PHILOSOPHICAL TRANSACTIONS OF THE ROYAL SOCIETY A
MATHEMATICAL, PHYSICAL & ENGINEERING SCIENCES

The Storegga Slide

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THE STOREGGA SLIDE

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[Plate 1]

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One of the World's largest known submarine slides is found in the Storegga area off the coast of Mid-Norway. The slide area has been investigated by seismic profiling, seabed sampling and long-range (Gloria) and medium-range side-scan sonars.

The 290 km long headwall is located at the shelf edge 100 km off the coast. The slide extends down the continental slope and into the abyssal plain to a distance of more than 800 km. The maximum thickness is 450 m and a total of about 5600 km^3 of sediment was involved in the sliding.

Three main slide events are distinguished. The First Storegga Slide was the largest (about 3880 km^3) and probably was formed 30000–50000 years BP. The two other events seem to have occurred in near succession about 6000–8000 years BP. The Second Slide, which consisted of more consolidated sediments than the First Slide, cut back 6–8 km headwards beyond the First Slide and removed some 450 km^2 of the continental shelf edge. It involved large blocks (olistoliths) of sediments that can be recognized in hummocky slide deposits both within the slide scar and on the abyssal plain. Two huge sediment slabs, 150–200 m thick and up to 10 × 30 km wide, were transported about 200 km down an average slope 0.3°. The Third Storegga Slide was limited to the upper part of the Second Slide scar, and probably occurred as a final, somewhat delayed stage of the Second Slide. In the deepest part of the Norway Basin, more than 750 km from the headwall, a thick (more than 6 m) fine-grained turbidite is related to the Second Storegga Slide. Several other turbidites are found in cores from within the slide scar and on the inner part of the abyssal plain. We believe that earthquake loading and decomposition of gas hydrates caused liquefaction of the sediments and thus triggered the slides.

1. Introduction

The Storegga ('great-edge') Slide is one of the largest translational underwater slides known. The 290 km wide headwall of the slide is centred at latitude 63° 30′ N, about 100 km from the coast of Møre and Trøndelag in Mid-Norway (figure 1). The slide itself extends from the edge of the continental shelf down to the abyssal floor, where it continues for a distance of probably more than 800 km from the headwall. The occurrence of small-scale sliding in this area was first suggested by Holtedahl (1971) and Sellevoll (1973), and the area was then mapped in greater detail by Bugge (1975) and Bugge *et al.* (1978). Later seismic profiling and sampling was carried out by IKU (Continental Shelf and Petroleum Technology Research Institute A/S, Norway) and the University of Bergen. In 1981, a joint cruise was undertaken by IKU and the Institute of Oceanographic Sciences, U.K., on board R.R.S. *Discovery* with long-range side-scan sonar (Gloria), medium-range side-scan sonar and air-gun seismic reflection profiler. This cruise investigated the Norwegian continental margin from 60° 30′ N to 72° 30′ N (figure 1), with a concentration of effort in the area of the Storegga Slide.

Widespread sliding has been known to exist on the west European Continental margin south of Norway since the first regional seismic reflection profiler survey of that margin in 1965 (Stride *et al.* 1969). Our survey of the Norwegian continental slope showed that, as well as the Storegga Slide, a number of other large and small slides occur on that margin. Most notable among these was a newly discovered large slide (the Traendjupet Slide) whose headwall indents the top of the continental slope at between 67° 20′ N and 67° 50′ N. These and other data have been described in a thesis by Bugge (1983).

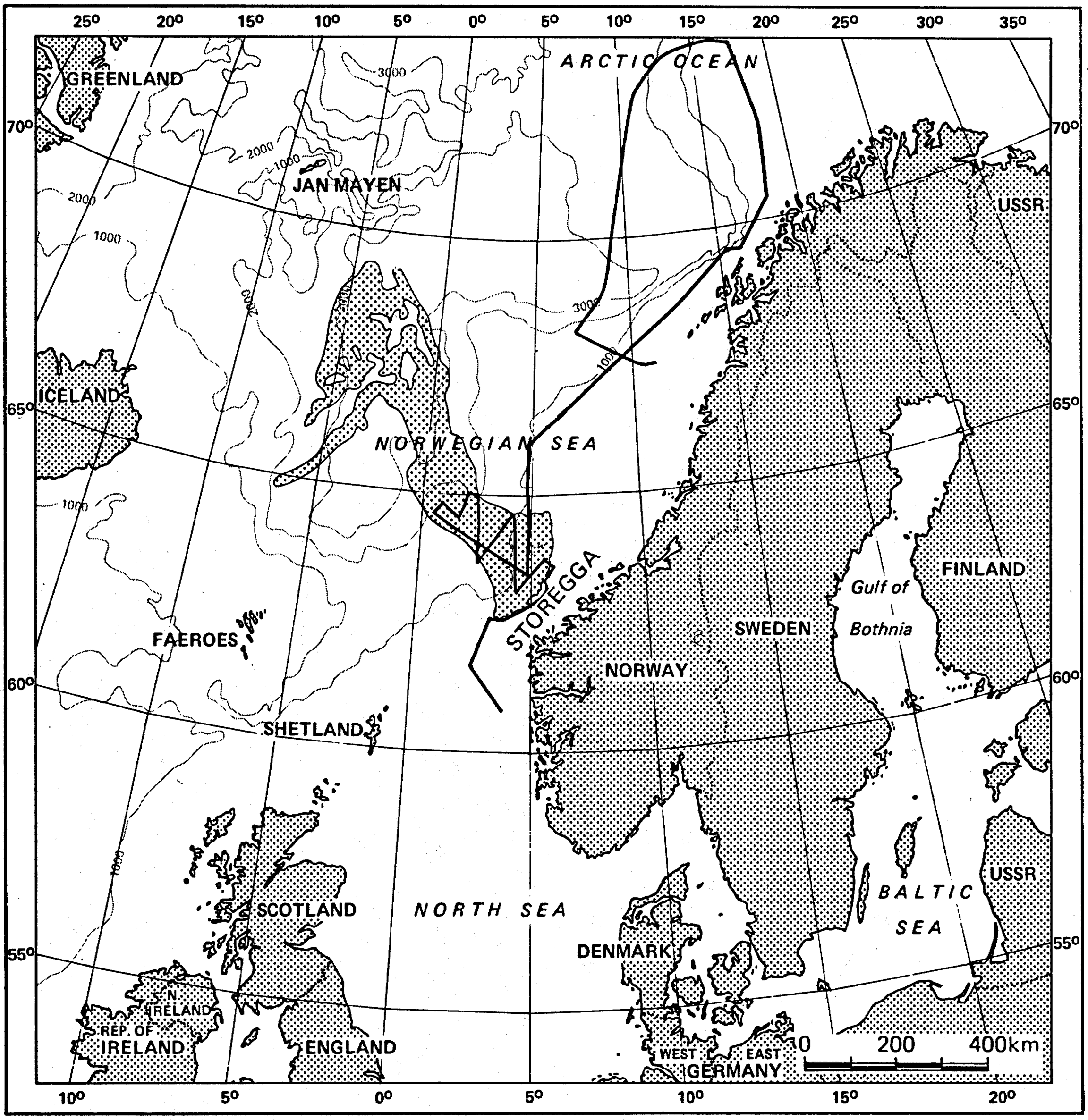

Figure 1. The location of the Storegga Slide. The slide (dotted pattern) whose headwall is 100 km off the coast of Norway, extends from a water depth of 150–400 m at the shelf edge for more than 750 km into the Norwegian Sea at depths of 3000–3500 m. The black line shows the ship's track of the long-range side-scan sonar (Gloria) survey.

2. Methods and data

A total of 2940 km of sparker (1.2 kJ and 4.7 kJ) and 1300 km of air-gun (80 in^3†) profiles were collected in the present study of the Storegga area (figure 2). These were supplemented by further profiles obtained by Lamont–Doherty Geological Observatory, U.S.A., and Bundesanstalt für Geowissenschaften und Rohstoffe (BGR), Federal Republic of Germany (figure 2).

† 1 in = 2.54×10^{-2} m.

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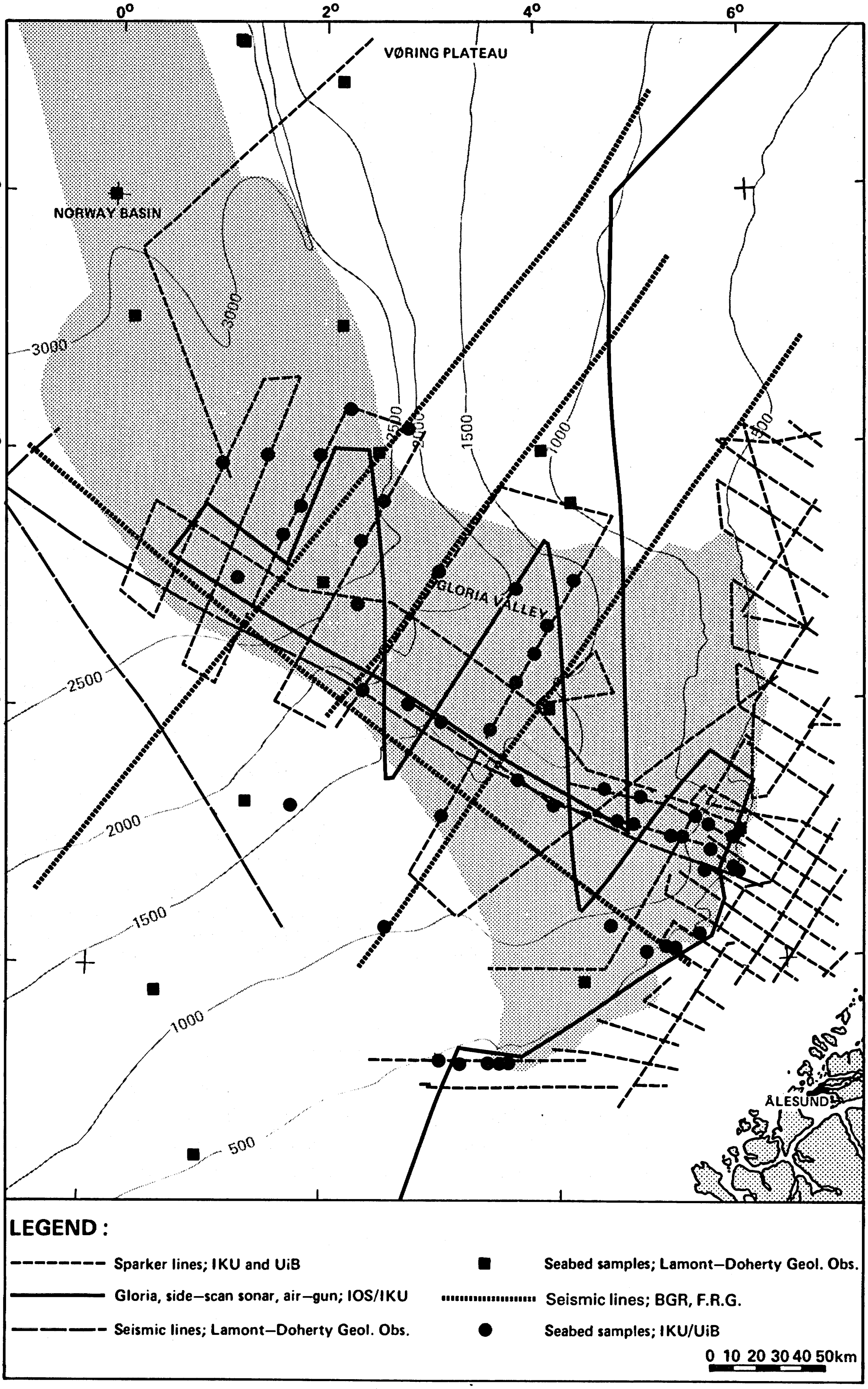

FIGURE 2. Location of seismic profiles, side-scan sonar coverage, and samples in the Storegga Slide area. Slide area is shaded. Depth contours are in metres.

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The surface morphology of the Storegga Slide was investigated by the use of both long-range and medium-range side-scan sonar. Sonograph coverage was obtained along 1300 km of track (figure 2). The long-range side-scan sonar (Gloria) has an operating frequency of 6.5 kHz and a towing depth of 30–40 m. It was used in this instance to a maximum range of 15 km to each side of the ship. The effective range, however, was unfortunately restricted to about 10–12 km because of refraction effects within the water column, particularly in the shallower water of the uppermost continental slope. The Gloria data formed a basis for the planning of later seismic profiling and sampling cruises. The hull-mounted medium-range side-scan sonar operated with a frequency of 31/37 kHz to a maximum range of 2.5 km on each side of the ship. The range obtained on the port-side record was limited because of a mechanical failure, whereas in water deeper than about 2300 m the equipment was more of use as a narrow beam echo sounder than as a side-scan sonar.

Thirtyseven gravity and piston core samples were collected in the Storegga area for this study (figure 2). A further thirty samples, taken for other purposes mainly by the University of Bergen, were also made use of, as well as lithological descriptions of fourteen samples obtained by Lamont–Doherty Geological Observatory. Apart from lithological and micro-palaeontological analyses undertaken by workers at the University of Bergen (Befring 1984; Eidvin 1984), geotechnical parameters such as undrained and remoulded shear strength, as well as water content, Atterberg limits and bulk unit mass were measured on seventeen cores.

Sea-floor photographs were taken at eight deep locations near the base of the slide and several locations on the headwall.

Ship positioning was based either on satellite navigation or Decca Main Chain supplemented by Loran-C.

3. Geological setting

Development of the passive-type Norwegian continental margin began with onlap of early Tertiary sediments over block-faulted Mesozoic sediments (Rønnevik *et al.* 1975). This was followed by progradation of a Miocene clastic wedge over an epeirogenically sinking floor, with contemporaneous uplift of the land (Jørgensen & Navrestad 1981). The tectonic development of the area is outlined in more detail by Bukovics & Ziegler (1985).

The Storegga Slide is situated within a broad embayment in the continental slope south of the Vøring Plateau. An isopach map of the Cainozoic sediments on the Mid-Norwegian continental margin (figure 3) indicates that their maximum thickness of 2500 m coincides with the area of the Storegga Slide (Sellevoll 1975). Shallow seismic reflection profiles show that subsidence was contemporaneous with deposition, and that the thickest Plio-Pleistocene sequence (probably exceeding 1500 m) is found near the shelf break. Quaternary deposits of mainly glacial origin near the shelf edge in the slide area range from less than 100 m to more than 300 m (Bugge 1980; Rokoengen 1980). On the western (deep-sea) side of the basin the Tertiary sediments abut against the buried Faeroe–Shetland Escarpment, representing the east-facing front of an Early Tertiary basaltic succession (Bøen *et al.* 1984).

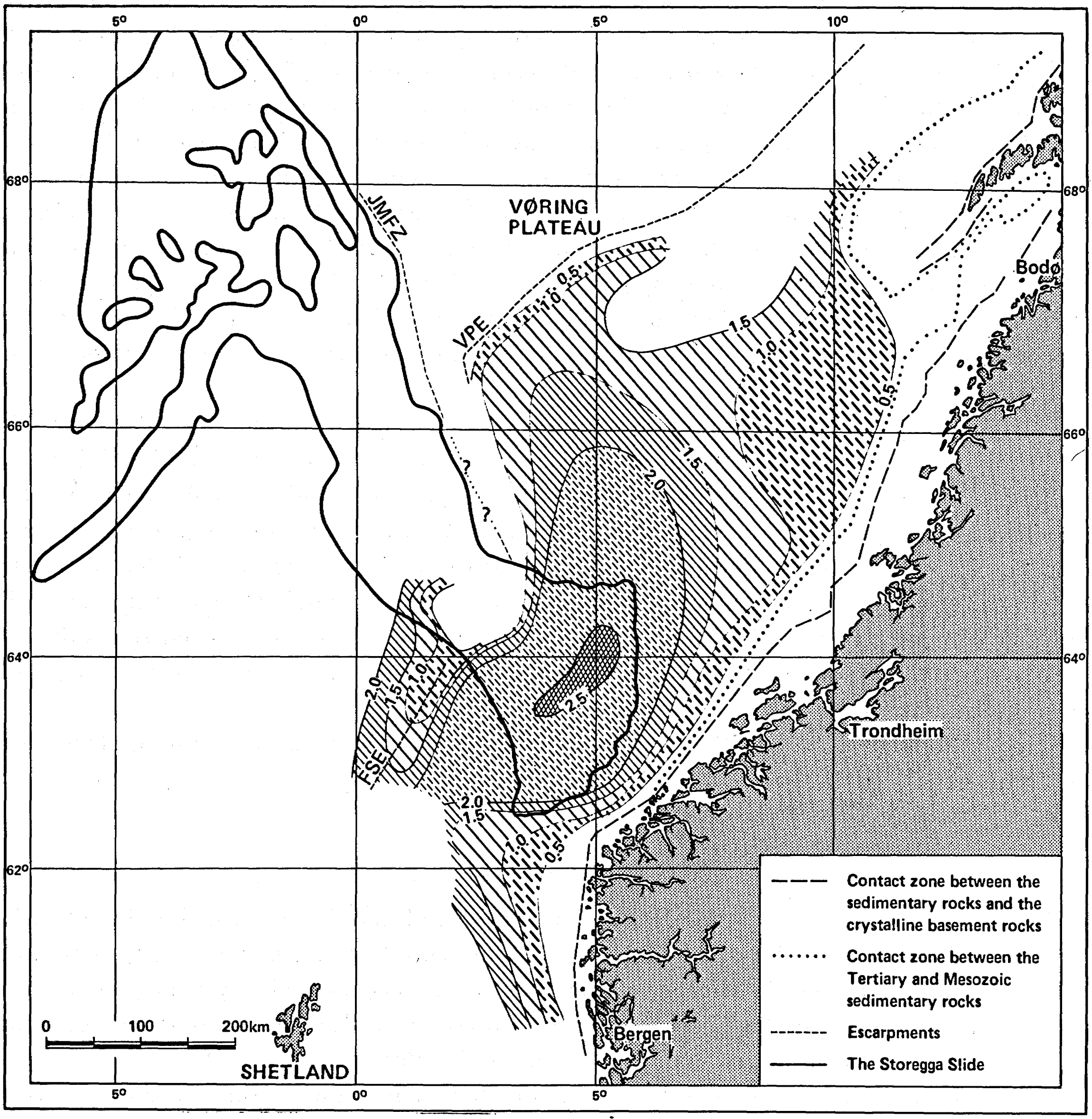

FIGURE 3. Isopach map of Cainozoic sediment thickness (in kilometres) on the Mid-Norwegian continental margin (modified from Sellevoll 1975). Abbreviations: FSE, Faeroe Shetland Escarpment; VPE, Vøring Plateau Escarpment; JMFZ, Jan Mayen Fracture Zone.

