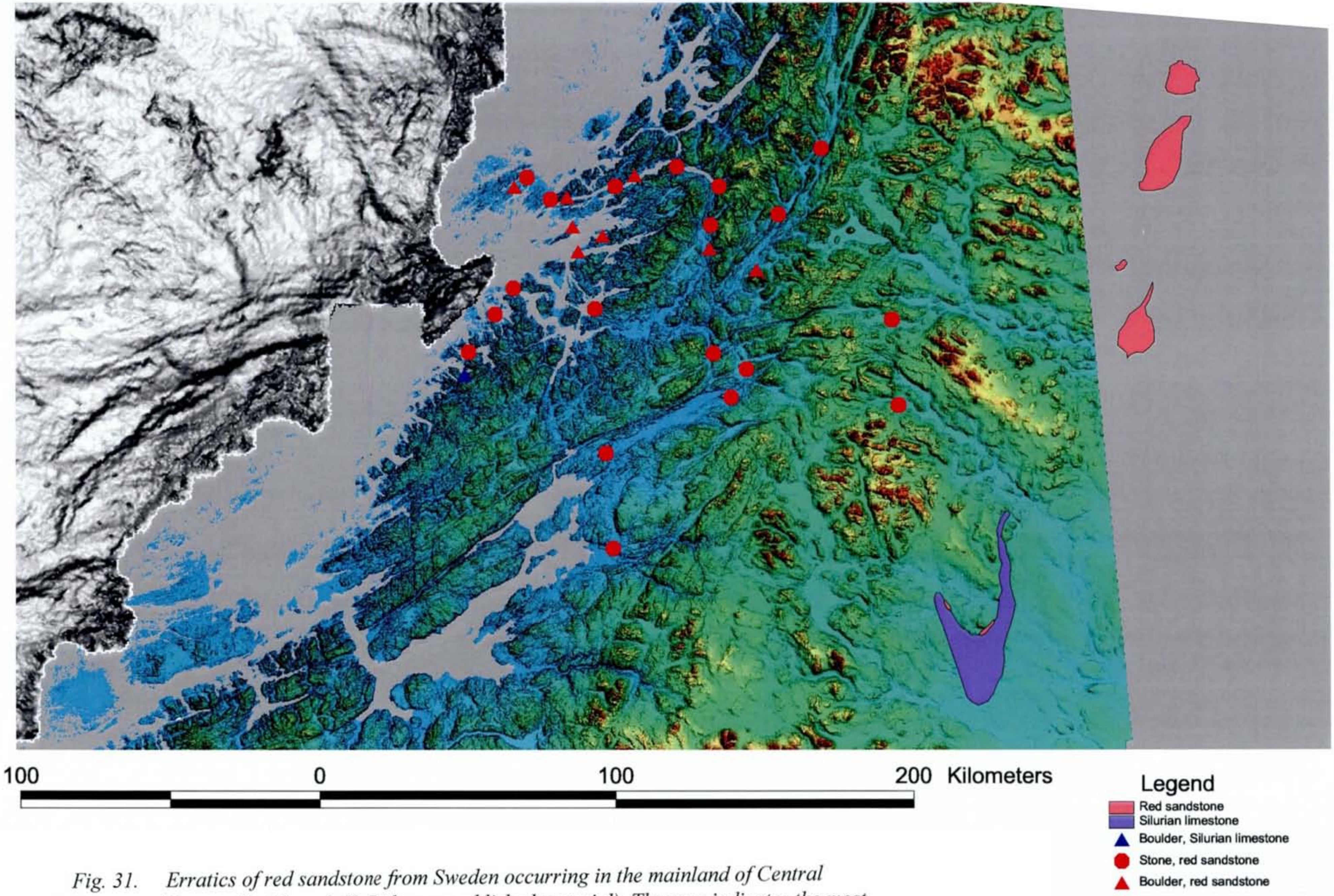


Fig. 31. *Erratics of red sandstone from Sweden occurring in the mainland of Central Norway (L. Olsen & K. Riiber, unpublished material). The map indicates the most frequent finds of these erratics. Single erratics of red sandstone are found in a wider area.*

