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A Giant Three-Stage Submarine Slide Off Norway

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Abstract

One of the largest submarine slides known, The Storegga Slide, is located on the Norwegian continental margin. The slide is up to 450 m thick and has a total volume of about 5,600 km^3. The headwall of the slide scar is 290 km long and the total run-out distance is about 800 km. The slide involved sediments of Quaternary to Early Tertiary age and occurred in three stages. Earthquakes combined with decomposition of gas hydrates are believed to be the main triggering agents for the slides. The first slide event is tentatively dated to be about 30,000 to 50,000 years B.P. and the two last major events are dated to be at 6,000 to 8,000 years B.P.

Introduction

Submarine slides can be several orders of magnitude greater than terrestrial slides. In this report we describe one of the largest underwater slides so far known, "The Storegga Slide," whose 290 km long headwall lies about 100 km off the coast of Norway (Fig. 1).

On the basis of bathymetric soundings, dredge samples, and one seismic line, Holtedahl [1] and Sellevoll [2] suggested that small-scale sliding had occurred in the Storegga area. A later study of the central and upper part of the slide, by means of shallow seismic profiling, demonstrated that sliding has occurred on a far larger scale [3].

A recent study by several university and institute groups has provided a much more extensive survey of the slide area. A total of 3,000 km of analog sparker profiles were obtained, together with 1,300 km of medium and long range (Gloria) side-scan sonar and airgun profiles. Forty-three core-samples have been collected and analyzed and improved bathymetric charts compiled. Some of this work has been described in theses by Bugge [4], Befring [5], and Eidvin [6], and will be reported in detail elsewhere [7]. This paper is a summary of the project, with revisions and updates resulting from our latest work.

The Storegga Slide

The 290 km long headwall of the slide is situated in water depths of 150 to 400 m and forms a scarp whose gradient is 10° to 20°. The slide scar extends downslope to 2,700 m water depth, and is recognized partly as an erosional and partly as a depositional feature (Figs. 1 and 2), while the area covered by slide deposits alone extends further out. Sediment core samples more than 750 km from the headwall in the Norway Basin are interpreted as distally deposited turbidites originating from the Storegga Slide [7].

Sediment samples and morphological features observed on medium and long range (Gloria) side-scan sonar show that the slide probably occurred in three events. On sonographs this is seen as lineaments or other morphological patterns on the sea floor that have been cut off by a later mass movement. A representative example is shown by the Gloria sonograph in Figure 3 where a parallel series of curved ridges, have been abruptly cut off by a slide. The ridges were formed