4. DESCRIPTION OF THE STOREGGA SLIDE

(a) *Boundaries of the slide*

The available data indicate that the Storegga Slide was, in fact, formed by three major slide events (figure 4). The initial description will relate to the slide as a whole, whereas in later sections we describe the result of the separate events in more detail.

The bathymetry and areal extent of the Storegga Slide are shown on figure 4. The headwall of the slide scar more or less follows the present-day shelf break. The break has retreated 6–8 km along a distance of 75 km in the central section, and 450 km^2 of the previously flat

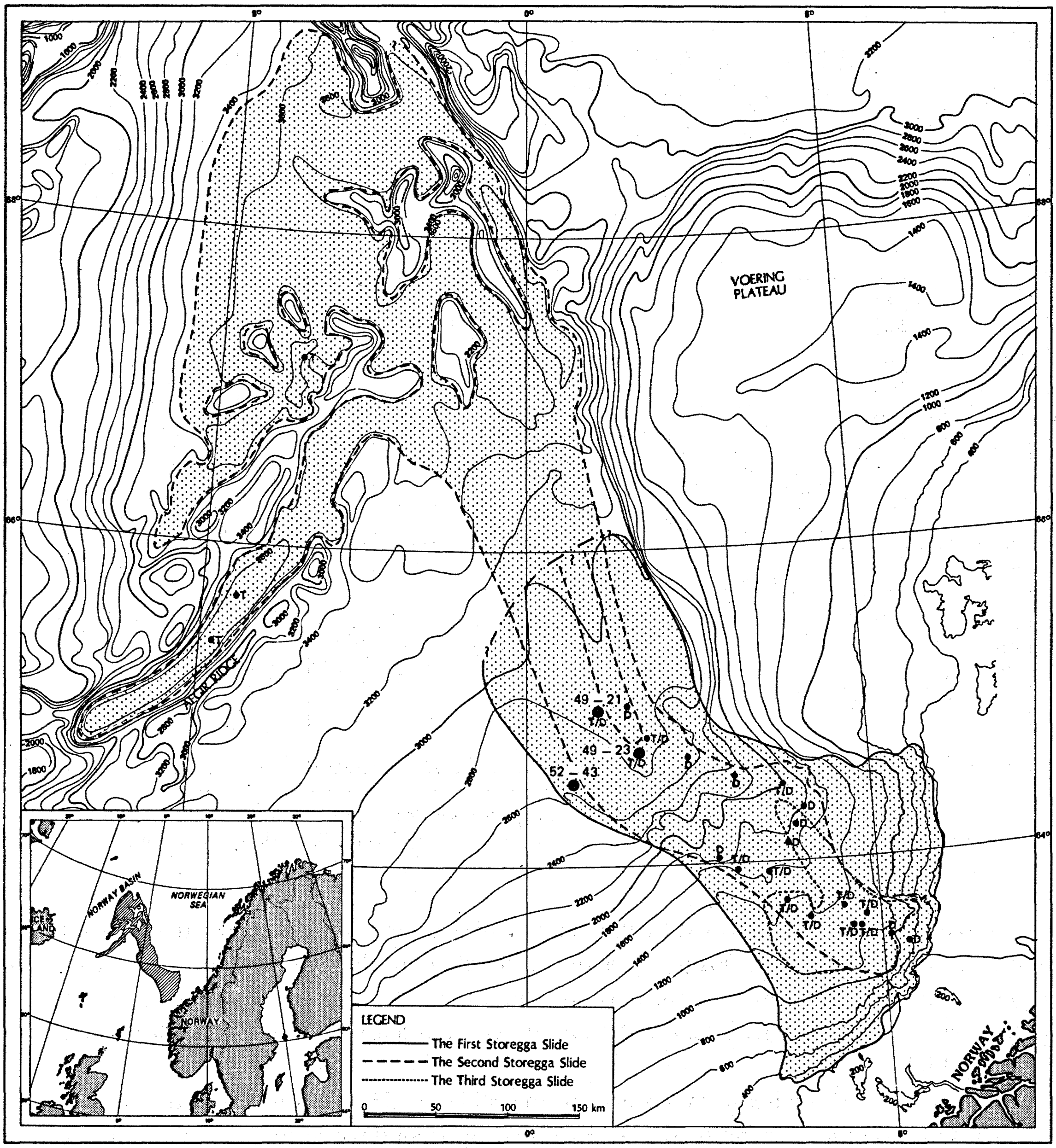

FIGURE 4. The Storegga Slide showing the areal extent of the three main slide events and the bathymetry. Depth contours are in metres. Sediment samples discussed in the text and samples containing turbidites (T) and debris flow deposits (D) are indicated. (From Bugge *et al.* 1987.)

continental shelf has been removed by the sliding. The total length of the headwall is 290 km, and the water depth over the top of the headwall varies from 150 to 400 m. The downslope extent of the slide will be further discussed below, but the slide travelled 300 km to the northwest down into the Norway Basin at a depth of 2800–3000 m, and then more than 500 km beyond that in the form of a giant turbidity current.

Examples of cross sections of the Storegga Slide are shown in figure 5. The southwestern boundary of the slide is well defined on all lines as either an erosional or depositional scarp.

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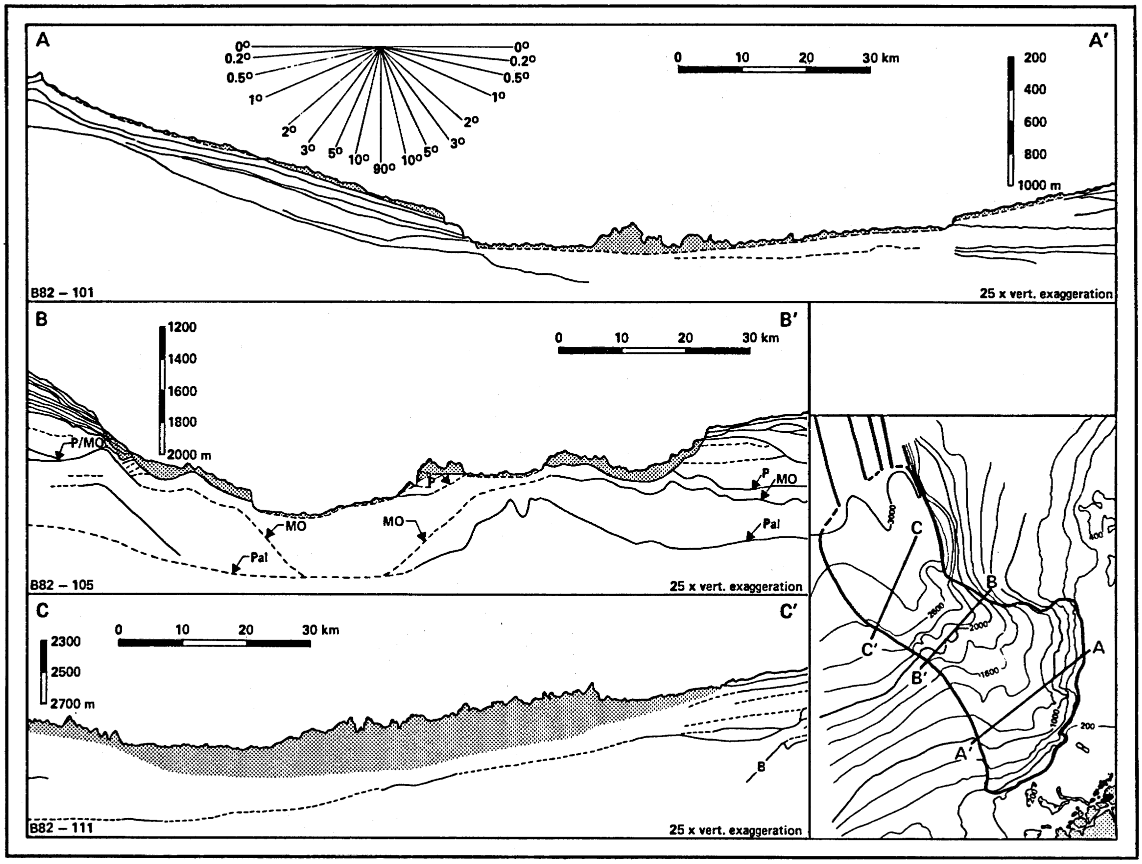

FIGURE 5. Cross sections of the slide scar based on sparker records. Abbreviations: P, Base of Pliocene; MO, Mid-Oligocene; Pal, Palaeocene–Eocene; B, Tertiary basalt. Slide deposits are shaded.

Down to about 900 m it is formed by the removal of sediments and is seen as an erosional scarp facing into the slide scar. From here down to 2300 m there is a southwestward facing depositional scarp 20 m or so high, beyond which there is a further erosional scarp 20–40 m high down to 2550 m. This is followed again down to at least 2700 m by a depositional scarp 30–35 m high.

Apart from the northeastern corner of the slide, which is well defined, much of the northeastern boundary is confused and disrupted by secondary sliding and slumping seen on seismic reflection profiles crossing the southern margin of the Vøring Plateau (for example, see figure 6).

The transition from the largely erosional slide scar to the main depositional zone of the Storegga Slide occurs at around 2600–2700 m water depth. In the central part of the depositional area there is a ridge, some 50 m high and 30–40 km wide, consisting of blocky slide material. This is probably the main depositional tongue extending into the abyssal plain of the Norway Basin. The largely erosional area of the slide scar covers 34000 km^2. A more detailed description of the areas and volumes related to the three major slide events is given below.

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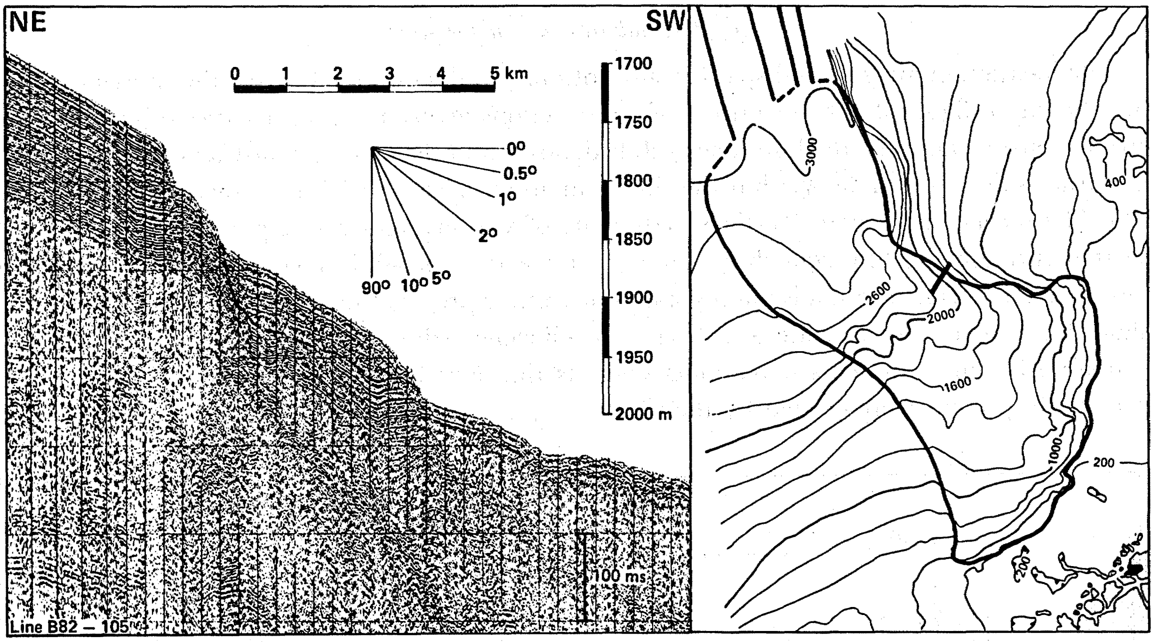

Figure 6. Secondary sliding along the northeastern boundary of the First Storegga Slide, seen on a sparker record.

(b) Gradients

The slope gradients are variable throughout the slide scar (figure 7). The headwall is, as expected, the steepest part of the slide, with an average gradient of 10–20° and local gradients of as much as 20–30°. However, in the central–upper part of the slide there are other scarps that are almost as steep as this, separated by floor sloping at 1–1.5°. Towards the margins of the central–upper zone the gradients are 1–3°, whereas further downslope the floor flattens to about 0.5° and then increases in slope again to about 1°. The average gradient above the 2700 m isobath is about 0.6°. Below 2700 m, in the deep ocean basin, the gradients are about 0.1°.

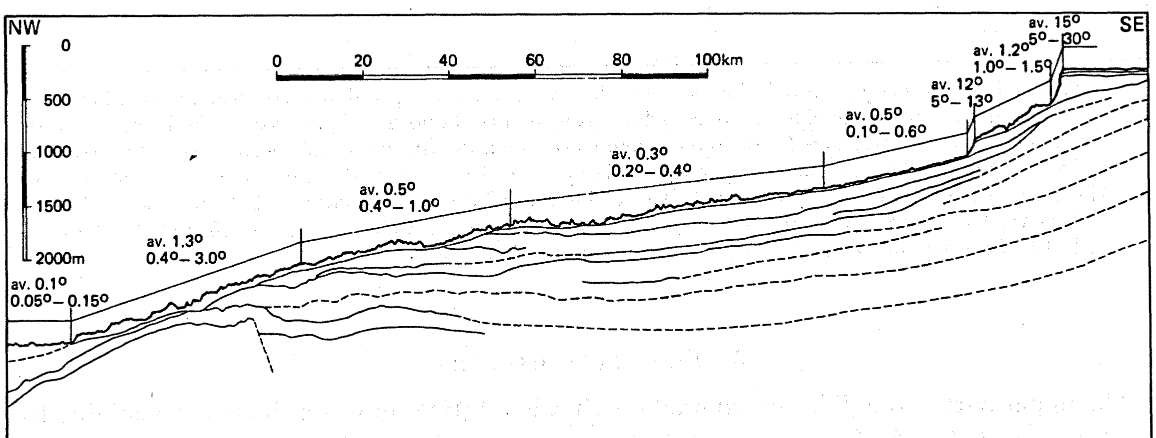

Figure 7. Slope gradients along the axis of the slide scar.

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(c) *Internal structure of the slide*

The location of air-gun and sparker sub-bottom profiles obtained across the Storegga Slide are shown on figure 2. The examples of cross sections given in figure 5 serve to illustrate the strong contrast between the hummocky slide deposits and the layered late-Cainozoic sediments on either side of the slide. Within the slide scar itself, because of the removal of much of the Plio-Pleistocene succession, Tertiary sediments of various ages are exposed. A longitudinal section through the Storegga slide scar together with a pre-slide reconstruction is shown in figure 8. The reconstruction is mainly based on seismic profiles from beyond the confines of the slide. Only in the lower slide area were pre-Pliocene sediments removed. The exposure of probable Eocene sediments hereabouts suggests that any Oligocene and Miocene sediments previously present were eroded by the slide.

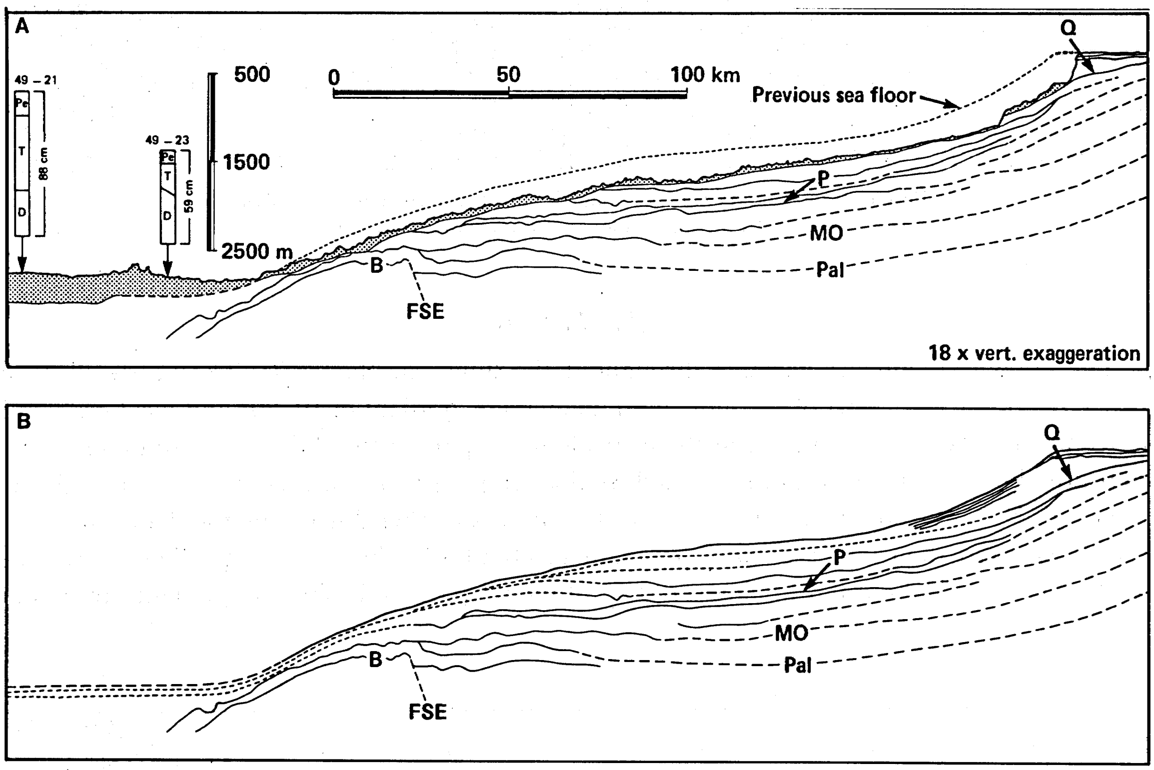

FIGURE 8. Longitudinal section through the Storegga Slide scar, (A) and a pre-slide reconstruction (B). Figure 8A illustrates that progressively older Tertiary sediments were mixed into the slide deposits with increasing water depth. The samples 49-21 and 49-23 contain debris flow deposits with lumps of Eocene–Oligocene sediments derived 70 km and 30 km upslope respectively. (Sample 49-21 is located 20 km to the northeast of this line.) Abbreviations: Q, Base of Pleistocene; P, Base of Pliocene; MO, Mid-Oligocene; Pal, Palaeocene–Eocene; B, Tertiary basalt; FSE, the buried Faeroe Shetland Escarpment. Slide deposits are shaded. In the cores: D, Debris flow deposit; T, Turbidite; Pe, Pelagic, post-slide deposit.