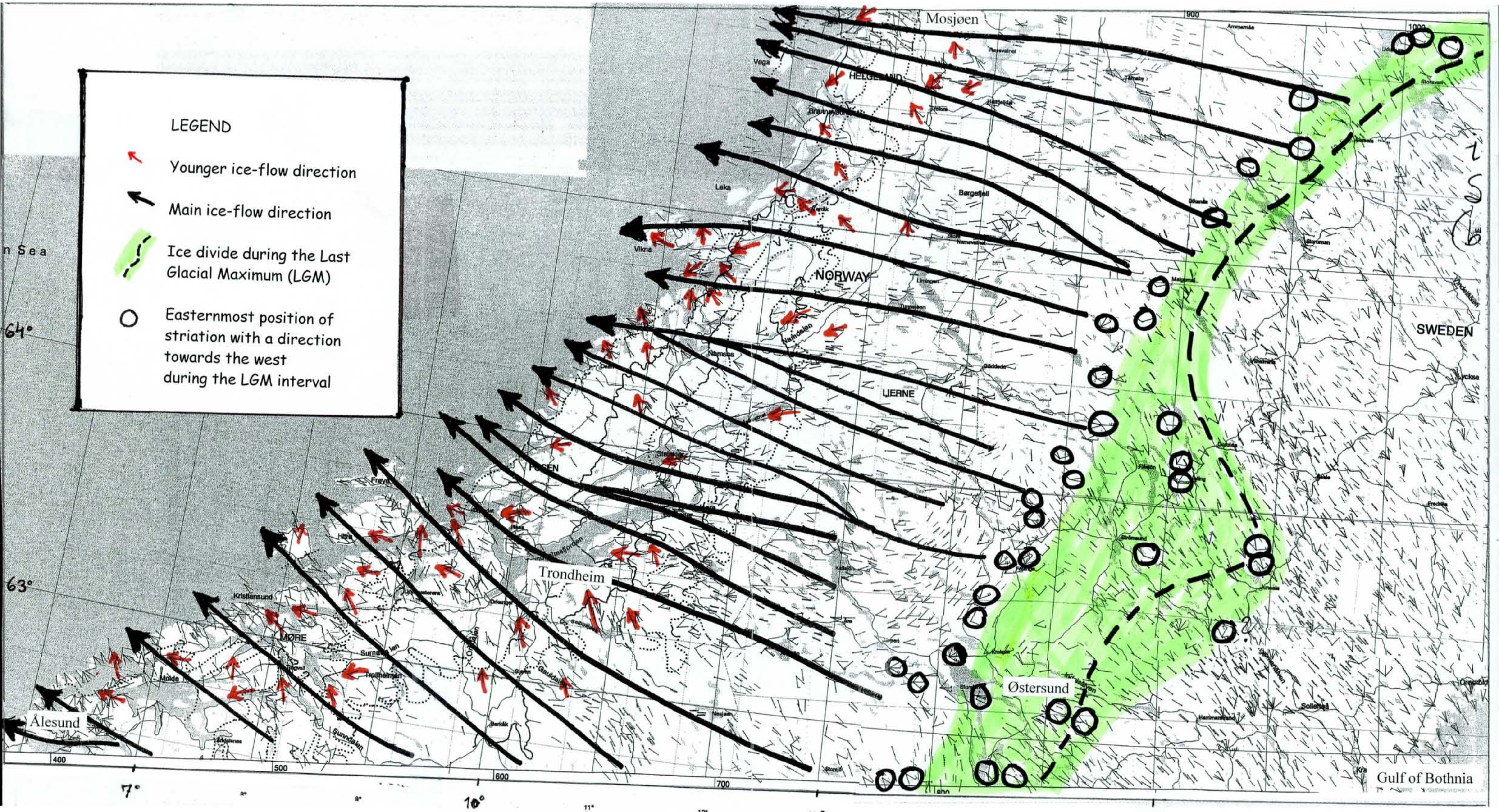


Fig. 32. Ice movements across Central Norway. Based on ice flow indicators (mainly glacial striation) from a map of Central Fennocandia compiled by the Geological Surveys of Finland, Norway and Sweden (Bargel et al. 1999)

