THE SOUTHERN FLANK OF THE STOREGGA SLIDE: IMAGING AND GEOMORPHOLOGICAL ANALYSES USING 3D SEISMIC

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Abstract

The Holocene Storegga Slide is one of the world's largest exposed slides and also the most studied of all the Norwegian slides. However due to its complexity it is far from being fully understood. Three-dimensional (3D) seismic combined with swath bathymetry data from the southern flank of the Storegga Slide have been used to study mass movement processes occurring in the region. The high spatial resolution provided by the 3D seismic data has allowed a detailed geomorphological analysis of sedimentary and deformational structures. The Holocene Storegga failure affected a significant part of the studied area. The predominant feature is a compression zone, comprising two lobes, where the seabed shows marked parallel ridges. Down slope it is possible to identify another compression zone. A relative chronology of events was established and it is proposed that these two compressions zones are the result of gravity-driven slope failures related to different stages of the Holocene Storegga Slide.

Keywords: 3D seismic, Storegga Slide, North Sea Fan, glacial debris flow, frontally confined submarine landslide.

1. Introduction

The Holocene Storegga Slide event was the last of a large number of palaeoslides that have occurred on the mid-Norwegian Margin (Bugge *et al.*, 1987, 1988; King *et al.*, 1996; Evans *et al.*, 1996, 2005; Nygård *et al.*, 2005). This last slope failure, which took place 8200 years ago, displaced between 2500 and 3500 km^3 of Pleistocene sediments (Haflidason *et al.*, 2005). The Storegga Slide depression separates the North Sea Fan (NSF) from the Vøring Plateau (Fig. 1). With an area of approximately 142 000 km^2 (King *et al.*, 1996), the NSF is one of the largest trough-mouth fans on the Norwegian Margin.

The main aims of this paper are: (1) to document the geomorphology and underlying stratigraphy using seabed and subsurface acoustic data of an area on the edge of the NSF; (2) to highlight the value of detail analyses of 3D seismic data; (3) to assess the recent history of mass movements events in the study area, and (4) to relate it with the development of the adjacent Holocene Storegga Slide.

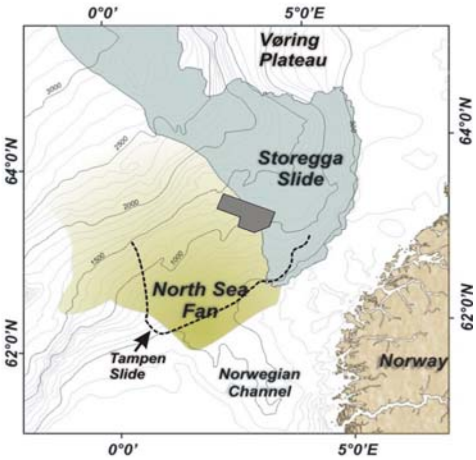


Fig. 1 – Lower section of Mid-Norwegian Margin bathymetrical map, with the location of its main features. The study area is marked in dark grey.

2. Data and methodology

This paper presents part of an extensive acoustic database gathered for interpretation of the mid-Norwegian continental margin (NDP, unpublished data 2004a,b): the seabed bathymetry provided by Norsk Hydro, covering the Storegga Slide scar, and Statoil's 3D seismic volume (LS0105) from the boundary between the NSF and the Storegga Slide (Fig. 1). The focus of this study was the morphologic features observed on the seafloor covered by the 3D seismic data (1610 km^2, extending from 980 m to 1370 m water depth).

The methodology used was based on the interpretation of 3D seismic data with a seismic interpretation package and a Geographic Information System (GIS), along with the seabed bathymetry. This study has involved stratigraphic interpretation and detailed mapping of the southern flank of the Storegga slide using the different acoustic datasets with the objective of generating an improved geomorphological interpretation of the area. This was carried out by obtaining digital elevation models (DEM) of key reflectors and their respective seismic attributes (e.g. amplitude map and amplitude coherence). Geomorphological characterization of several surfaces was then carried out using spatial analysis tools and interpretation of seismic attribute 3D images (i.e. draping the map attribute on top of the related DEM). The incorporation of the seismic information into a GIS environment has improved greatly the geological interpretation, allowing extended geomorphological analyses.

3. Slope morphology

The study area seabed can be sub-divided into five morphological zones, according to their characteristics as topography, seismic signature and degree of disintegration (Fig. 2). These morphological zones reflect distinct erosional, compressional and depositional processes acting at the seabed. The five zones will be named in this paper as: *Zone S* (Storegga main failure); *Zone Ch* (higher compression zone) subdivided in two lobes: *Ch*[1] and *Ch*[2]; *Zone Cl* (lower compression zone); *Zone B* (blocky debris) and *Zone U* (undisturbed North Sea Fan).