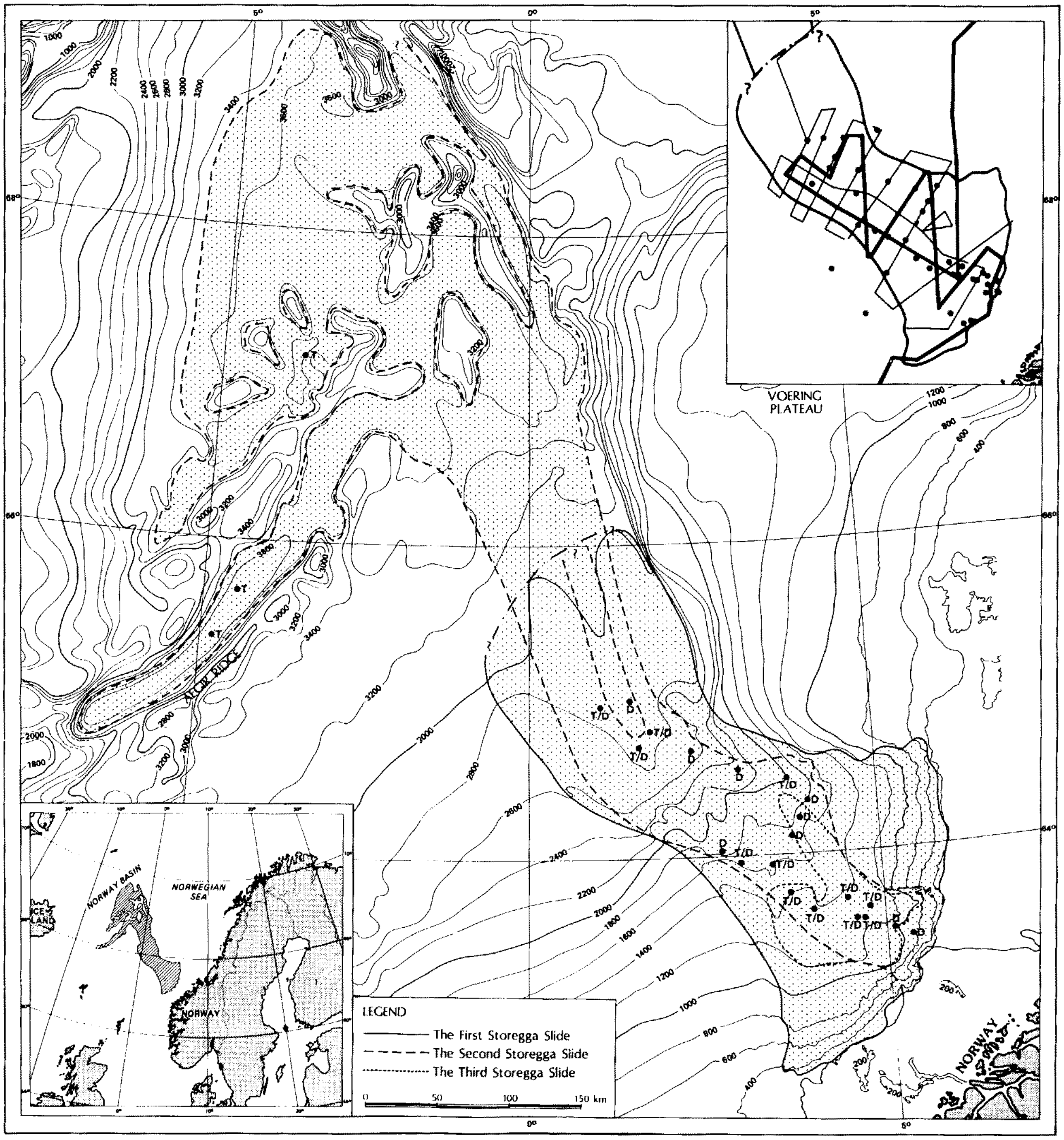

Figure 1. The area affected by the Storegga Slide. Three main slide events are identified and well documented out to 400 km from the headwall, while the distal extent of the Second Storegga Slide is not yet fully mapped. The upper right inset map locates the analog sparker data (thin lines), medium and long range (Gloria) side-scan sonar and airgun data (heavy lines), and sediment core samples (dots). Core samples containing turbidites (T) and debris flows (D) are shown on the main map. Depth contours are from Bugge [4] and Perry and others [25].

by what is termed the First Storegga Slide. The Second Storegga Slide occupied the central part of the area of the First Slide and truncated the curved ridges. At a later stage the Third Storegga Slide cut another scarp parallel to the one made by the Second Slide.

The separate slide events can also be placed in order by consideration of the sedimentology, radiocarbon datings, and variation in the foraminiferal faunas of the core samples [7]. For instance, a core sample which was recovered at about 2,600 m water depth