5. THE SLIDE HISTORY

The upper part of the slide (based on data above 900–1000 m water depth) was subdivided by Bugge *et al.* (1978) into a central 75 km wide strongly developed slide scar with steep headwall and several secondary scarps downslope, and somewhat broader flanking areas with smaller-scale headwall scarps and smaller-scale surface roughness. Beyond the confines of these areas there is smooth undisturbed sea floor. Later morphological data allow this broad subdivision to be extended downslope throughout the slide scar, whereas an evaluation of all the data, relating to surface relief, sub-bottom profiles and samples, suggests a three-stage history for the slide as a whole.

(a) *The First Storegga Slide*

The first and major slide event (the First Storegga Slide) comprised almost the entire area of the present slide scar with its 290 km long headwall (figure 4). Because it is flanked by several hundred metres of well-layered relatively soft, mainly clayey Plio-Pleistocene sediments, it must be presumed that it removed such sediments across the whole width of the slide. These sediments are now found downslope in the form of acoustically transparent or semitransparent deposits with small-scale surface roughness (figure 9).

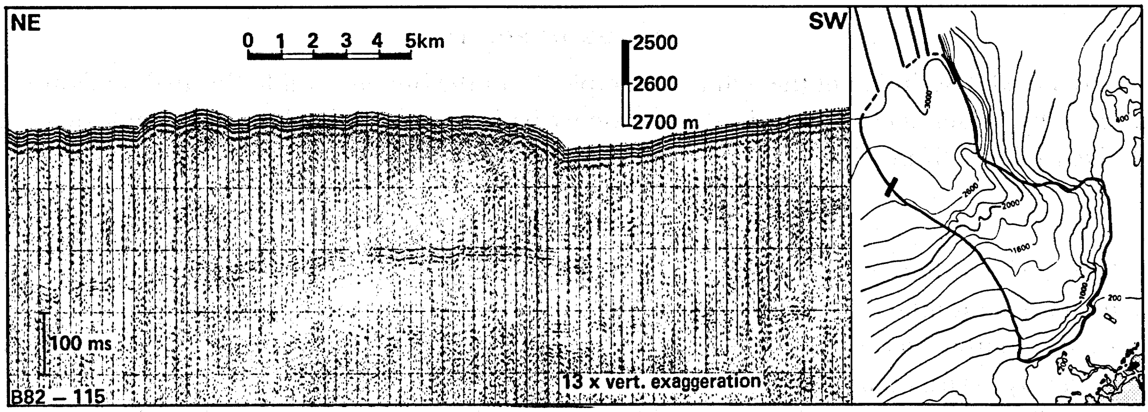

FIGURE 9. Sparker record of the acoustically semitransparent and probably homogeneous deposits of the First Storegga Slide. This section of the southwestern boundary of the slide represents a depositional scarp, 80–100 m high. Note the small-scale surface roughness on the slide.

(b) *The Second Storegga Slide*

The Second Storegga Slide (figure 4) occurred after the First Slide had removed the uppermost, layered sediments. It cut deeper into the more consolidated sediments in the central 50–80 km section of the First Slide, removing up to 200 m of sediment above the 1400 m depth contour and 100 m or so of sediment below that level. The slide probably developed retrogressively such that the headwall retreated 6–8 km onto the continental shelf, leaving the steep edge called Storegga. The northeastern boundary down to 1400 m is characterized by a marked scarp about 200 m high near the headwall and decreasing to about 70 m at 1400 m water depth. Beyond this level, seismic profiles show that for some distance the scarp is buried by further slide accumulation (probably of the Third Slide) down to the 1700 m contour. From here the slide margin follows the northern slope of a broad northwest-trending valley, here named the Gloria Valley (located in figure 2).

Except for its extreme upper part, the southwestern margin of the Second Slide is ill-defined down to 1500 m. From the evidence provided by bathymetry in the upper part and from seismic profiles this margin is considered to have been rather straight initially, with any resulting scarp later removed by the Third Slide. Further downslope the margin is again marked by an erosional scarp, which remains within the confines of the First Slide all the way down, except for an area at around 2000 m. Here the Second Slide deposited two huge and probably largely unbroken sediment slabs or sheets (figure 10) transported from a location upslope in the slide scar (discussed below). One of these has partly slid beyond the margin of the First Slide. Below this is the depositional area of the Second Slide also to be discussed below.

(c) *The Third Storegga Slide*

The Third (and last) Storegga Slide (figure 4) could either have occurred almost synchronously with the Second Slide or perhaps some time after it. Its chief headwall is at 1000 m, well below that of the Second Slide. The slide seems generally to have been confined to the shallower part of the Second Slide scar, except for the southwesternmost portion where it also affected the First Slide. Here it locally headed in a more northerly direction.

6. Slide deposits

A detailed description of the sediment samples from the Storegga Slide (located on figure 2) is given by Jansen *et al.* (1987). In this section we will summarize the data on the slide deposits derived mainly from seismic profiles.

(a) *Deposits of the First Slide*

Because later slide events incorporated deposits of the First Slide, the main areas where these deposits remain intact form the flanks of the later slides to the southwest and northeast.

In the southwestern area, such slide deposits occur below 1000 m water depth and are acoustically transparent. In contrast, in the northeast, seismic profiles show accumulations below 850 m water depth that are more blocky (e.g. line A–A′ on figure 5). These deposits may be derived from overconsolidated glacial till and relatively coarse-grained glaciomarine sediments that occur further upslope hereabouts (Bugge 1980). Further north again, however, finer-grained and laminated sediments were probably involved in the slide.

Below 2700 m the deposits of the First Slide may be distinguished from those of the Second Slide by differences in surface relief and seismic signature. The deposits of the First Slide have a relatively even surface and are acoustically semitransparent (figure 9), whereas those of the Second Slide consist of large and small sediment blocks resulting in a hummocky surface, and are not as acoustically transparent. The deposits apparently do not have a clear-cut lower boundary. This is probably because the underlying sediments were disrupted and partly intermixed when they were overrun by the slide. Thus at present we cannot precisely define the thickness of the slide deposits from the seismic data. However, an estimate of the volume of sediments removed from the slide scar (discussed below) in relation to depositional area suggests depositional thicknesses of the order of 130–200 m for the First Slide.

Because of the thickness of overlying glaciomarine and Holocene sediments or because they are covered by deposits of later slide events, samples of the deposits of the First Slide have not been obtained as yet. However, the semitransparent acoustic properties suggest that the original sediment was fine-grained and normally consolidated.

(*b*) *Deposits of the Second Slide*

Micropalaeontological investigations of the debris flow and turbidite deposits resulting from the Second Slide have shown that they contain a mixture of sediments that originated on the upper continental slope, at intermediate depths, and in the deep sea (Jansen *et al.* 1987). Clasts of undisturbed Eocene and Oligocene siliceous sediments are common in the debris flow deposits of the Second Slide. This shows the relatively deep stratigraphic position of the glide plane in the lower part of the slide scar.

The First Slide removed the topmost layered, relatively unconsolidated younger sediments. Because post-slide sediment accumulation seems to have been moderate before the Second Slide occurred, the Second Slide had to cut into firmer, more consolidated sediments. This is reflected in the blocky, uneven slide deposits, as shown by both surface morphology and samples. The terms 'olistolith' for the blocky material and 'olistostrome' for the slide deposit (as used, for instance, by Moore *et al.* (1976) for the large submarine Bassein Slide) are probably applicable here, except that some of the blocks are so huge that the term olistolith may not be quite apt.

Two very large slabs, or sediment sheets, were observed on a seismic profile (figure 10) resting at a water depth of 2000–2500 m. These are 150–200 m thick, and appear on sonographs to be 10 km wide and perhaps 30–50 km long. Although the sonographs suggest some surface fracturing, the slabs are probably largely intact. Because of their size and in particular their great thickness relative to their present location, their most likely original location is on the upper part of the slide scar of the Second Slide at about 1000 m water depth, where the slide scar is sufficiently deep to have accommodated them. Velocity pull-up on the seismic profile suggests a velocity of sound within the blocks of slightly less than 2.2 km s^{-1}, which indicates relatively consolidated sediment. Similar estimates made on three profiles crossing the scarp at 1000 m depth within the slide scar vary from 2.0 km s^{-1} to slightly more than 2.1 km s^{-1}. Given the uncertainties inherent in such estimates, these velocities support the likelihood that the two large slabs originated from the vicinity of the scarp at 1000 m water depth. This implies a transported distance of 200 km down an average slope of 0.3°.

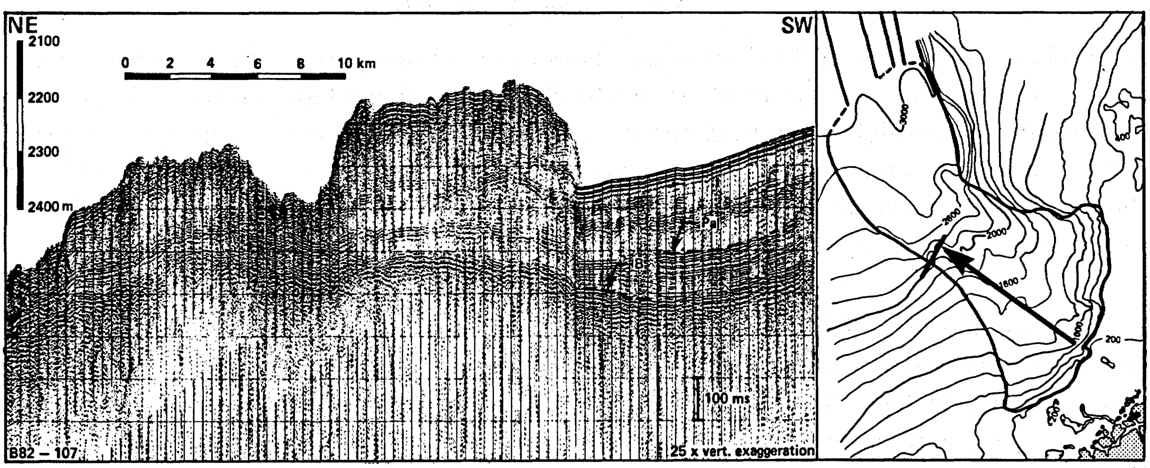

FIGURE 10. Sparker record of two sediment slabs that slid about 200 km down an average slope of 0.3° during the event of the Second Slide. The possible pathway is indicated by the arrow in the location map on the right. The slabs are 150–200 m thick and about 10 × 30 km wide. Abbreviations: Pal, Palaeocene–lower Eocene; B, Tertiary basalt.

The smaller sediment blocks, some hundred metres or so in size, produce a very irregular sea-floor topography, with local relief of up to 100 m or more. Apart from disrupting the seismic profiles, this causes problems for sampling in that samples could originate from the surface of blocks or the depressions between blocks. In particular, the post-slide deposits will vary in thickness and character because of the influence during sedimentation of the highly variable local topography.

Two depositional tongues that head north-northwest from the base of the slide scar have, for the first 150 km at least, a very hummocky topography typical of the blocky deposits of the Second Slide. Because of this, and because they lie above the supposed deposits of the First Slide, the tongues are taken to be blocky deposits of the Second Slide.

Most of the Second Slide deposits on the uppermost half of the slide scar consist of glacial or glaciomarine Quaternary sediments. Some are heavily overconsolidated, with undrained shear strengths of more than 100 kPa. Amino acid analyses on a sample of slide-transported glaciomarine sediment indicate an age of 100000–200000 years (Jansen *et al.* 1987). The seismic profiles suggest that Pliocene sediments were also involved in the sliding hereabouts. However, there are difficulties in distinguishing between these and the Pleistocene sediments. The section reproduced in figure 8 suggests that, with increasing water depth, progressively older Tertiary sediments were mixed into the slide deposits until, at depths between 2400 and 2700 m, only late Palaeocene–Oligocene sediments and some slide deposits remain above the basaltic basement. This is supported by the identification of Eocene and Oligocene slide-transported sediments in two cores (49–21 and 49–23, see figure 8) near the base of the slide. These consisted of lumpy Eocene–Oligocene silt–claystone directly overlain by graded sandy turbidites and a thin (10 cm) superficial layer of Holocene pelagic sediments. The nearest exposures of Eocene and Oligocene sediments are about 70 km and 30 km southeast of cores 49–21 and 49–23 respectively. A further example of the effect of sliding is given by earlier palaeomagnetic studies of a core now known to be within the slide. The overconsolidated glaciomarine clay of this core showed a change in magnetic declination of 180° (Løvlie & Holtedahl 1980). As described below, we also assign a massive turbidite, found in the Norway Basin some 750 km from the headwall, to the Second Slide.

(*c*) *Deposits of the Third Slide*

This last and smallest of the three major slides recorded in the Storegga area removed only *in situ* sediments in the vicinity of its headwall. Further downslope, however, it probably redistributed earlier slide deposits, giving rise to blocky accumulations extending downslope for 100 km or so in two main lobes. These partly buried the flanking scarp of the Second Slide to the northeast, whereas the flanking scarps on the southwest was partly removed by this last major slide.

(*d*) *Turbidite deposits*

Turbidites are identified in many of the core samples taken from areas of both rough and smooth accumulation. They all occur below a Holocene layer, and immediately overlie or are found within slide deposits. One particularly well-graded turbidite is located on a topographic high in a very uneven area immediately above a debris flow deposit containing lumps of Eocene–Oligocene sediment (sample 49–21, see figure 8). An unrelated, post-slide turbidity current is unlikely to have followed the complex route to its present location, but would have followed the more open and evenly sloping valley that lies to the north of the sample position.

It is thus concluded that this turbidite, and probably the others as well, occurred as a consequence of the sliding (Bugge *et al.* 1987; Jansen *et al.* 1987).

The most distal deposits, at about 750 km from the headwall, consist of a sheet of fossil-free clay probably covering the entire deep basin of the Norwegian Sea at depths below the 3500 m contour. Cores up to 6 m long were obtained from this deposit without reaching its base, and 3.5 kHz records indicate that its thickness may be as much as 20–30 m. This has been interpreted as a massive distal turbidite related (as a result of carbon datings) to the Second Slide (Eidvin 1984; Jansen *et al.* 1987), perhaps comparable to the 'homogenites' or 'unifites' described from the Mediterranean (see, for example, Stanley 1981). The sediments within this turbidite may have largely been derived from several metres of unconsolidated glaciomarine sediments deposited within the slide scar subsequent to the First Slide, as well as from the First Slide deposits themselves.

(*e*) *Slide dimensions*

The estimated areas, thickness and volumes of the three main slides are shown in table 1. The volume estimates were derived by the use of a palaeobathymetric map (figure 11). This was constructed by extrapolation of depth contours from the undisturbed area outside the slide area

TABLE 1.

	first slide	second slide	third slide	total
Run-out distance/km	350–380	800–850	100–130	850
area of slide scar/km^2	34000	19200	6000	34000
total slide-influenced area/km^2	52000	88000	6000	112500
maximum thickness/m	280	330 (second and third)		430
average thickness/m	114	88 (second and third)		160
volume/km^3	3880	1700 (second and third)		5580
volume of deposits left in slide scar today/km^3	400	950 (second and third)		1350
volume of deposits below 2700 m/km^3	3480	750 (second and third)		4230

and by using the seismic profiles to obtain the best palaeocontours from both a morphological and geological point of view. Because the Third Slide occurred largely within the Second Slide and partly involved the same sediments there is uncertainty in attempting to distinguish between the volumes of the two slides. Their volumes were therefore calculated together.

The total volume of sediments removed from the slide scar above the 2700 m isobath was calculated by measuring the volume between the palaeo and present sea floors. This was found to be 4230 km^3. The total volume of sediments involved also includes those slide deposits still present within the slide scar today. The overall volume of the latter was estimated at 1350 km^3, giving a total slide volume of 5580 km^3. The thickness of the First Slide and the combined thicknesses of the Second and Third slides were then estimated from the seismic profiles. The volume of the last two slides thus calculated is about, or somewhat greater than, 1700 km^3, and that of the First Slide, being the difference between the total volume of 5580 km^3 and 1700 m^3, is thus about 3880 km^3. The Second Slide also redistributed a considerable portion of the First Slide deposits in addition to the above calculated volume of 1700 km^3.