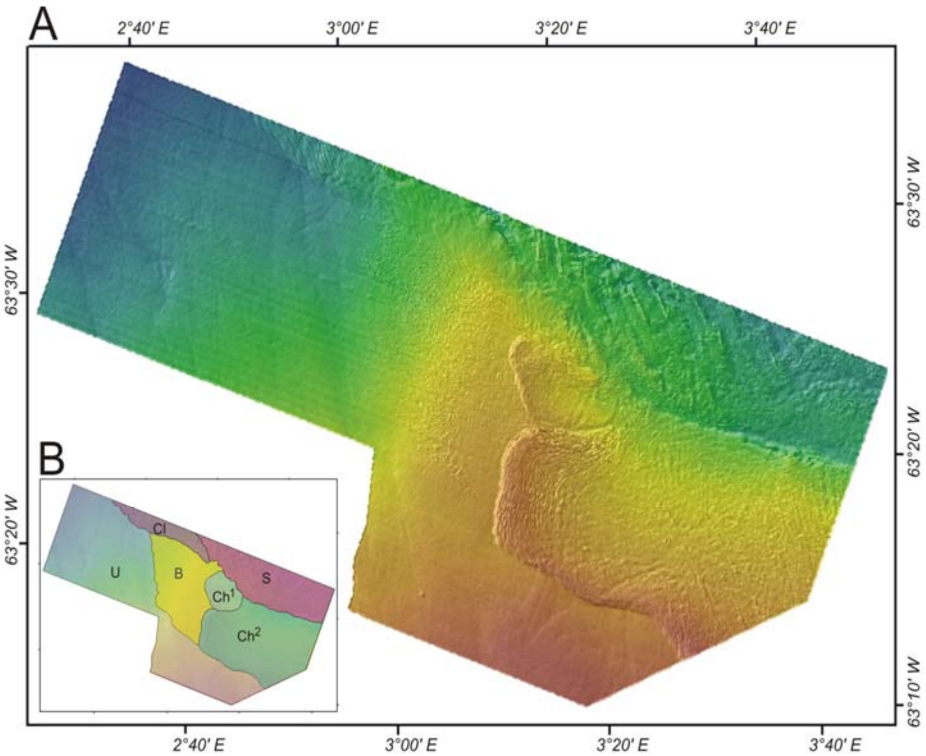


Fig. 2 (A) Image of the seabed from the 3D seismic volume, obtained by tracking the first seismic reflection. (B) Distribution of the five zones identified on the detail study area.

Zone S

Zone S corresponds to the seabed depression where the sediments appear largely remoulded by the Holocene Storegga deep failure. A progressive lost of coherence is observed heading upslope, from a seismic reflection character where it is still possible to recognize the original stratification to chaotic and transparent facies, through approximately 500 m (**Fig. 3**). The displaced Tampen Slide deposits can be easily recognized within a succession of "pop-up" blocks, closer to the edge due to compression, and within a succession of graben and horst blocks, due to escape of material and resulting extension (**Fig. 3**).

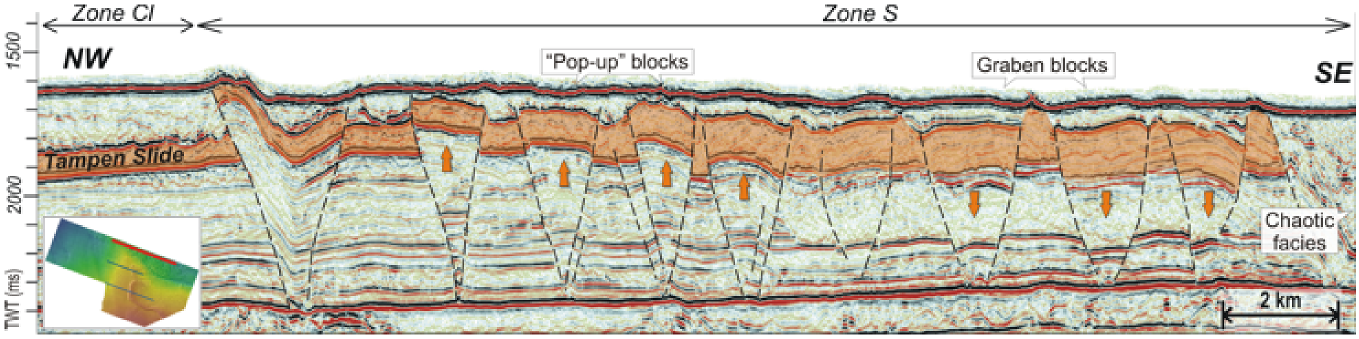


Fig. 3 – Section of the seismic profile across Zone S, showing a succession of "pop-up" blocks, of graben blocks and chaotic facies within the material remoulded by the Holocene Storegga deep failure. It is marked on the map the presented section (red) and Fig. 4 and 6 profiles (blue).