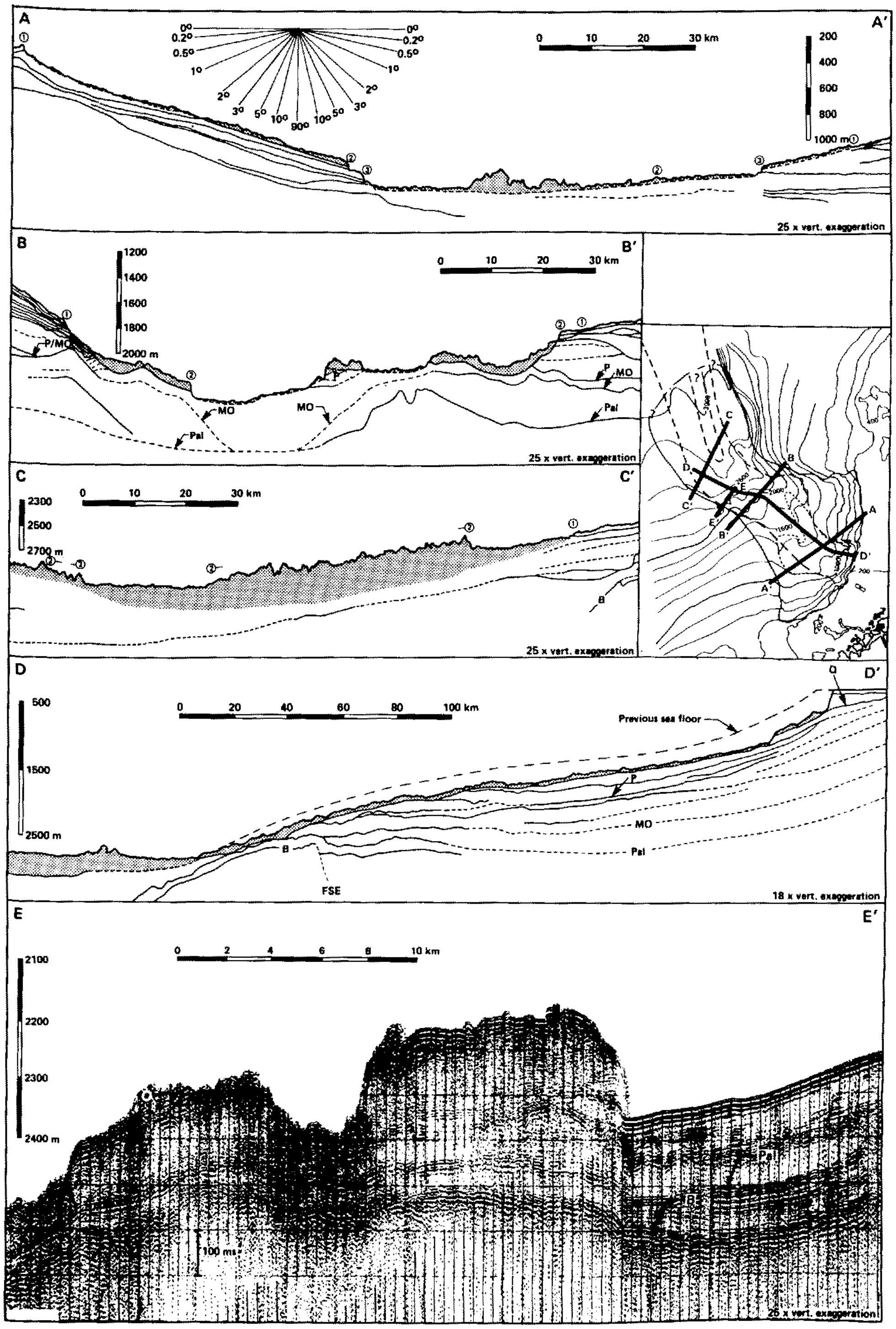

Figure 2. Cross sections of the Storegga Slide based on analog sparker profiles. ①, ② and ③ in A to C mark the lateral extent of the three slide events. The pre-existing sea floor is reconstructed in D. E is a sparker record of two very large sediment slabs, up to 10 × 30 km wide and 200 m thick, still intact after sliding 200 km on an average slope of 0.3° during the Second Slide event. Q = Base of Pleistocene, P = Base of Pliocene, MO = Mid Oligocene, Pal = Paleocene/Lower Eocene, B = Tertiary basalt, FSE = buried Faerøy-Shetland Escarpment. Slide deposits are shaded.

in an area affected only by the First Slide, contains 5.5 m of undisturbed glacial sediments. On the basis of extrapolation and dating of an ash layer in the core the age for the bottom of the core is estimated at 30,000 to 35,000 yrs. Because of its location on top of deposits of the First Slide, the slide must be older than this. Radiocarbon datings of pelagic and hemipelagic deposits immediately overlying deposits of the Second Slide indicate a much younger age for this slide (6,000 to 8,000 yrs). These and similar examples together with an overall evaluation of all available data support the previously mentioned theory that the Storegga Slide occurred in three events.