From these reconstructions we conclude that in the central area the First Slide removed 100 m or less of sediment in the uppermost portion, about 200 m from between the 1400 m and 2400 m isobaths, and slightly more than 100 m below the 2400 m isobath. In the areas flanking the central area less than 50 m of sediment was removed. Most of the sediments were clayey

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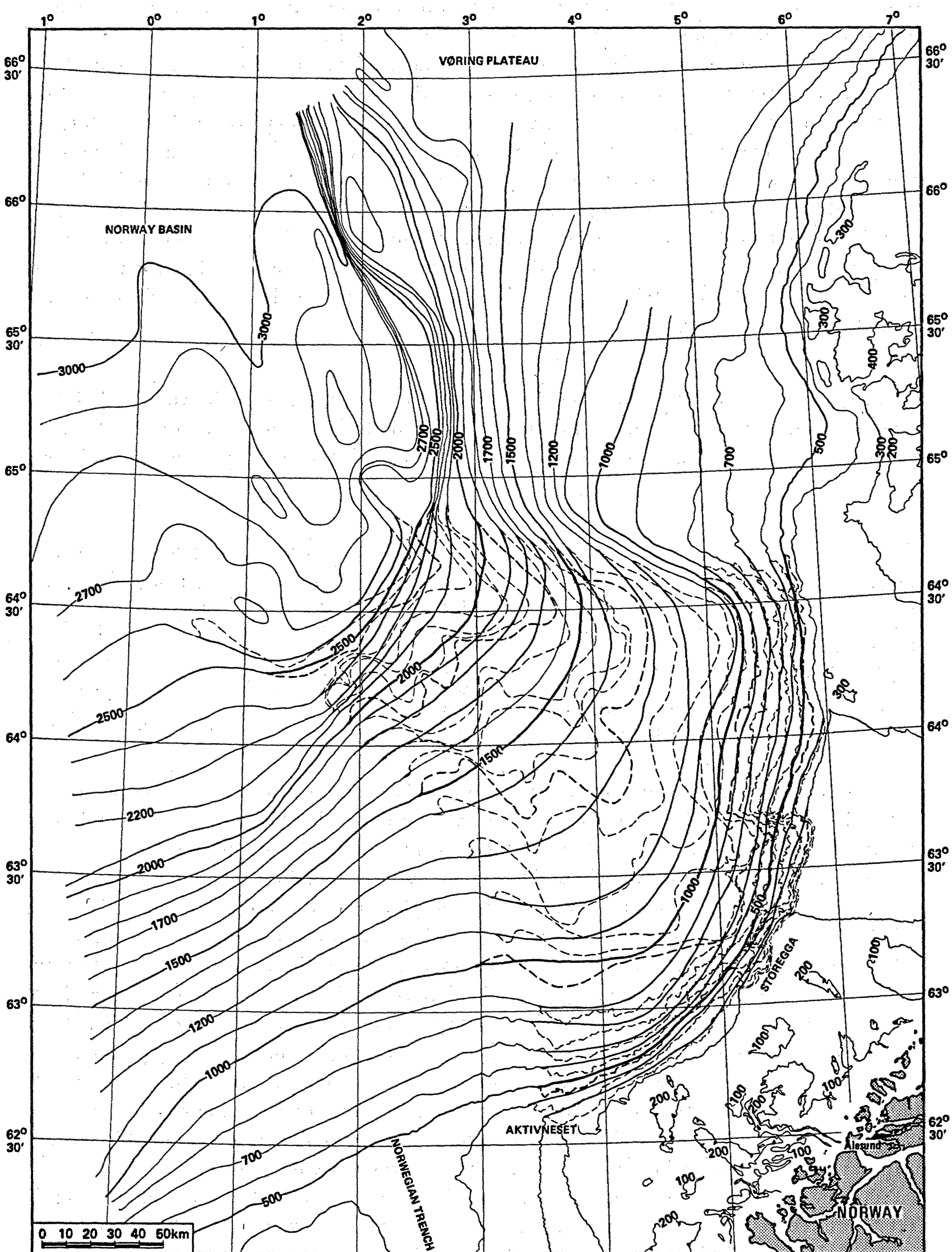

FIGURE 11. Reconstructed palaeobathymetric map of the Storegga area as it was before the sliding. The present bathymetry of the slide scar is shown by broken lines.

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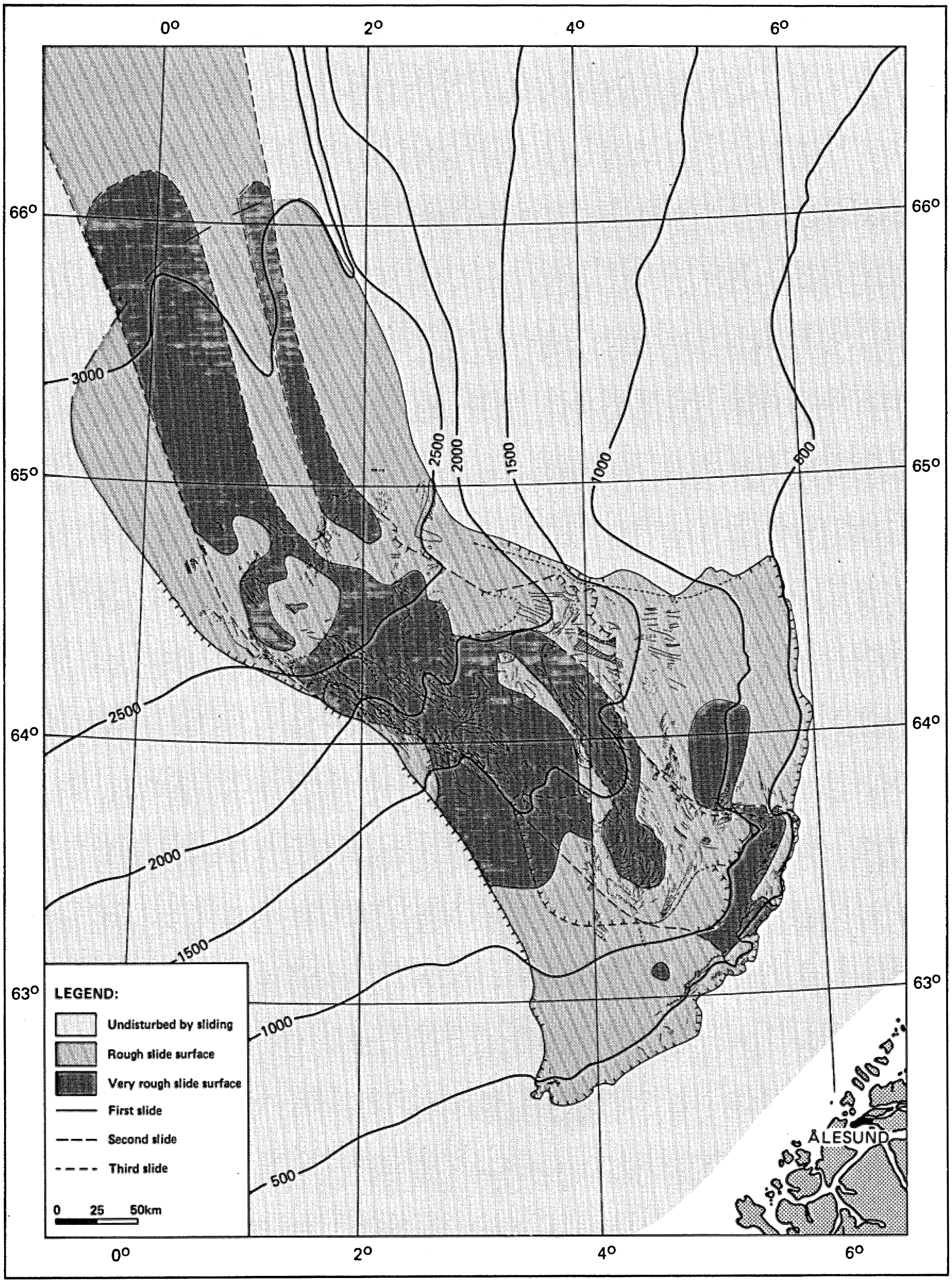

FIGURE 12. Salient features of the Storegga Slide based on the long-range side-scan sonar Gloria and partly on intermediate range sonographs. Classification of seabed roughness is based on seismic data as well. Because side-scan sonar coverage is only partial, many more linear elements exist than those shown. Ticks indicate downslope sides of scarps. The broken line near the northern boundary of the slide represents the probable original edge of the slide, above which there has been secondary sliding.

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and normally consolidated, and were ultimately deposited in the deep ocean basin below 2700 m. The depositional area covered roughly 25000 km^2, and the average thickness of the slide deposits was about 150 m. Any remnants of these within the central slide scar were removed by the Second Slide, whereas about 400 km^3 of deposits now remain in the flanking areas.

The Second and Third slides together comprised at least 1700 km^3 of mainly more consolidated sediments. The thickness of these varied from 250–300 m in the upper portion of the slides, to 130–150 m and about 50 m downslope in the northerly and southerly portions, respectively. About 950 km^3 of slide sediments were deposited within the slide scar to a thickness varying from less than 20 m to more than 100 m. The remaining 750 km^3 are largely found as blocky material in the central section of the depositional area below the 2700 m isobath. Two depositional tongues of blocky Second Slide material, probably more than 200 km long, extend into the Norway Basin. Beyond here, less compacted sediments of the Second Slide were transformed into the large turbidity current, described above, which dispersed them as far as 750 km out into the Norwegian Sea.

Finally, the seismic profiles in some places bear clear evidence of disturbance in the sediments up to some hundred metres below those deposits that were actually transported. This was presumably caused by the sliding. If these sediments were to be included in the volume of sediments influenced by sliding, the total volume would be increased far above the present estimate of 5580 km^3.

7. Morphology of the slide surface

(*a*) *Side-scan sonar observations*

The use of long-range (up to 15 km on each side of the ship) and medium-range (up to 2.5 km on each side of the ship) side-scan sonar over the Storegga Slide has yielded much data concerning the surface of the slide. This has not only proved useful in the present study, but will benefit any later more detailed studies with photography, deep-towed high resolution side-scan sonar or submersibles, for instance. Figure 12, plate 1, represents salient features from the long-range (Gloria) data, as well as some generalized trends from the medium-range sonographs. It is not possible on this scale to indicate the many detailed features from the latter data.

It is important to note that the two side-scan sonar systems, although viewing linear trends and variations in surface texture at different scales and resolution, agreed well with one another in the results obtained. This increases confidence in interpretation of the sonographs. As explained above, Gloria gave the better results on the lower continental slope and the medium-range side-scan sonar on the upper slope. On the sonographs presented here (located in figure 13) weak backscatter of sound and shadowed areas appear dark toned on long-range (Gloria) sonographs, whereas the converse applies to the medium-range sonographs (weak backscatter and shadows are light toned).

On the continental shelf edge above the headwall of the Second Slide iceberg plough marks were well observed (Lien 1983*a*, *b*). Such features were not noted on the Second Slide itself, which was perhaps not surprising considering the extreme roughness of the floor. However, the surface of the First Slide at just beyond the northern margin of the Second Slide showed slope-parallel linear features down to a depth of about 550 m, which we interpret as probable iceberg

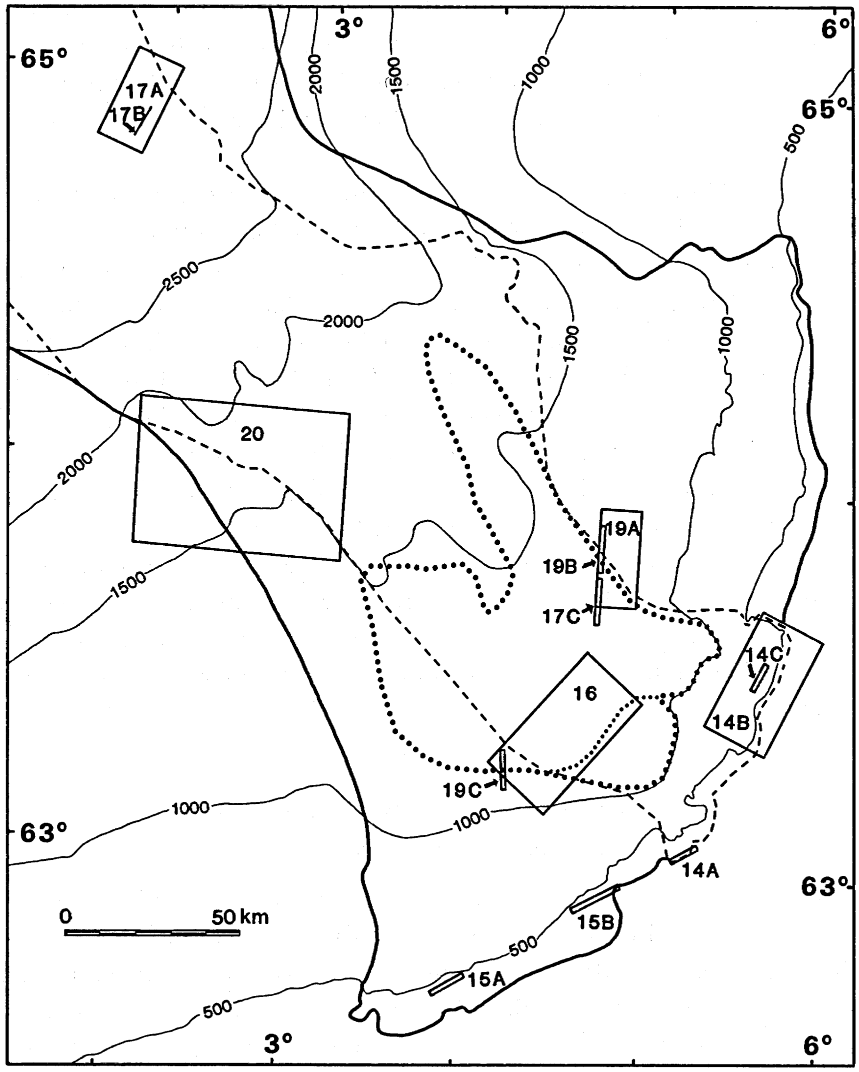

FIGURE 13. Location diagram for figures 14–20. The boundaries of the three Storegga slides are shown. Thick continuous line, First Slide; dashed line, Second Slide; dotted line, Third Slide. Depth contours are in metres.

plough marks. These were earlier interpreted as small end moraines (Holtedahl & Sellevoll 1972).

The steep headwall of the Second Slide was well seen on the sonographs (see figure 14A, B). Apart from the main scarp itself, there are also usually several secondary scarps or steps immediately below and largely parallel to it. These are up to 20–35 m high with a separation of 100 m or so, and are interpreted as scarp-parallel rotated blocks or ridges of *in situ* sediments. Such features were called 'shear ridges' by Janbu (1980).

This interpretation is supported by the presence of ponded sediments below some of the scarps and by the truncation of small-scale linear features (about 50 m separation) by the scarp below. Elsewhere, this uppermost part of the Second Slide is characterized in profile by a blocky (20–30 m) relief, within which sinuous along-slope ruckling or slump folding is dominant (figure 14B), but also with some downslope-trending lineations evident (figure 14C). Probable sediment infill occurs in lows within the blocky topography.

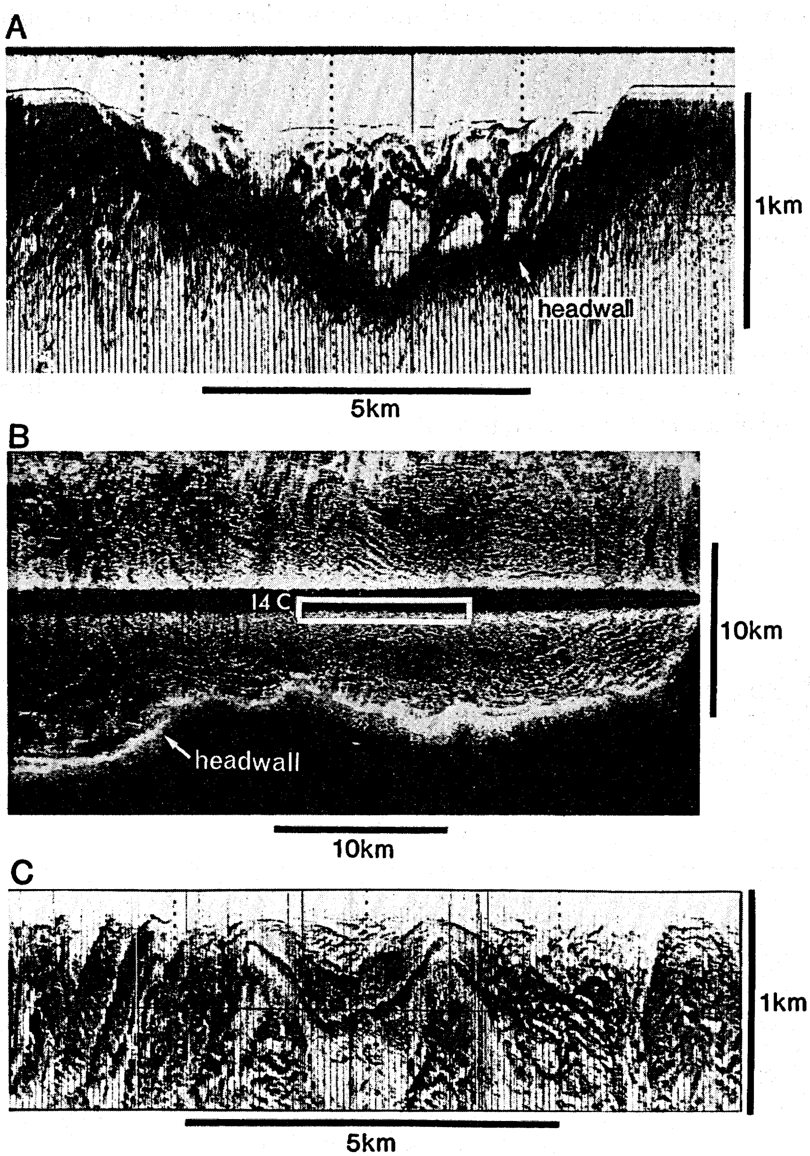

FIGURE 14. (A) Medium-range sonograph (located in figure 13) of section of the steep headwall of the Second Storegga Slide. Downslope is towards the top of the page. Note the rough floor downslope of the headwall interpreted as largely composed of rotated slump blocks. Note that in this and subsequent medium range sonographs strong backscatter of sound is represented by darker tones, and weak backscatter and shadow zones by lighter tones. Note also that this and subsequent medium-range sonographs do not represent true-plan views. Allowance for this should be made in estimating shape and orientation of features. (B) Long-range (Gloria) dual-channel sonograph (located in figure 13) of a section of the steep headwall of the Second Storegga Slide, and the surface of the slide for 15 km or so below the headwall scarp. Downslope is towards the top of the page. Note that on this uppermost part of the slide its surface relief is dominated by sinuous slope-parallel ruckling or slumping with a 0.5 km or so crest separation (see figure 16). Note that, in contrast to the medium-range sonographs, in this and subsequent long-range sonographs strong backscatter of sound is represented by lighter tones, and weak backscatter and shadow zones by darker tones. Also note that the Gloria sonographs represent almost true-plan views. (C) Medium-range sonograph of the disturbed surface on the upper part of the Second Storegga Slide (located within the boxed area on figure 14B). Downslope is towards the top of the page. Note that although sinuous along-slope trends predominate in the central part of the figure, towards either side of the central zone downslope lineations are also clearly visible.