Zone Ch

The most prominent feature in this area is a compression zone (Zone Ch), situated at water depths varying from less than 985 m to 1370 m. It is a mass transport deposit characterized by crenulation or destruction of most of the seismic reflectors throughout the top 200 ms (TWT). This zone comprises two lobes (Ch^1 and Ch^2) and appears well preserved at the present-day seabed as sub-parallel ridges of ~150 m width over an area of 380 km^2 (**Fig. 4**).

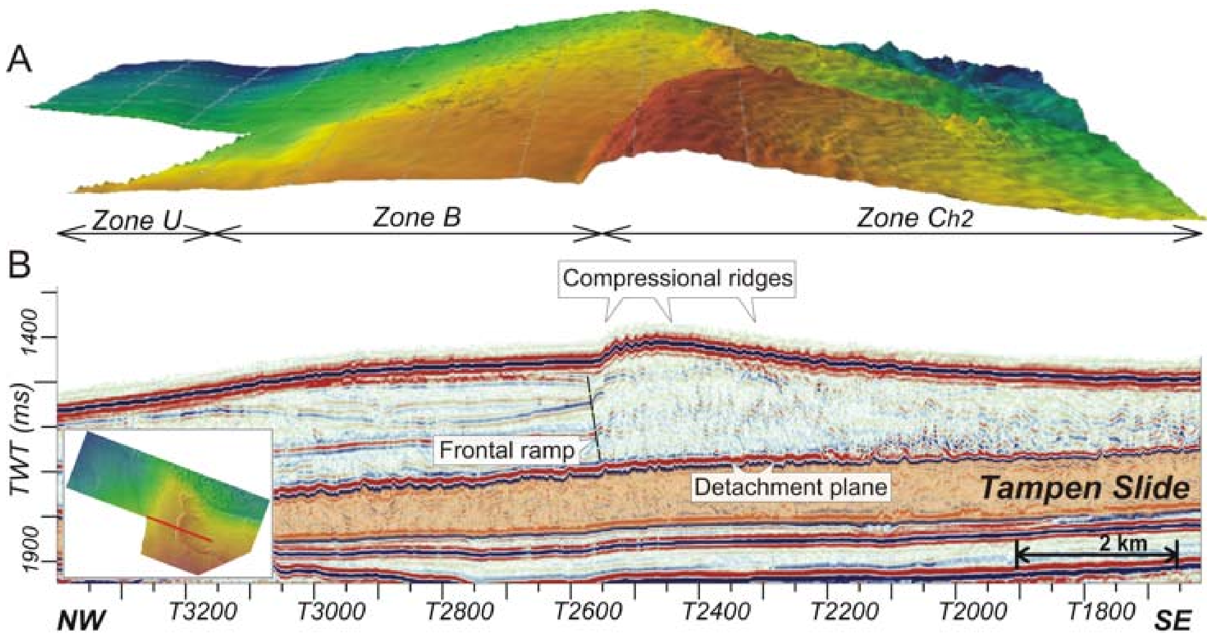


Fig. 4 *- (A) 3D perspective view of the present-day seabed cutting through Ch^2 looking towards northeast Note the height difference between the front of both lobes of compression, Ch^1 and Ch^2. (B) Seismic profile across the toe region of the Ch^2 zone, showing compressional ridges, frontal ramp and well-defined detachment plane following the top of Tampen Slide deposits.*

The deformation, by shortening and thickening of a succession of hemipelagic/glacimarine sediment units, has resulted in a sequence of low angle thrust faults. The thrust faults can be traced down to a well-defined detachment plane on the top of the Tampen Slide deposits. Near the seabed surface the thrust faults are expressed as concentric fold traces oriented transverse to the flow direction.

An area, 6x1 km, remains totally undeformed separating the two lobes Ch^1 and Ch^2 (**Fig. 5**). Both lobes are cut by the Holocene Storegga event giving a minimum age to these compression features. The smaller of the two lobes shows an internal boundary between the frontal area of the compression zone, with characteristic compression structures, and a central area where the material was considerably remoulded and no internal structure was preserved. This marked boundary presents a curved amphitheatre shape, with steep sidewalls and a flat base at the top of Tampen deposits.