The First Storegga Slide comprises the entire area

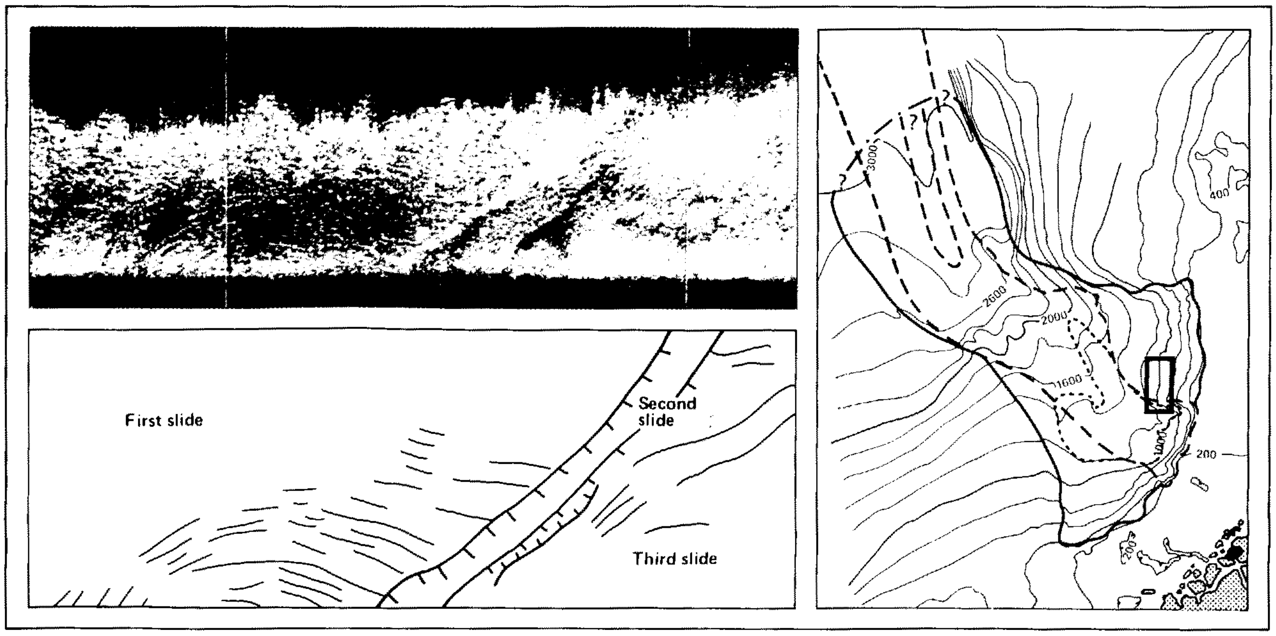

Figure 3. Gloria sonograph from the Storegga slide scar showing that the Second Slide was a later event than the First Slide and truncated the ridges left on the sea floor by the First Slide. The Third Slide later cut a further parallel scarp. Downslope is towards the bottom left of the page.

of the slide scar (above 2,700 m water depth) and involves mainly normally consolidated clayey sediments, which are interpreted to be Plio-Pleistocene in age. The morphology of the slide scar of this first slide as well as the depositional area is relatively smooth (Fig. 4a).