Excepting the probable iceberg plough marks mentioned above, the surface of the upper part of the First Slide is normally characterized by small-scale blocky and generally along-slope trends with a relief of 10 m or so. These seem to be best developed on a traverse along the uppermost, southeastern, portion of the slide at about 500 m water depth. Here the surface exhibits a pervasive sinuous pattern of trends sub-parallel to the slope, with 10–15 m relief, 40–60 m separation and a crest length of up to 3 km or so (figure 15A, B). This we interpret as a ruckled surface, although in the absence of high-resolution profiles it is not possible to attribute with confidence either a tensional or compressional origin to the features. Further downslope from here, at about 1500 m water depth, longitudinal (downslope) trends, both large and small, become predominant. There are also indications of longitudinal shears separating trains of transverse cracks somewhat similar to those previously described on a much smaller slide by Prior *et al.* (1982, figure 3).

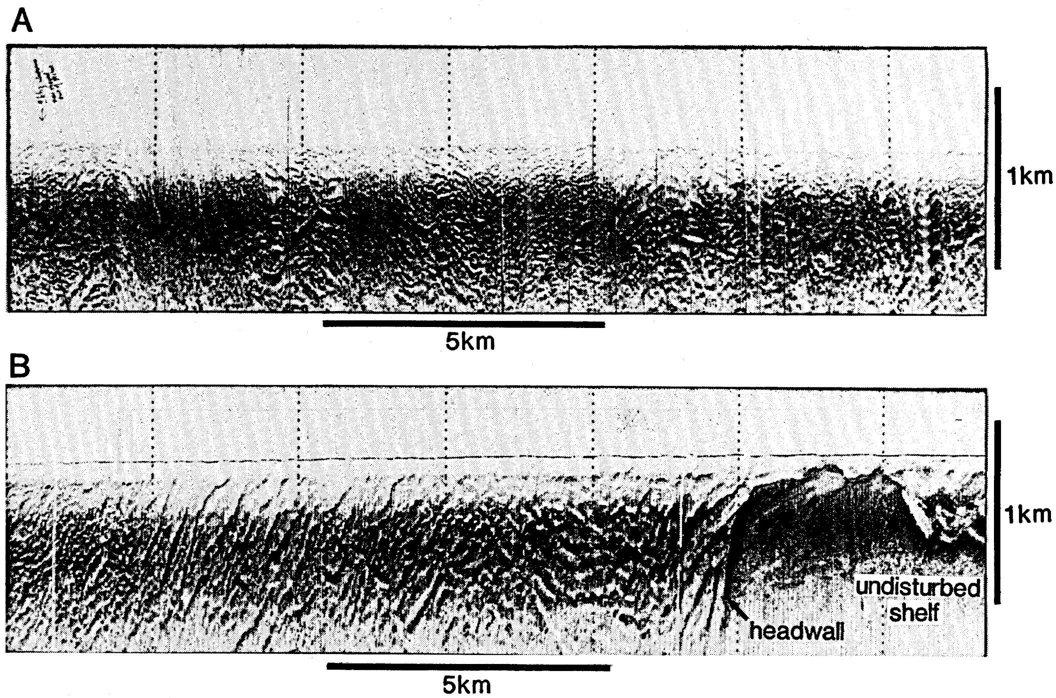

FIGURE 15. Medium-range sonographs (located in figure 13) of the uppermost part of the First Storegga Slide. Downslope is towards the top of the page. Note the pervasive sinuous pattern of largely along-slope (transverse) lineations. These have a separation of approximately 50 m and a relief of up to 15 m.

The headwall region of a major secondary scarp associated with the Third Slide is shown in figure 16 (and depicted by the line of small dots in figure 13). This appears to be comparable to the headwall region of the Second Slide in that a series of relatively large scarp-parallel features (possible rucklings with a separation of 1–2 km) are seen on Gloria sonographs, and short and curving smaller, low-relief (100 m separation and about 5 m high) scarp-parallel features on the medium-range sonographs. Likewise, further downslope in the depositional area of the Third Slide downslope trends predominate. Here there is apparently a longitudinal shear zone, with both small-scale trends and larger ones of about 0.5 km separation and up to 50 m high seen on medium-range sonographs, and large-scale longitudinal strips of rougher and smoother floor 5 km or so wide seen on Gloria sonographs.

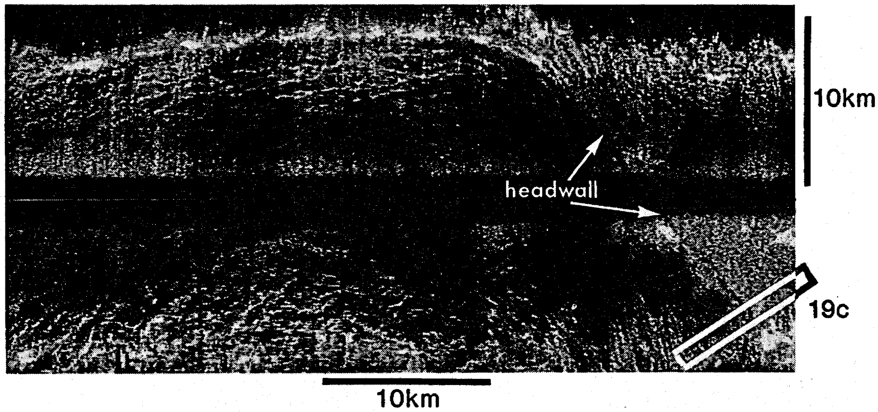

FIGURE 16. Long-range (dual-channel) sonograph (located in figure 13) showing part of the headwall scarp of the Third (last) Storegga Slide (right-hand side of figure), and a major secondary scarp associated with the Third Slide (centre and left top of sonograph and located as a line of small dots in figure 13). A series of scarp-parallel lineations below the scarp are comparable to those below the headwall scarp of the Second Slide (figure 14B). These contrast with lineations on the surface of the First Slide (top-right corner). Note also the generally lower level of sound backscatter evident from the surface of the Third as compared to the First Slide (most evident towards the bottom right corner). Downslope is towards the bottom of the page.

The essentially blocky nature of the deposits of the Second and Third Slides is confirmed by both the side-scan sonar and profiler data (see figure 17A–C). However, as in the case of the Third Slide, the main depositional areas of the First and Second Slides exhibit predominant longitudinal trends. This is particularly so along the southwestern margin of the slides, where long (up to 20 km) curving downslope lineations are seen on Gloria sonographs and subsidiary shorter lineations on the medium-range sonographs. There are also, however, areas of conflicting trends (mainly longitudinal or transverse) at both large and smaller scales.

On the northern side of the Second Slide at about 1700 m water depth there are two broad (1–2.5 km) strips of sea floor exhibiting a relatively strong acoustic backscatter. They originate at the lateral head scarp of the Second Slide and trend downslope more or less along the axis of the Gloria Valley for 20 km. These may represent large examples of submarine chutes, smaller examples of which have been described by Prior & Coleman (1981) and Prior *et al.* (1981).

Further down the northern margin of the slide, at about 2400 m water depth, local secondary sliding or rotational slumping related to the First Slide (seen on a seismic profile) has dammed a 25 km long sediment pond. This shows up as an area of very low backscatter on a Gloria sonograph (figure 18).

Other patches of relatively smooth sea floor can be related to deposits at the base of the First Slide, to later infill of depressions in the slide surface, or to a minor (possibly backrotated) depression at the base of the headwall of the slides. A probable high rate of post-slide sediment deposition evident below the scarp of the Third Slide (see figure 19C) may be caused by its location just below the scarp and downslope from the deepest zone of floor influenced by the Norwegian Current, which is generally slope parallel and heading north.

On some eight or so of the crossings of prominent scarps within the slide area, the sonographs show a truncation of linear features above the scarp, and a discordance with other linear features below the scarp. Usually the scarp represents the headwall of either the Second or the Third Slide. This reinforces the conclusion that the slide forming the scarp represents a younger

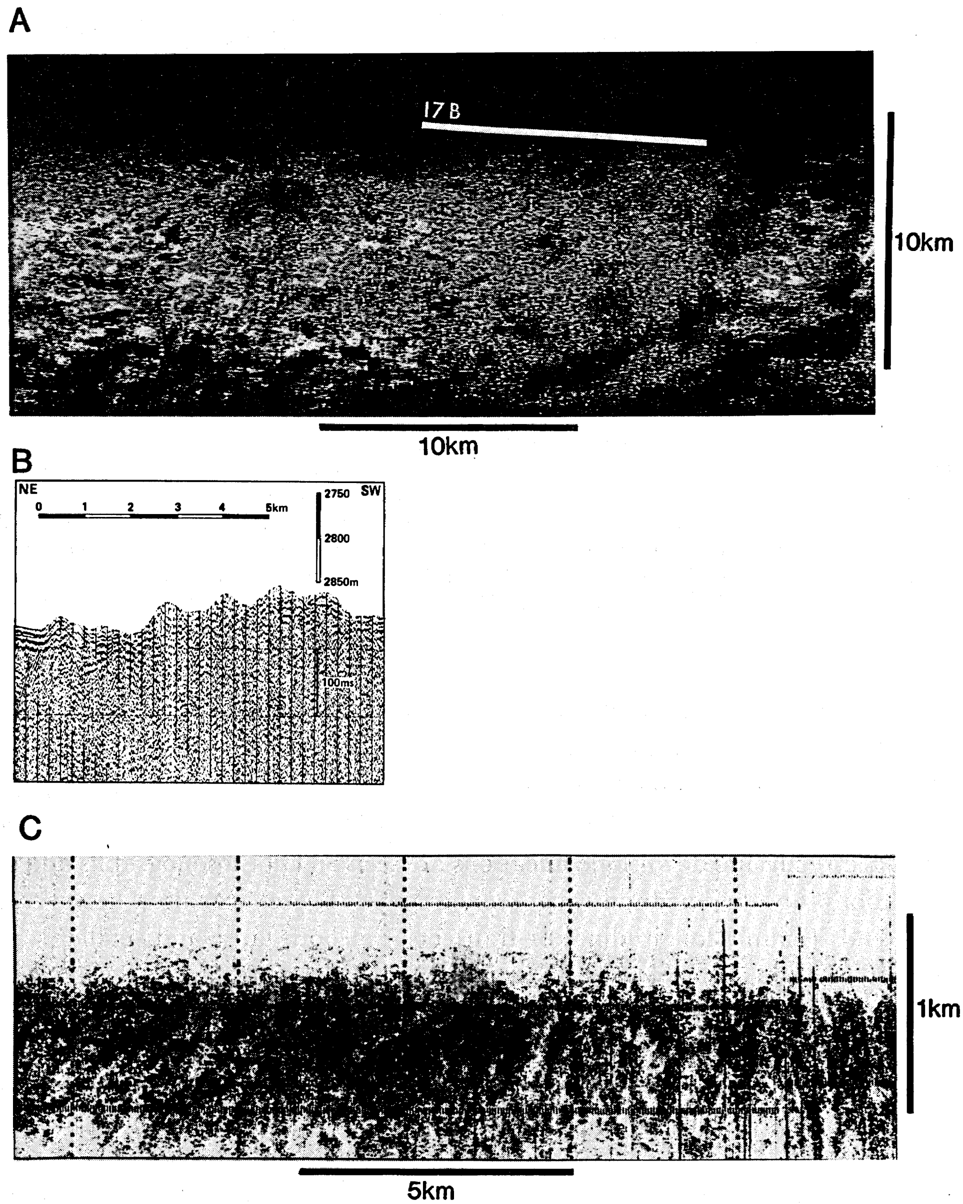

FIGURE 17. (A) Long-range sonograph (located in figure 13) on the lower part of the Second Storegga Slide (2700–2800 m water depth). Downslope is towards the bottom of the page. This sonograph typifies the blocky nature of much of the slide, many of the larger blocks visible here being 1 km or more across. (B) Sparker record (located in figures 13 and 17A) illustrating the essentially blocky nature of the deposits of the Second Slide. (C) Medium-range sonograph (located within the boxed area in figure 19A) on the Third Storegga Slide. Downslope is towards the top of the page. This sonograph typifies the blocky nature of much of the surface of the slide, within which some along-slope (after allowing for scale distortion) lineations are apparent towards the left-hand side of the sonograph, and downslope lineations towards the right. Most of the individual blocks here (dark blobs) are 100 m or less across.

event that that which produced the lineaments above the scarp. A good example of such a truncation is shown in figure 19A, B. Here, at a water depth of 1200–1300 m, both the long-range and medium-range sonographs show both large-scale and smaller-scale curved along-slope lineaments on the First Slide abruptly cut off by a 75–100 m high scarp representing the headwall of the Second Slide. Similar truncations of linear features are also seen on crossings

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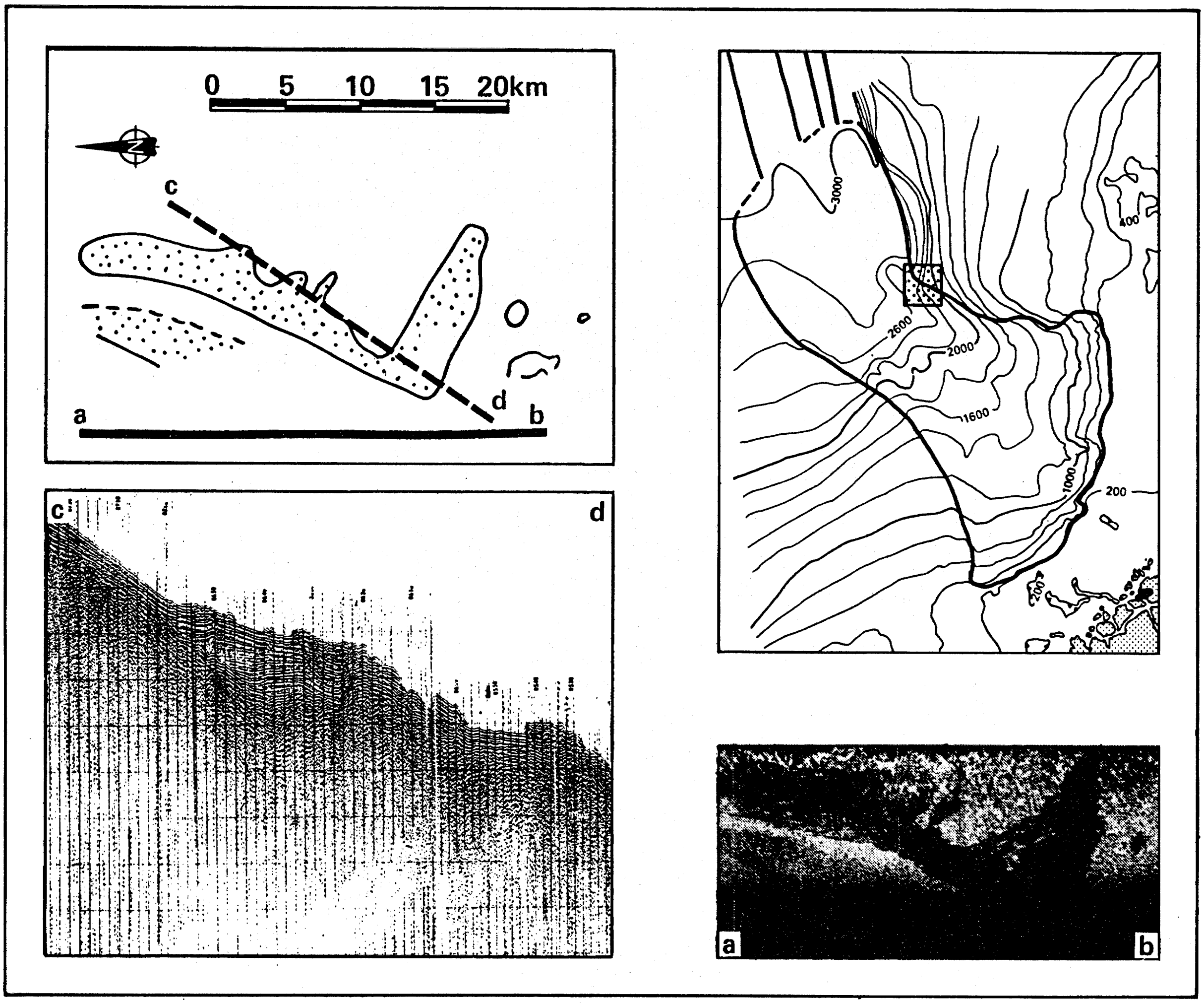

Figure 18. Secondary local sliding has dammed a 25 km long sediment basin at a depth of 2200–2400 m close to the northeastern margin of the First Storegga Slide. Original sparker and Gloria records on the lower left and right, respectively.

of the headwall scarp of the Third Slide (see figure 19C). A less obvious mismatch of linear trends occurs across the 100 m high headwall scarp of the Second Slide near the southwestern margin of the Storegga Slide. Here, in 1600 m water depth, the lineaments below the scarp are slightly more scarp-parallel than those cut off above it (figure 20).

(*b*) *Sea-floor photographs*

Sea-floor photographs were taken at eight deep locations and at two places on the headwall of the slide. At most of the deep locations a thin layer of post-slide foraminiferal mud was sufficient to obscure detail of the slide surface. The only feature indicative of sliding was a small detached block seen on one photograph. In the headwall of the slide scar, however, there is evidence in the photographs of downslope sliding and/or grain flow.