Zone Cl

Down slope it is possible to identify another set of similar ridges related to a different compression zone, Zone Cl. Swath bathymetry shows that this compression zone, observed at the northern edge of the 3D seismic volume, extends west and north of the study area. This compression zone corresponds to a complex arrangement of thrust and fold systems that are approximately parallel and extend for tens of kilometres in the dip direction and are inline with the zone S. As in zone Ch, the detachment plane lies on top of the Tampen Slide. The seismic internal structure also resembles that described for zone Ch.

Zone B

A blocky deposit dominates Zone B, a region of 93 km^2 in the central part of the study area. This deposit includes detached tabular blocks of ~100 to 200 m in width and ~5 m high and is associated with chaotic layer on the seismic data (**Fig. 4 & 6**). The thickness increases towards the north. In addition, a well-developed detachment plane can be observed in front of the Ch^1, ~600 m apart from it (**Fig. 6**).

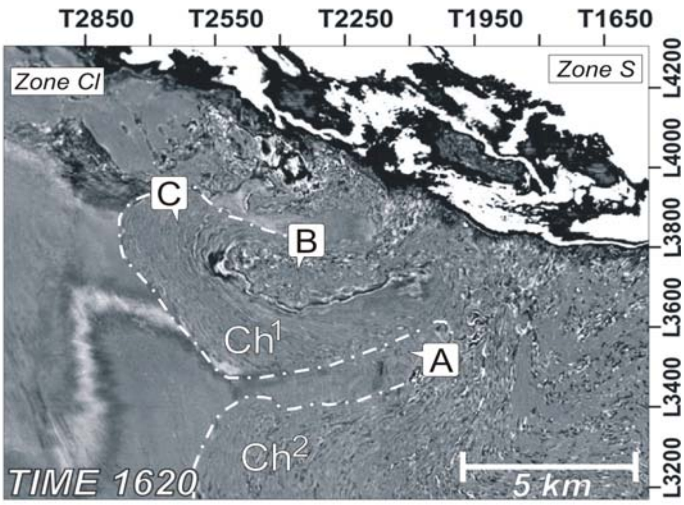


Fig. 5 *- Detail of a time slice through the 3D seismic volume at 1620 ms depth showing the sub-zone Ch^1 in the centre of the image. It is possible to identify the undisturbed area (A) between the two lobes and the Ch^1 internal boundary the frontal area of the compressional facies (C) and the chaotic facies (B)*

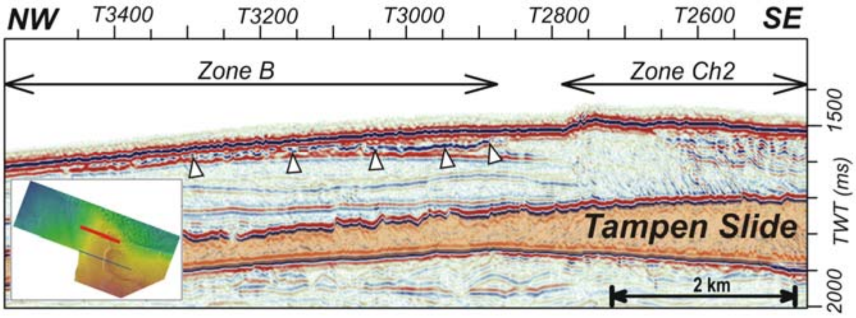
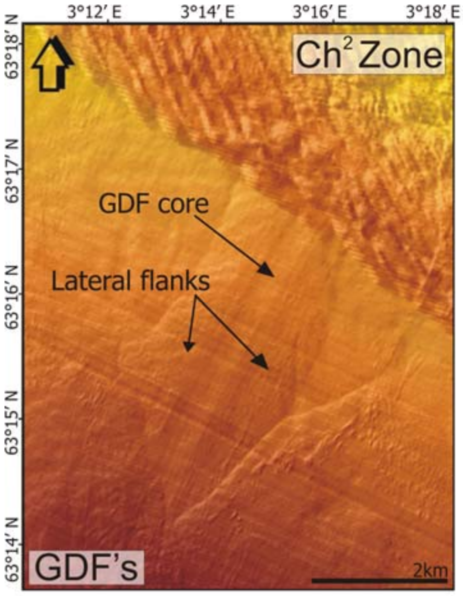


***Fig. 6** – Seismic profile across Zone B and Zone Ch[1] (Line 3800), showing the chaotic layer related to the blocky deposit identified at the seabed. Arrows point the base of the deposit. It is marked on the map the presented profile (red line) and profile on Fig. 4 (blue line).*



Zone U

In the areas of the North Sea Fan undisturbed by the Storegga Slide Complex (Zone U), it is possible to identify several glacial debris flow (GDF) deposits, from the last and uppermost sequence of glacigenic debris flows deposited during the Late Weichselian maximum (King et al. 1998).