The Second Slide is located in the central part of the slide scar that resulted from the First Slide. It cut deeper into the seabed (Fig. 2A and B) and, as most of the soft sediments had been removed previously by the First Slide, it involves more consolidated sediments. Nevertheless, its deposits are the most extensive and far-traveled, being recognized as a turbidite at least 750 km out into the Norway Basin. Its generally more consolidated nature is particularly well reflected in the slide deposits, which are characterized by lumps and blocks up to tens and hundreds of meters across (Fig. 4b). Two very large far-traveled sediment slabs up to $0.2 \times 10 \times 30$ km in size were also associated with this Second Slide (Fig. 2E). Evidence from seismic profiles suggests that they probably originated from a scarp at about 1,000 m water depth, and were transported for a distance of 200 km on a slope of 0.3°. Similar but smaller blocks described as olistoliths within olistostromes were observed in the Bassein Slide, Bay of Bengal [8].

The Third Storegga Slide influenced only the central and upper part of the slide scar and the sediments involved were probably much the same in consistency as those of the Second Slide.

The volumes of sediments involved in the three slide events, and their thicknesses and run-out distances are given in Table 1. The volume of the First Slide is estimated to be about 3,880 km^3 and the Second and Third Slides together about 1,700 km^3. The total volume of about 5,580 km^3 makes this one of the worlds largest slides [4].

Slide Mechanism

The slides moved hundreds of kilometers on slopes of less than 0.6° within the slide scar and on slopes of less than 0.1° on the deep floor. We believe that the relatively soft and fine-grained sediments of the First Slide moved in the form of debris flows, and were partly deposited both within the slide scar and beyond it in water depths of 2,700 to 3,000 m, that is, about 350 to 400 km from the headwall. The Second Slide comprised mainly more consolidated sediments which probably slid on liquefied layers where excess pore pressure allowed the layers to act as lubricants below the sliding sediments. The seismic data shows that the main glide planes tended to follow certain seismic reflectors (Fig. 2D) which probably represented weak zones. Gas has been observed both as free gas in the sediments and as gas hydrates in the vicinity of the Storegga Slide (for example, Fig. 5), therefore, we suggest that the presence of gas may have accelerated the liquefaction and helped maintain the excess pore pressure during the sliding.