(*c*) *Discussion of morphology*

Much of the Storegga Slide is masked by a Holocene deposit of variable thickness. Its average thickness in 40 samples is 90 cm, but this thins to less than 25 cm below 1600 m water

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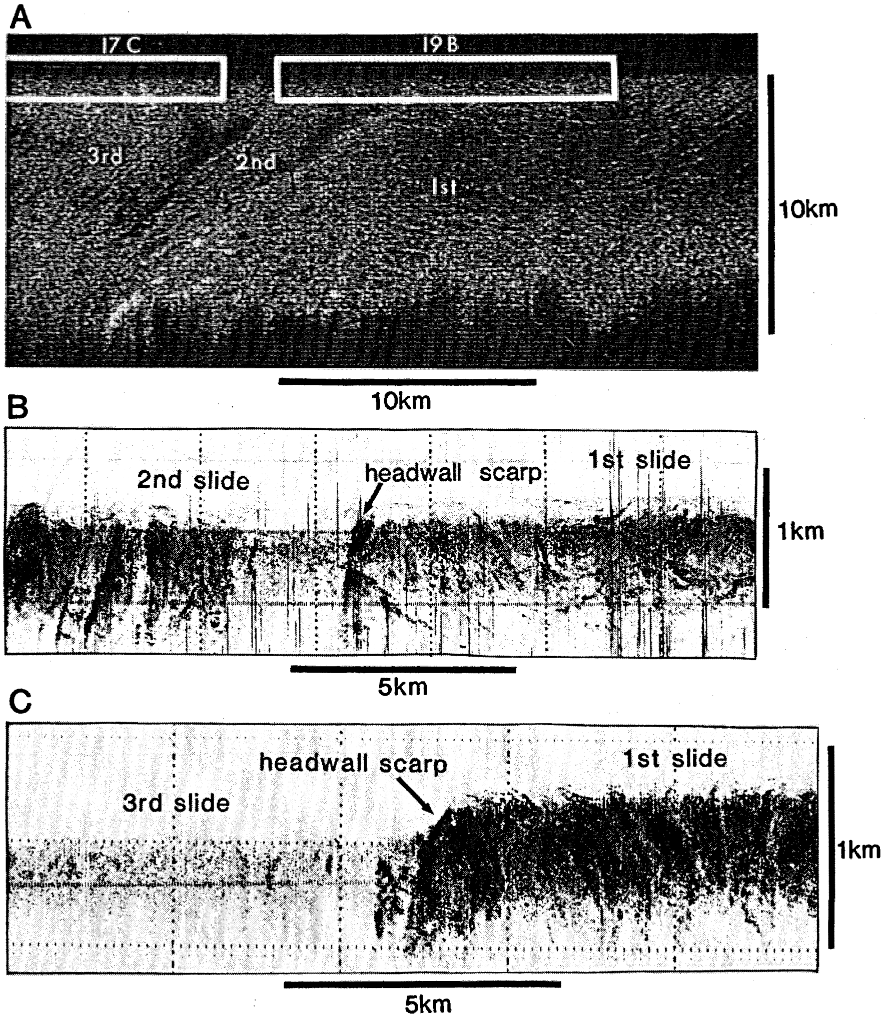

FIGURE 19. (A) Long-range sonograph (located in figure 13) showing a pattern of curved, but basically along-slope, lineations (with a separation of about 0.5 km) on the ruckled surface of the First Storegga Slide (right-hand side of sonograph). These are abruptly truncated by the headwall scarps of the Second and Third Storegga Slides. A pattern of scarp-parallel, basically downslope, lineations are faintly evident on the surface of the Third Slide (left-hand side of sonograph). Downslope is towards the top of the page. (B) Medium range sonograph (located in boxed area in figure 19A) showing along-slope lineations on the First Storegga Slide truncated by the headwall scarp and associated downslope lineations of the Second Storegga Slide. Downslope is towards the top of the page. (C) Medium-range sonograph (located in the boxed area in figure 16) crossing the headwall of the Third Storegga Slide. Strong contrast is shown between the rough surface of the First Storegga Slide (with slope-parallel lineations on right-hand side) and the partly sediment-obscured surface of the Third Slide (on the left below the scarp). Downslope is towards the left.

depth. This tends to obscure the fine detail sometimes evident in high-resolution sonographs obtained in other parts of the World over some extremely youthful slides of fresh appearance. Also, because of the enormous extent and multiple nature of the Storegga Slide, it is perhaps not surprising that its surface morphology does not so clearly exhibit the relatively simple patterns of extensional–compressional features seen on some much smaller slides (for example, Prior & Coleman 1982). Thus the surface of the Second Slide, before it moved, would have represented the disturbed floor left by the First Slide, and that of the Third Slide the disturbed floor left by the Second Slide. The surface morphology, and sediment texture may therefore

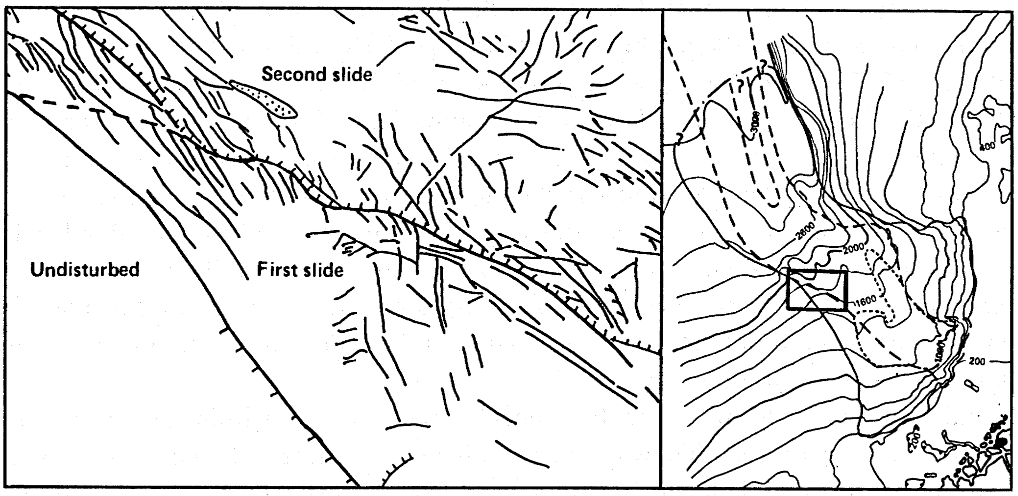

FIGURE 20. Seabed features based on Gloria and medium-range side-scan sonar near the southwestern margin of the Storegga slide scar (located in figure 13). The slight change in lineation along the centre is interpreted as being caused by the somewhat different orientation of features within the two different slide events of the First and Second Storegga Slides.

have passed through up to three phases of remoulding. It is interesting to note that the huge far-travelled sediment slabs, described from the southwestern margin of the slide, bear on their surface a rough relief of 10 m or so together with indications of two sets of linear trends. Unless this surface disturbance developed during the downslope translation of the slabs it should represent features relict from the First Slide.

Despite the above reservations, we may draw some conclusions regarding the morphology of the slide. Firstly, the extremely rough surface of most of the slide generally displays a pattern of linear elements. These tend to align in either an along-slope or headwall scarp-parallel (transverse) direction, or in a downslope (longitudinal) direction. As the headwall scarp bends around to form the lateral scarp bounding each slide there is, of course, a point at which the scarp-parallel trends adjacent to the scarps become 'longitudinal' rather than 'transverse'. At least some of the scarp-parallel 'steps' at the headwalls of the slides are interpreted as rotational secondary slump-like features.

The longitudinal trends are thought to represent longitudinal shears due to differential movement within the mass of the slide (as described by Prior *et al.* 1982). The sliding (or gliding) of individual randomly arranged large slabs described by Prior *et al.* (1982) were also observed by us, but they incorporate far larger slabs. We did not observe any clear cut zone of arcuate banding into a series of compressional ridges near the base of the slide, as noted by Prior *et al.* (1982). However, our side-scan survey did not extend to the distal limit of the Storegga Slide as a whole.

8. Slide mechanisms

As mentioned above, more than 4000 km^3 or 75% of the sediment involved in the three Storegga slides was transported down to the deep ocean basin below 2700 m. About 750 km^3 of this consists of blocky deposits assigned to the Second Slide. The Eocene–Oligocene silt–claystone contained in core 49–21 (figure 8) is interpreted as being sampled from one of these blocks, which occur within piles of blocky sediments up to 50 m high or as individual

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blocks. A seismic profile, indicated in figure 2, shows that such blocks also occur in the depositional tongue at least 100 km further out into the Norway Basin. The average slope angle is about 0.11° (1:500) and the deposit is about 60 m thick. The transport of such large blocks in the form of a fluidized sediment flow or debris flow depends on excess pore-water pressure either as pure pore water or as a muddy interstitial slurry or matrix. To maintain the excess pore pressure sufficiently long to transport the blocks several hundred kilometres the fluidized portion of the flow should have been relatively thick and probably fine-grained, with low permeability, otherwise the pore water would have escaped too rapidly and the slide would have come to a halt. In this context, it is interesting to note that samples of the older Tertiary sediments, which outcrop only in the lower portion of the slide scar, are frequently more clay-rich than the Plio-Pleistocene units.

The sediment blocks forming the hummocky accumulation within the slide scar were probably transported in a similar way. The gradients were rather higher, however, mainly varying from 0.5° to 1.5°. These blocks may have been transported over a shorter distance than those described above because the gliding layer lost its excess pore-water pressure more rapidly. This could have taken place through the presence of a thinner gliding layer, or possibly a rougher underlying surface, which aided the escape of a liquefied supporting layer. Some additional pore water was probably derived from the sea water and added to the glide layer during the sliding.

The same mechanism probably also acted below the two very large sediment slabs described above. A glide-plane with high excess pore-water pressure probably acted as a lubricant for the slabs. The great size of the slabs prevented the escape of this lubricant long enough for them to travel almost 200 km on a slope of only 0.3° (1:190). The southernmost slab seems to have slid very gently over an almost undisturbed sea floor for the last few kilometres and then come to rest on the previously normally consolidated clayey sediments without producing obvious distortions on the seismic profile (figure 10).

Because the First Slide consisted of mainly soft and clayey sediments a somewhat different flow mechanism probably operated. The average gradient from the headwall to the base of the slide scar at 2700 m is only 0.6°, and locally less. It is therefore reasonable to assume that the sediments moved as a partially liquefied debris flow with enhanced pore water pressure, and that the sediments thus may have become almost completely remoulded.

The seismic data shows that the main glide planes tended to follow certain seismic reflectors that probably represent weak zones. As gas has been observed both as free gas in the sediments and as gas hydrates in the vicinity of the Storegga Slide (figure 21), the presence of gas may have accelerated the liquefaction and helped maintain the excess pore pressure during the sliding.

Some cores show a progressive increase in the liquefaction of the slide sheets in the upwards transition from coarse debris flow deposits into turbidites. Furthermore, a very large turbidity flow travelled more than 750 km out into the Norway Basin. Such turbidity currents are likely to have originated largely from the stirring of uncompacted surface sediments during the course of the slides (Jansen *et al.* 1987).

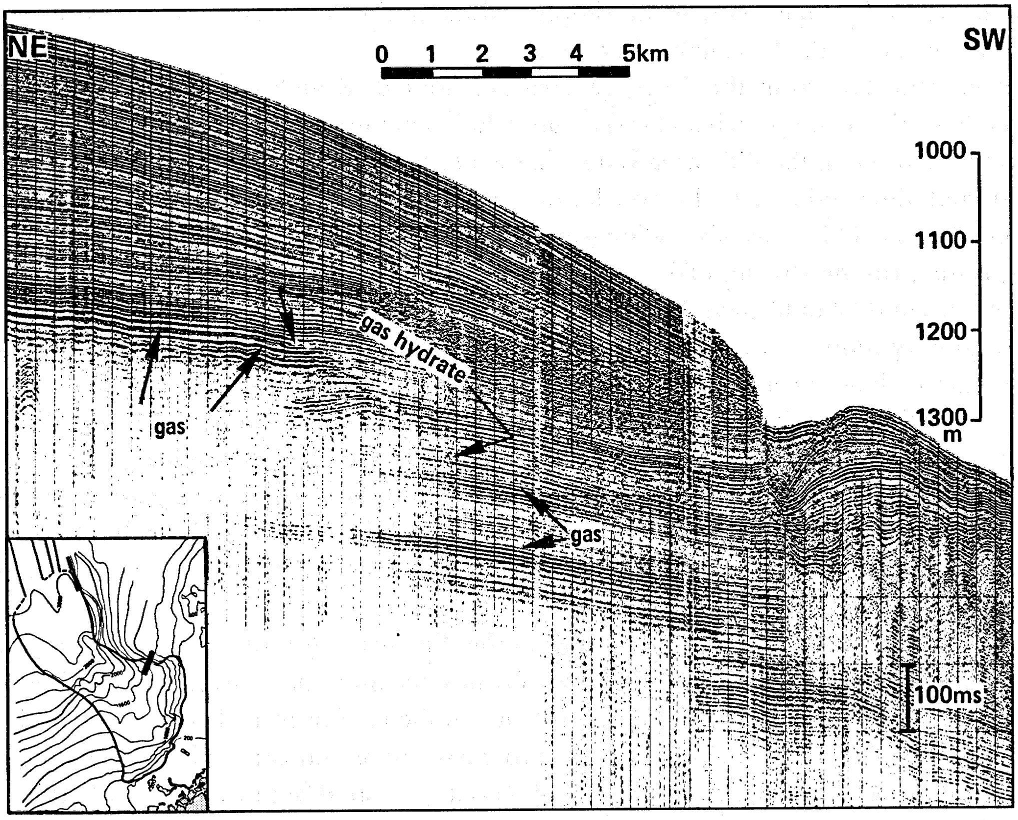

Figure 21. Shallow gas observed on a sparker record across the northeastern margin of the First Storegga Slide at about the same sub-bottom depth as the glide plane of the slide. The gas is concentrated both along bedding planes, probably as free gas, and as gas hydrates sub-parallel with the sea floor and cutting across bedding planes.

9. Triggering mechanisms

Compared with the more accessible subaerial landslides the triggering mechanisms of submarine slides are rarely proven. Gravity is the main driving force, aided by one or more mechanisms. Very rapid accumulation is known to have caused underconsolidation and consequent sliding in some sediments, for example on the Mississippi Delta front (Prior & Coleman 1978) and the west coast of Canada (Luternauer & Swan 1978; Prior *et al.* 1982). The generation of methane gas in the sediments by post-depositional biogenic activity (Prior & Coleman 1978) or the liberation of gas and water from layers of gas hydrates (Carpenter 1981) are also possible mechanisms. Among the most frequently suggested triggering mechanism for submarine slides, however, are earthquakes. Three large historical slides, Grand Banks (Heezen & Ewing 1952), Messina (Ryan & Heezen 1965), and Orleansville (Heezen & Ewing 1955) were all associated with earthquakes, and many older slides are also suggested to have had the same cause, for example, the Kayak Trough Slide (Molnia *et al.* 1977), a slide off the Malaspina Glacier (Carlson 1978), the Bassein Slide (Moore *et al.* 1976), and the Agulhas Slump (Dingle 1977). Other possible mechanisms include excess pore-water pressures or oscillatory motions imposed on pore waters by waves or by sea-level changes, ice-induced forces in glaciated areas (such as possibly pertained at the time of the First Slide), downslope undercutting or upslope loading, or simply sedimentation on a steep slope, with eventual sliding along the weakest available horizon.

Geotechnical data from the Storegga area are limited. Rough estimates of slope stability were made by the method of slices for the upper 25 km of the central portion of the slide (Bugge *et al.* 1978). Although the slide area is now known to be far larger and more complex than the data at that time indicated, the conclusions of Bugge *et al.* (1978) still give some idea of pertinent factors. Thickness of the slide was set at 300 m, the slope angle at 1.5°, and the pore-water pressure (in the absence of data) assumed to be hydrostatic. Based on total stress analysis, the shear strength should have been below 170 kPa for instability to have resulted from the force of gravity alone. Based on an effective stress analysis the maximum angle of internal friction should have been as low as 2.6°. The glide planes of the slides were as much as 450 m below the pre-existing sea floor. Thus through the normal process of consolidation the sediments at that depth should have been relatively firm with a theoretical estimated shear strength of at least 900 kPa. Any slide is extremely unlikely to produce a glide plane in such firm sediments unless aided by much weaker layers. The seismic profiles show that both the slip planes and glide planes tend to follow seismic reflections that probably represent layers of relatively weak sediments.

Immediately outside the northern margin of the slide scar gas is observed on seismic profiles at water depths of 1000–1300 m. The most obvious accumulations are along bedding planes (see figure 21) or as free gas in the sediments beneath these. However, there are also indications of the presence of a gas hydrate layer parallel to the sea floor and cutting across bedding planes at a sub-bottom depth of about 300 m. The observed gas is at about the same sub-bottom depth as the glide plane of the First Slide. It is therefore possible that the sliding was aided by the presence of gas or the decomposition of gas hydrate, with associated liberation of any free gas held below such a layer.

Ringdal *et al.* (1982) listed all known earthquakes and identified zones of significant earthquake activity on the Norwegian continental margin. One of their three zones of peak ground accelerations is sited in the Storegga area.

All recorded earthquakes for the period 1970–1981 were also listed by Browitt & Newmark (1981) for the area. A combination of the two data sets shows that there have been 17 earthquakes of magnitude 5 or more in Norway and adjacent waters so far this century. This suggests that earthquakes of magnitude 6.0 to possibly 7.5 could well have occurred in the Storegga area within the last 10000 years.

Slope stability may be drastically reduced by earthquake loading (see, for example, Karlsrud & Edgers 1982), together with associated increases in pore-water pressure, rapid upwards migration of gas and possible decomposition of any gas hydrate giving free gas and water (resulting in further excess pore-water pressures). Considering the relatively high risk of earthquakes of magnitudes 6 or over and the likely presence of gas in the sediments, we think it reasonable to suppose that at least parts of the liquefied sediment flows that occurred in the Storegga slides were originally caused by earthquakes. The mechanical influence on the sediments from ground acceleration and displacement would have helped the sliding to start, following which a retrogressive slide would have developed. Other factors may have contributed, such as ice loading on the shelf edge during the last glaciation, rapid sedimentation due to the proximity of the ice front, or gas liberation (either during a lowering of sea level, during a period of raised water temperature or during earthquakes themselves).

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10. Dating of the slide events

Some ancient slides have been tentatively dated by radiocarbon measurements (Summerhayes *et al.* 1979; Embley 1982) and some by comparison of post-slide sediments deposited on the slide scar with sediments outside the scar (Dingle 1980; Solheim & Kristoffersen 1984). For recent slides, the timing of submarine cable breaks has proved of great value in several instances (see, for example, Edgers & Karlsrud 1982).