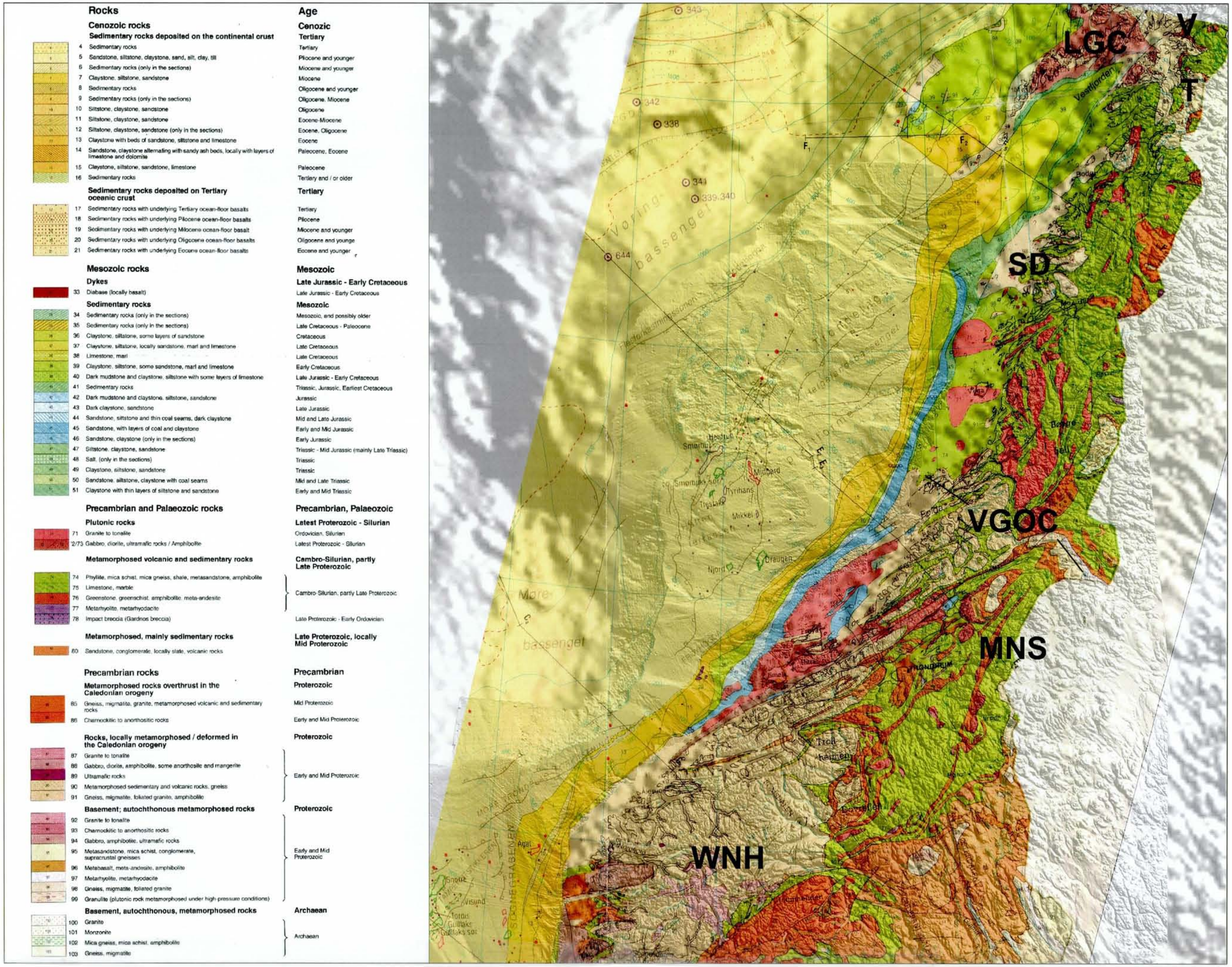
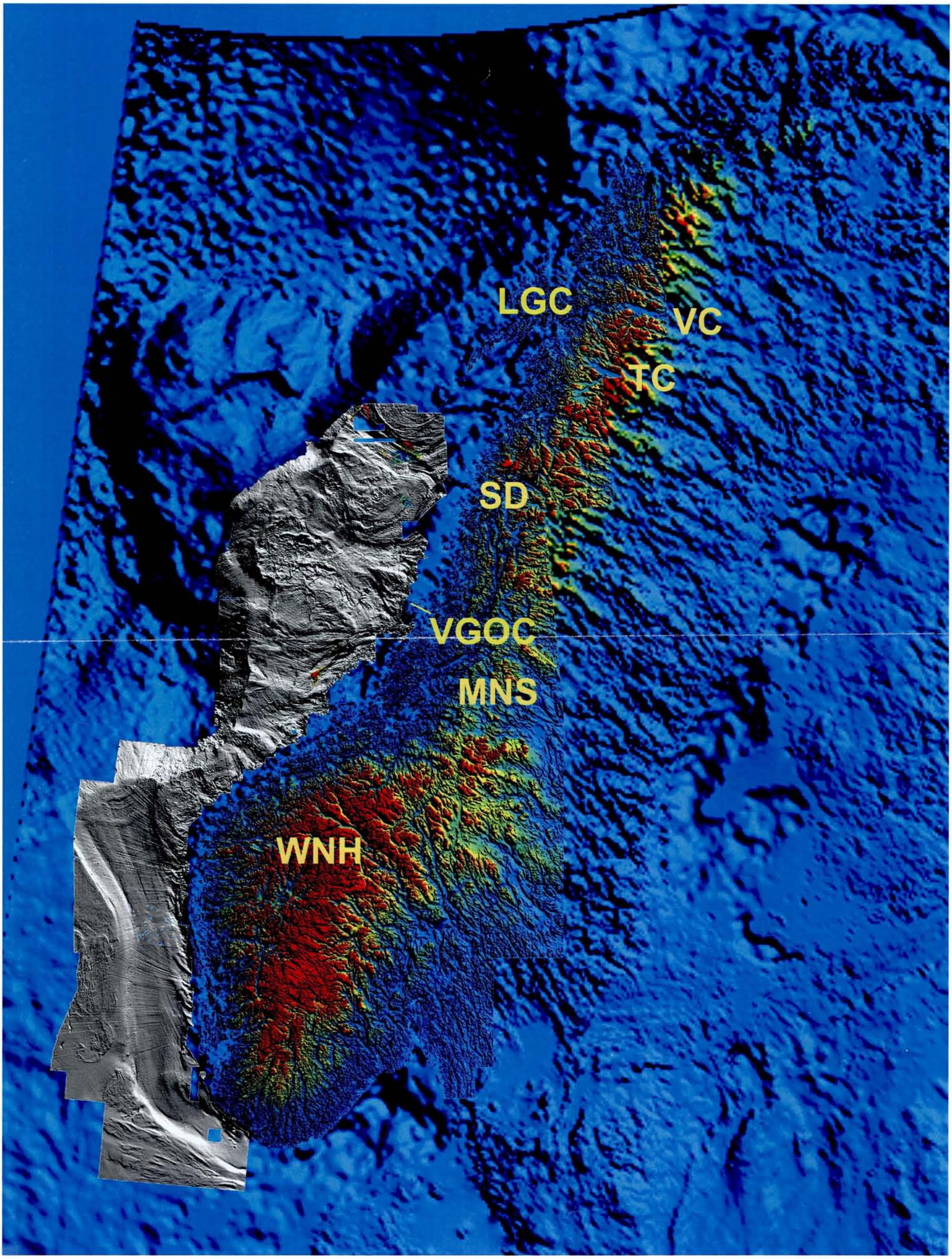


Fig. 33. Major bedrock (and morphologic) provinces between 61° and 68° N. WNH – Western Norway High; MNS – Mid-Norway Saddle; VGOC – Vikna-Grong-Olden Culmination; SD – Svartisen Dome; V – Vestfjorden ; T – Tysfjord.



ig. 34. Major morphologic provinces between 61° and 68° N. WNH – Western Norway High; MNS – Mid-Norway Saddle; GOC – Vikna-Grong-Olden Culmination; SD – Svartisen Dome; VC – Vestfjorden Continuation ; TC – Tysfjord Continuation.