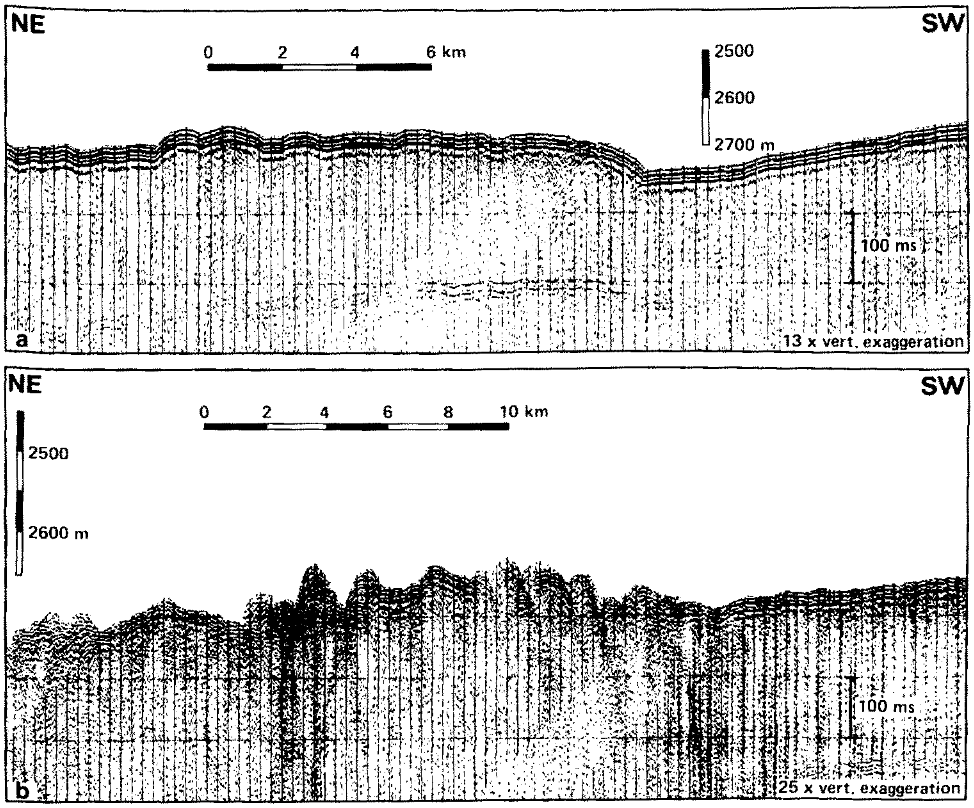

Figure 4. (a) A sparker record of the relatively homogeneous deposits of the First Slide, here in the eastern part of the Norway Basin, 250 km from the headwall of the slide. Note the fairly even surface and that the deposits here form a positive accumulation. A core recovered not far from this line contains 5.5 m of undisturbed glacial sediments deposited after the event of the First Slide. (b) A sparker record of the blocky and uneven deposits of the Second Slide.

There is evidence in some cores of a progressive increase in the liquefaction of the sediment failures which were deposited as coarse debris flow deposits in the basal sections and grade upwards into turbidites (Fig. 6). The most distal parts of the slide deposits consist of a sheet of fossil-free clay covering the entire deep basin of the Norwegian Sea at depths below the 3,500 m contour. Cores up to 6 m long were obtained from this deposit without reaching its base, while 3.5 kHz records indicate that its thickness may be as much as 20 to 30 m. We interpret the deposit to consist of distal turbidites comprised of the upper parts of a Bouma sequence [9]. Similar distal turbidites in the Mediterranean were described as unifites [10].

Age of Sliding

Micropaleontological investigations of the debris flow and turbidite deposits have shown that they contain a mixture of sediments that originated on the upper continental slope, and in the deep sea, as well as at depths intermediate between these areas. 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 of the Second Slide in the lower part of the slide scar.

The deposits of the First Slide have not been sampled by coring because they are covered either by de-

Table 1. Run-Out Distances, Dimensions, and Volumes of the Three Main Slide Events in the Storegga Area

	First slide	Second slide	Third slide	Total
Run-out distance	350–380 km	800–850 km	100–130 km	850 km
Area of slide scar	34,000 km^2	19,200 km^2	6,000 km^2	34,000 km^2
Total slide influenced area	52,000 km^2	88,000 km^2	6,000 km^2	112,500 km^2
Maximum thickness	280 m	330 m		430 m
Average thickness	114 m	88 m		160 m
Volume	3,880 km^3	1,700 km^3		5,580 km^3
Volume of deposits left in the slide scar today	400 km^3	950 km^3		1,350 km^3
Volume of deposits below 2,700 m	3,480 km^3	750 km^3		4,230 km^3