Iceberg scouring is known to have taken place on the Norwegian shelf 11000–13000 years ago (Lien 1983*a*, *b*) and most of the scours are still relict. In the Storegga area iceberg plough marks are recognized on side-scan sonographs from the shelf adjacent to most of the slide headwall. In the northeastern and shallowest part of the slide scar of the First Slide, iceberg plough marks also seem to occur on the slope. This implies that the First Slide probably predated the iceberg scouring (11000–13000 years BP).

Sample 52-43 was recovered from the depositional area of the First Slide to the south of the area affected by the Second Slide (see figure 4) at a depth of 2800 m. It contains more than 6 m of undisturbed glaciomarine sediments below 70 cm of post glacial clay. An ash layer at about 50 cm was correlated with a known regional ash layer dated to 10600 years BP (Jansen *et al.* 1983). The relatively thick glaciomarine sequence below the ash layer indicates that a significant period of time with a glacial environment must have elapsed after the First Slide occurred. Supported by $\delta^{18}O$ analysis Jansen *et al.* (1987) suggest an intervening period of undisturbed sedimentation of about 30000–50000 years.

A glacial unit, the Storegga Moraine, which has a thickness of 10–30 m along the shelf edge at Storegga was cut by the Second Slide. From radiocarbon dating the glacial unit is tentatively dated to about 13000–13300 years BP (Bugge 1980). This means that the Second Slide probably occurred after that time.

Radiocarbon dating of two samples immediately overlying debris flow – turbidite sequences from the Second Slide (49-21 and 49-23, see figures 4 and 8) suggest that the Second Slide took place between 6000 and 8000 years BP (Bugge 1983). Two datings from the most distal turbidites close to the Aegir Ridge in the Norway Basin (figure 4) support this (Eidvin 1984). There are no radiocarbon datings from deposits of the Third Slide. Available data (including a several metres thick post-slide deposit in some samples) suggests that it was more or less coeval with the Second Slide (Bugge 1983; Befring 1984; Eidvin 1984). Younger ages of 3000–5000 years BP obtained in three cores probably record smaller mass displacement events that followed the main phases of the Second and Third slides, and that were confined to topographic depressions (Jansen *et al.* 1987).

11. Conclusions

1. The headwall of the Storegga Slide is 290 km long. The slide scar, which covers an area of 34000 km^2, extends downslope for 200–250 km, narrowing slightly towards the depositional area at the base of the continental slope below 2700 m. Slide deposits have been mapped for a further 500–550 km beyond here. The total run-out distance could therefore be more than 750 km. The average gradient of the whole slide scar is about 0.6°, but it varies from 0.1° to about 3°, with some local slopes as steep as 20°. The slope of the surface of the depositional area to the northwest is about 0.1°.

2. Three different slide events are distinguished in the slide area. The First Slide probably occurred in Mid-Weichselian time (30000–50000 years BP), and comprised the whole 290 km wide slide scar. Most of the sediments involved were soft uncompacted clay of Plio-Pleistocene age. The volume of this slide was about 3880 km^3, and the bulk of its deposits consist of acoustically semitransparent sediments found in the Norway Basin below 2700 m water depth. Only 400 km^3 of deposits now remain in the slide scar, although much more was probably originally dumped there and has been removed by the later sliding.

The Second Storegga Slide took place in the central part of the slide scar at about 6000–8000 years BP (as indicated by radiocarbon dating). The headwall is 75 km long and the slide broadened only slightly downslope. Most of the sediments involved were semi-consolidated, ranging in age from Pleistocene in the uppermost slide scar to Eocene in the lower part. The slide travelled well out into the abyssal plain, probably more than 750 km from the headwall.

The Third Storegga Slide was limited to the upper part of the Second Slide scar, influencing only a third of that scar. Its precise dating is not yet known, but it probably occurred as the final stage of the Second Slide, delayed sufficiently to be defined as a separate event.

The volume of the last two slides was about 1700 km^3, of which about 950 km^3 was deposited in the slide scar and the remainder in the Norway Basin. This does not include any deposits of the First Slide removed by the later ones.

3. The extremely uneven and frequently blocky surface relief of the slide is to some extent ordered, in that linear trends are visible on sonographs. These may be distinguished as slope or scarp-parallel transverse trends (some of which in the headwall region are back-rotated slump blocks) and downslope, longitudinal trends interpreted as shear due to differential movements within the mass of the slide. Truncation of trends by the headwall scarps of the Second and Third slides testifies to the sequential development of the three main slides.

4. A debris-flow mechanism was probably dominant in the First Slide, which mainly comprised soft clayey sediments. During the Second and Third slides the sliding sediments probably flowed down the gentle slope (as low as 0.1°) on a liquefied layer. Blocks 50–100 m across were transported down the 250 km long slide scar and possibly more than 150 km beyond into the Norway Basin. Two huge sediment slabs, 200 m thick and 10×30 km wide, were probably carried 200 km from the upper part of the slide scar down to 2000–2500 m water depth near the southwestern margin of the slide on an average gradient of only 0.3°. Turbidites, resulting mainly from the Second Slide, are also widely recognized through the immediate slide area, and a very thick distal turbidite found in the Norway Basin 750 km from the headwall is related to the Second Slide.

5. The triggering mechanism for the slides may have involved a combination of factors. However, the known seismic activity in the area suggests that earthquakes are a likely primary cause, perhaps in association with other factors, such as ice loading (in the case of the First Slide) and the presence of gas and gas hydrates and excess pore-water pressures.

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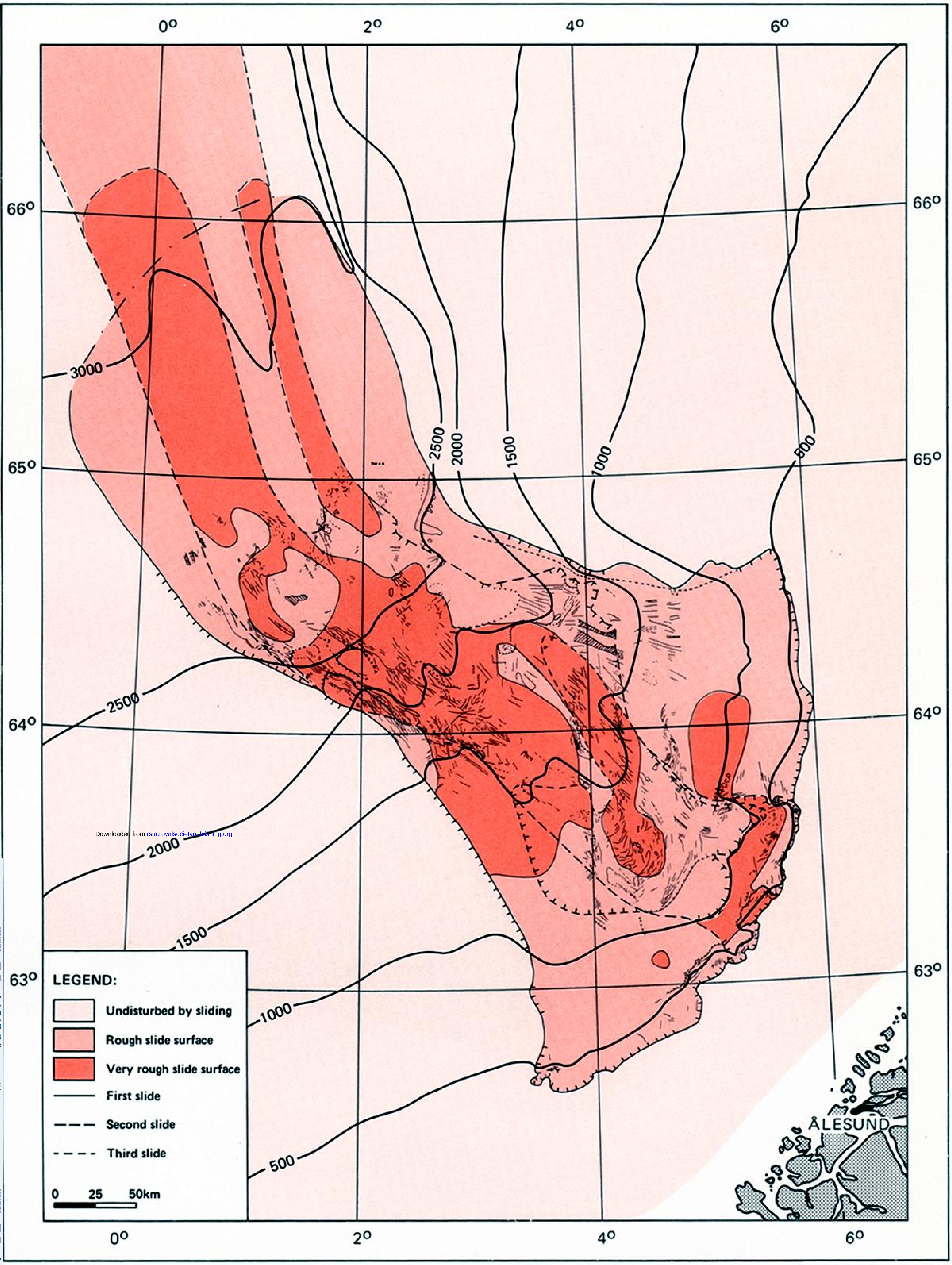

FIGURE 12. Salient features of the Storegga Slide based on the long-range side-scan sonar Gloria and partly on intermediate range sonographs. Classification of seabed roughness is based on seismic data as well. Because side-scan sonar coverage is only partial, many more linear elements exist than those shown. Ticks indicate downslope sides of scarps. The broken line near the northern boundary of the slide represents the probable original edge of the slide, above which there has been secondary sliding.

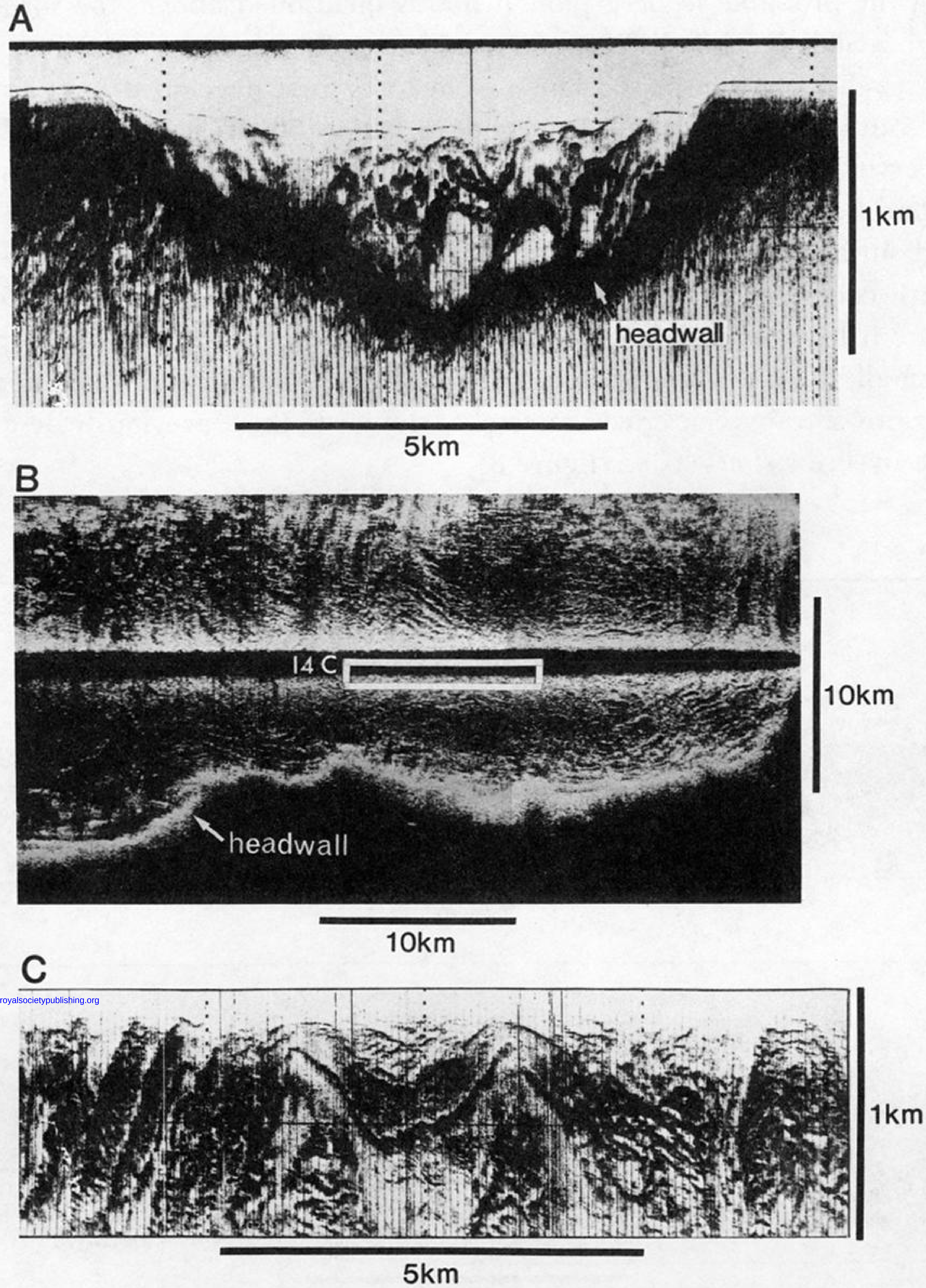

FIGURE 14. (A) Medium-range sonograph (located in figure 13) of section of the steep headwall of the Second Storegga Slide. Downslope is towards the top of the page. Note the rough floor downslope of the headwall interpreted as largely composed of rotated slump blocks. Note that in this and subsequent medium range sonographs strong backscatter of sound is represented by darker tones, and weak backscatter and shadow zones by lighter tones. Note also that this and subsequent medium-range sonographs do not represent true-plan views. Allowance for this should be made in estimating shape and orientation of features. (B) Long-range (Gloria) dual-channel sonograph (located in figure 13) of a section of the steep headwall of the Second Storegga Slide, and the surface of the slide for 15 km or so below the headwall scarp. Downslope is towards the top of the page. Note that on this uppermost part of the slide its surface relief is dominated by sinuous slope-parallel ruckling or slumping with a 0.5 km or so crest separation (see figure 16). Note that, in contrast to the medium-range sonographs, in this and subsequent long-range sonographs strong backscatter of sound is represented by lighter tones, and weak backscatter and shadow zones by darker tones. Also note that the Gloria sonographs represent almost true-plan views. (C) Medium-range sonograph of the disturbed surface on the upper part of the Second Storegga Slide (located within the boxed area on figure 14B). Downslope is towards the top of the page. Note that although sinuous along-slope trends predominate in the central part of the figure, towards either side of the central zone downslope lineations are also clearly visible.

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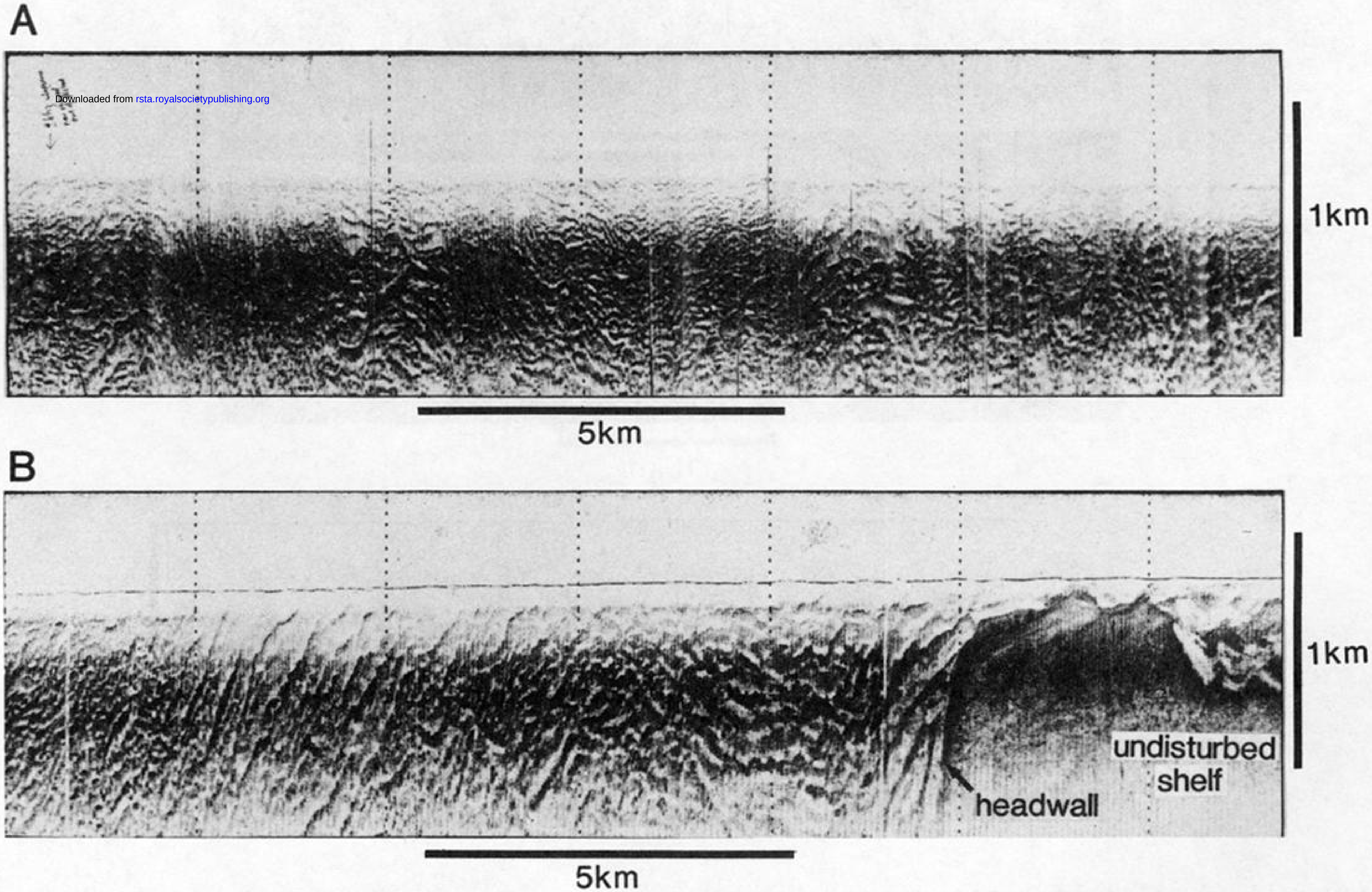

IGURE 15. Medium-range sonographs (located in figure 13) of the uppermost part of the First Storegga Slide. Downslope is towards the top of the page. Note the pervasive sinuous pattern of largely along-slope (transverse) lineations. These have a separation of approximately 50 m and a relief of up to 15 m.