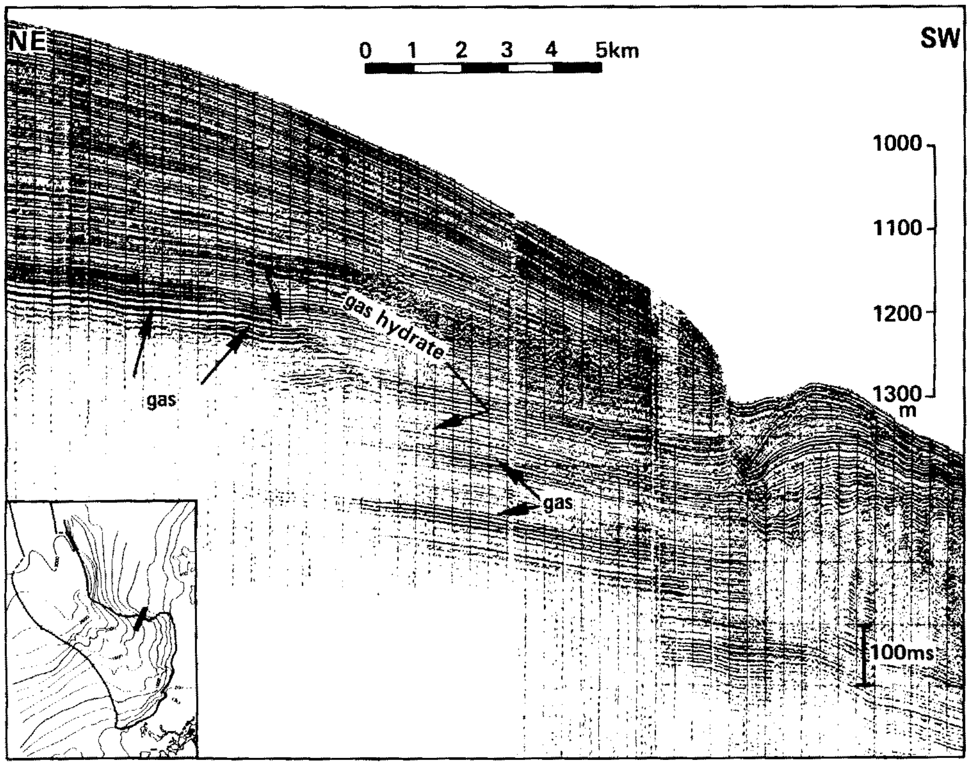

Figure 5. The presence of shallow gas indicated on a sparker record across the north-eastern margin of the First Storegga Slide. The gas is concentrated along bedding planes, probably as free gas, and in gas hydrates sub-parallel with the sea floor and crossing the bedding planes.

posits from later slide events or thick in situ glacial and Holocene deposits. Thus, no direct dates for this event can yet be provided. As mentioned above, cores with up to 6 m of undisturbed glaciomarine sediments have been described from areas influenced only by the First Slide [7,11,12]. Correlation of these sediments with the $\delta^{18}O$ record of neighboring cores outside the slide area indicates at least 30,000 years of undisturbed sedimentation since the first slide event.

A series of ^{14}C dates of pelagic and hemipelagic deposits overlying the most distal turbidites and from the main area of accumulation at the base of the continental slope indicate an age of 6,000 to 8,000 years B.P. for the Second Slide. Younger ages of 3,000 to 5,000 years B.P. obtained in three cores probably record smaller mass displacement events confined to topographic depressions that followed the main phases of the Second and Third slides.

The last major slide event in the Storegga area occurred almost entirely within the upper part of the slide scar of the Second Slide and travelled for a distance of only about 100 km. There is as yet no definite age for this slide. However, it seems to have occurred relatively soon after the Second Slide, perhaps as a final stage of that event when the seabed was still in motion.

Triggering Mechanism

Earthquakes are among the most frequently suggested triggering mechanisms for submarine slides, both for historical [13–16] and ancient slides [8,17–19]. On the basis of existing records of seismicity, it is concluded that earthquakes of magnitude 6.0 to 7.0 or even 7.5 might have occurred in the Storegga area over a time scale of 10,000 years [4]. Preliminary calculations of stability during earthquakes suggest that earthquake loading is the most probable triggering agent for the Storegga slides.

The continental shelf and extreme upper part of the slope in the Storegga area was probably covered in ice during the last-glacial period up to about 13,000 years B.P. [20]. The ice sheet could have introduced horizontal forces as well as an additional vertical load at the time of the First Slide. Calculations show, however, that this possible contribution, together with gravity forces of the displaced sediments, were probably too small to trigger the sliding [3].

Underconsolidation due to rapid sediment accumulation is known as a major triggering agent in other parts of the world [21–23]. Today the sedimentation rate is very low in the Storegga area. However, when the ice-front was stationed at the shelf edge, the sedi-

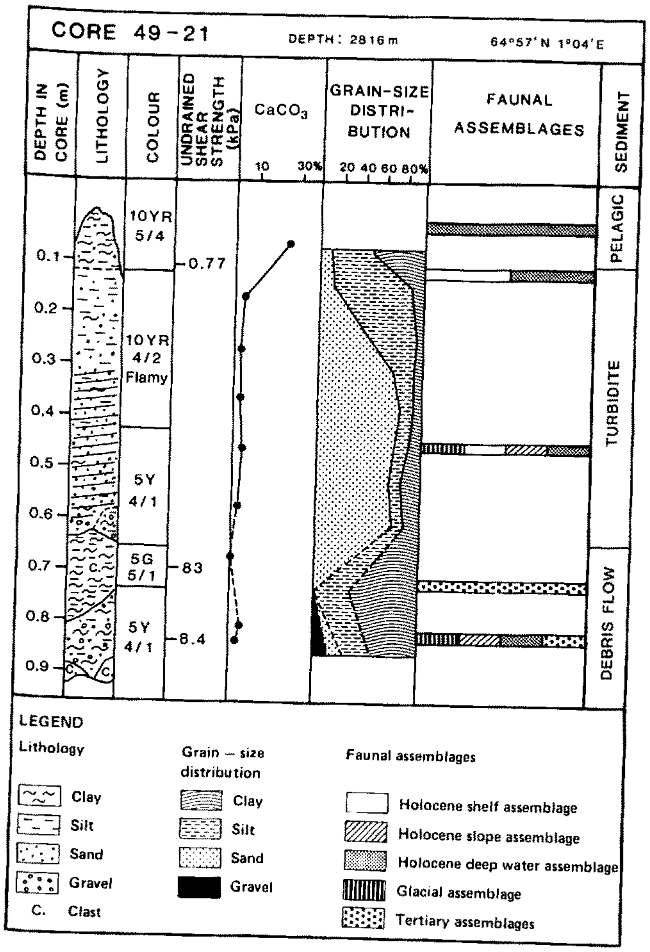

Figure 6. Core 49-21 (64°57'N, 1°04'E, 2816 m water depth) represents deposits of the Second Storegga Slide. Note the transition from debris flow deposits at the base to an upward fining turbidite. (Modified from Befring [5] and Eidvin [6].)

mentation rate might have been high enough to promote underconsolidation. Such conditions may have prevailed when the First Slide took place. Thus, underconsolidation can not be excluded as a possible contributing factor for the triggering of the First Slide.

Shallow gas accumulations, particularly in the state of gas hydrate (clathrate) are believed to have caused sliding on the U.S. Atlantic continental slope [24]. When the icelike crystalline lattice of water and gas is decomposed, water and free gas are released and may consequently weaken the sediments above the clathrate. In the Storegga area the presence of gas hydrates is indicated in seismic data by reflectors that are sub-parallel to the sea floor and that cross geological bedding planes at water depths of 975 to 1,100 m and subbottom depths of about 300 m immediately to the north of the slide (Fig. 5). As these supposed gas hydrates are at the same depth as parts of the gliding plane, we believe that decomposition of gas hydrates may have contributed to the triggering of at least the Second Slide, and to the liquefaction and, hence, downslope transport of the sediments as well. However, the main triggering mechanism for the slides was likely to have been earthquake loading, with another possible contribution of ice loading for the First Slide.

Conclusions

The Storegga Slide, with its 290 km long headwall, is one of the largest underwater slides so far described. The slide deposits probably extend more than 800 km into the Norwegian Sea, and at least 5,500 km^3 of Tertiary and Quaternary sediments were involved in the sliding. We distinguish three main slide events. The first probably occurred before 30,000 years B.P., and the second and third at 6,000 to 8,000 years B.P. The average slope gradient within the slide scar is 0.6°, while in the more distal parts, where sediments were transported in the form of debris flows and turbidity currents for a further 500 km, it is less than 0.1°. Individual very large sediment slabs 200 m thick and up to 30 km across slid 200 km down a slope of 0.3°.

The Storegga slides, together with extensive sliding observed further north on the Norwegian continental slope [4], clearly demonstrate how submarine sliding has been active in molding the continental margin off Norway. Hence, this study reinforces the view that sliding in various forms is a major agent in the evolution of passive continental margin morphology.

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