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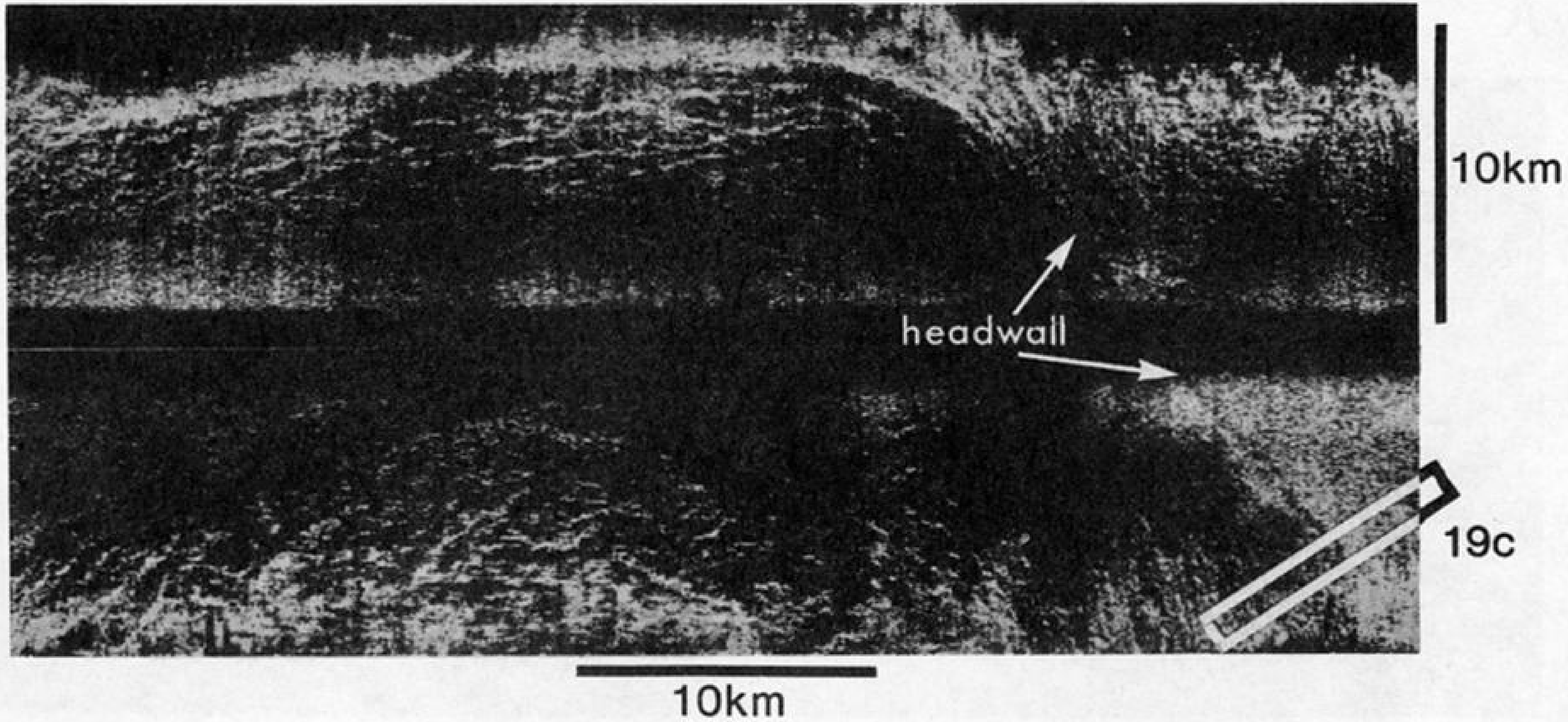

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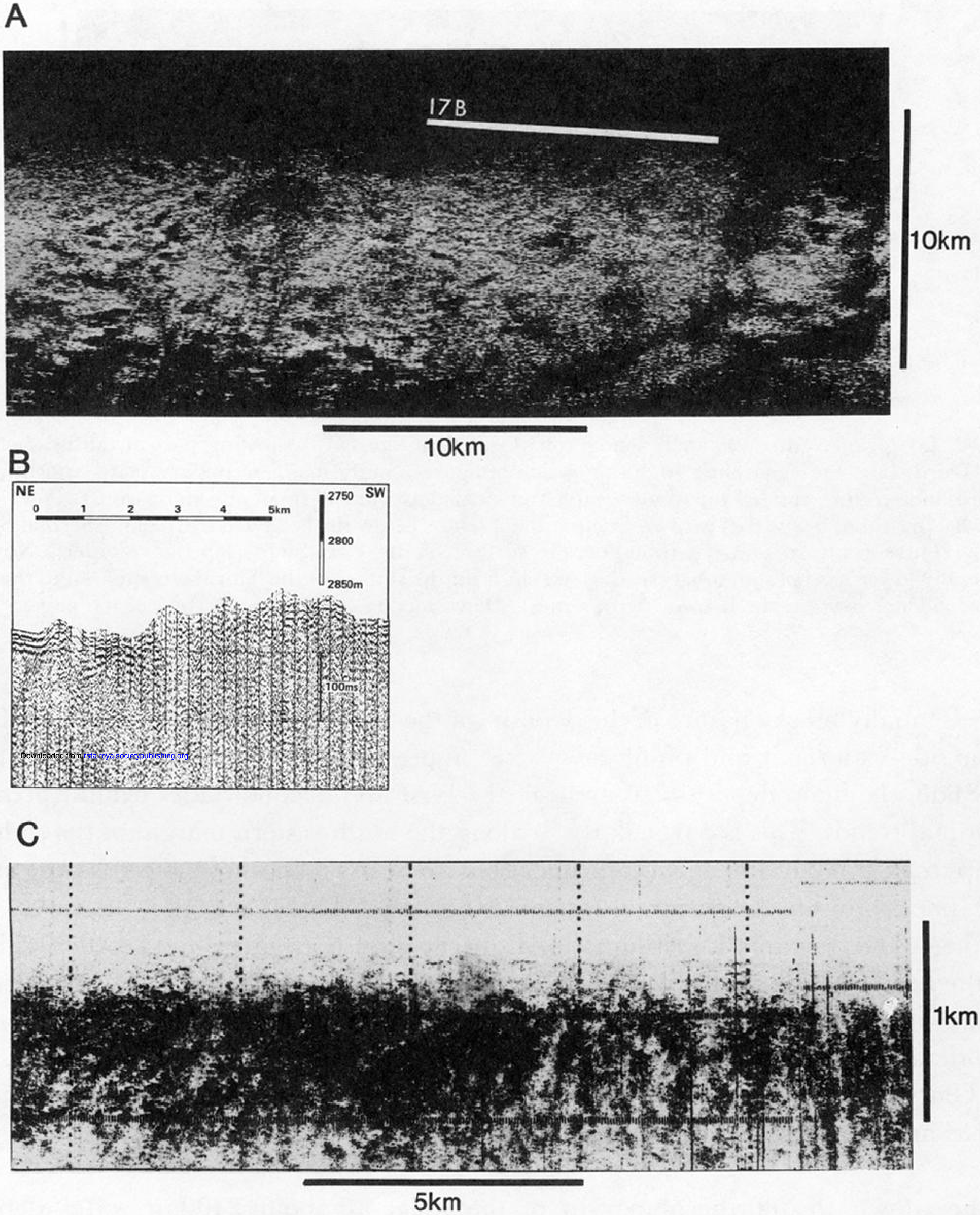
FIGURE 16. Long-range (dual-channel) sonograph (located in figure 13) showing part of the headwall scarp of the Third (last) Storegga Slide (right-hand side of figure), and a major secondary scarp associated with the Third Slide (centre and left top of sonograph and located as a line of small dots in figure 13). A series of scarp-parallel lineations below the scarp are comparable to those below the headwall scarp of the Second Slide (figure 14B). These contrast with lineations on the surface of the First Slide (top-right corner). Note also the generally lower level of sound backscatter evident from the surface of the Third as compared to the First Slide (most evident towards the bottom right corner). Downslope is towards the bottom of the page.



GURE 17. (A) Long-range sonograph (located in figure 13) on the lower part of the Second Storegga Slide (2700–2800 m water depth). Downslope is towards the bottom of the page. This sonograph typifies the blocky nature of much of the slide, many of the larger blocks visible here being 1 km or more across. (B) Sparker record (located in figures 13 and 17A) illustrating the essentially blocky nature of the deposits of the Second Slide. (C) Medium-range sonograph (located within the boxed area in figure 19A) on the Third Storegga Slide. Downslope is towards the top of the page. This sonograph typifies the blocky nature of much of the surface of the slide, within which some along-slope (after allowing for scale distortion) lineations are apparent towards the left-hand side of the sonograph, and downslope lineations towards the right. Most of the individual blocks here (dark blobs) are 100 m or less across.

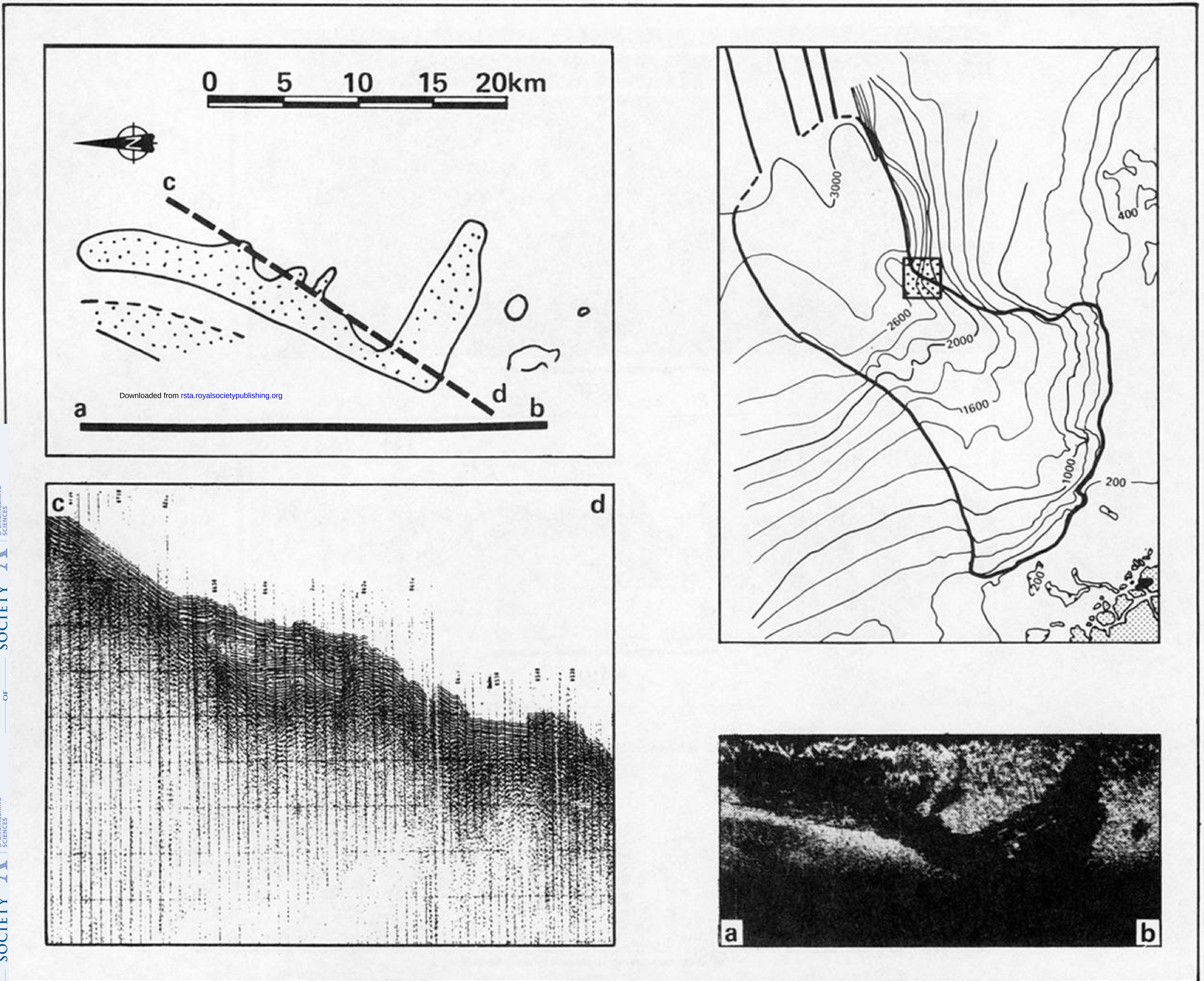


FIGURE 18. Secondary local sliding has dammed a 25 km long sediment basin at a depth of 2200–2400 m close to the northeastern margin of the First Storegga Slide. Original sparker and Gloria records on the lower left and right, respectively.

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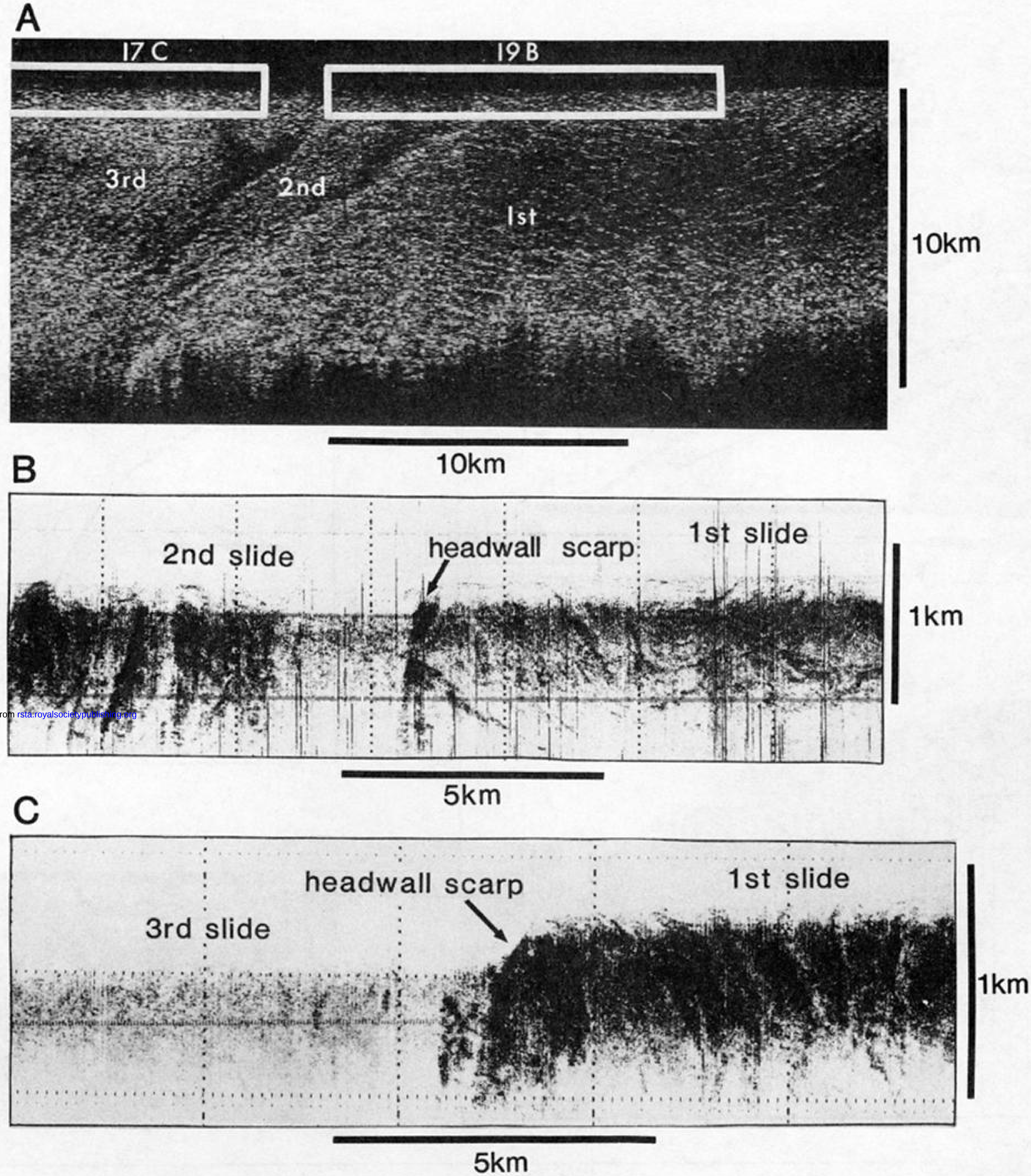

FIGURE 19. (A) Long-range sonograph (located in figure 13) showing a pattern of curved, but basically along-slope, lineations (with a separation of about 0.5 km) on the ruckled surface of the First Storegga Slide (right-hand side of sonograph). These are abruptly truncated by the headwall scarps of the Second and Third Storegga Slides. A pattern of scarp-parallel, basically downslope, lineations are faintly evident on the surface of the Third Slide (left-hand side of sonograph). Downslope is towards the top of the page. (B) Medium range sonograph (located in boxed area in figure 19A) showing along-slope lineations on the First Storegga Slide truncated by the headwall scarp and associated downslope lineations of the Second Storegga Slide. Downslope is towards the top of the page. (C) Medium-range sonograph (located in the boxed area in figure 16) crossing the headwall of the Third Storegga Slide. Strong contrast is shown between the rough surface of the First Storegga Slide (with slope-parallel lineations on right-hand side) and the partly sediment-obscured surface of the Third Slide (on the left below the scarp). Downslope is towards the left.