These deposits indicate long run-out transport towards the north, showing from a very well developed central core with strong chute-flank separation suggesting a laminar movement within the GDF core (**Fig. 7**).

***Fig. 7** - Detail from the sea-floor image (obtained from the 3D seismic data) showing GDF's deposits, on the area adjacent to the Ch^2 zone. The central GDF deposit, 2 km width, with strong chute-flank separation displays marked flow lines concentrated along the core suggesting a laminar movement within the GDF core. This GDF deposit is partially covered by more recent GDF deposits.*

4. Discussion

The higher lateral resolution and three-dimensional capacities provided by the 3D seismic data have allowed a greater understanding of the geometries (internal as well as external) and relative chronology of the main sedimentary features. In this section some of its aspects are discussed and a summary model of seabed development that incorporates these main features is presented in Conclusions.

Low angle thrust faults that originated at the flow base and extend through to the top of the flow deposit are common features near the termini of mass transport deposits (Frey-Martinez *et al.*, 2006). These thrust faults are thought to be oriented transversely to the flow direction; this implies that the source of the material is ESE of the study area. Although zone Ch is interpreted as the termini of mass transported deposit, it does not exhibit the conventional picture of a fully developed slope failure; this failure did not break through or overthrusted the down-slope sediments. Nevertheless it presents all the main characteristics of frontally confined submarine landslides (Frey-Martinez *et al.*, 2006): compressional toe region buttressed by a frontal ramp, small bathymetric expression compared to the total thickness and implying a relative modest downslope movement **(Fig. 8)**. In addition, the compression zone Ch presents a gradual transition from a fragile environment, at the base of mass deposit (characterized by faulting), to a ductile environment, on the upper of the mass deposits (characterized by folding). This gradation must reflect the increase in shear strength and reduction in pore water with depth due to consolidation.

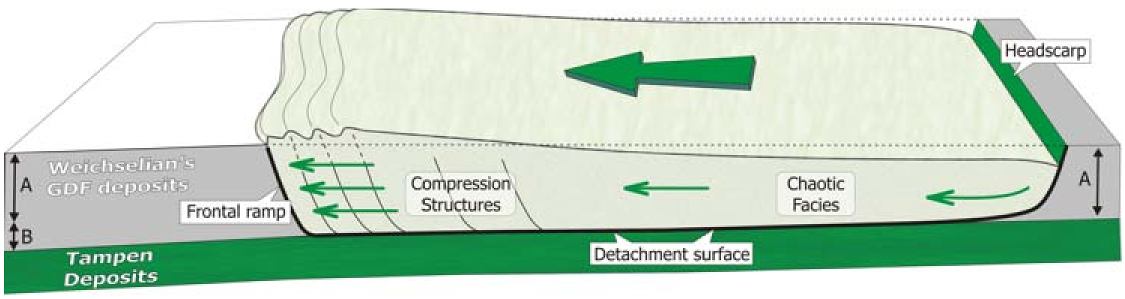


***Fig. 8** - Schematic representation of the internal structure of zone Ch. The mass translation stops against frontral ramp without abandoning the detachment surface that lies on top of Tampen Slide deposits; development of compression structures at the toe region and gradual lost of internal structure upslope. Note: The thickness of Weichselian GDF deposits increases significantly downslope. No real scale.*

Downslope translation stops when the stress developed by the mass movement becomes lower than the strength of the foreland. That can happen by lost of mass potential energy and/or by the increase of the foreland strength. Considering that the thickness on the sediments above the detachment plane (the top of the Tampen Slide) increases into the NFS **(Fig. 8)** is reasonable to believe that the propagation of the mass movement downslope was prevented by the increase of foreland strength resultant from increase of thickness.

The zone Ch previously interpreted as result of lateral compression formed during the north-dipping mass-flow classified as Lobe 5 (Haflidason *et al.*, 2004), is now consider being associated to main failure on the Ormen Lange area (Bryn *et al.*, 2005). In both interpretations, the zone Ch is referred as being part a major compression zone that incorporates both Ch and Cl zones. However the Ch zone must had occurred in an early phase of sliding than Cl, as the Cl compression zone is directly related with the main Storegga failure and Ch compression zone is cut by its failure escarpment (**Fig. 9** and **10B**).

Lobe Ch^1 presents a retrogressive failure resulting of the removal of toe support and increased shear strain during the main failure event. During this small-scale failure, the central part of Ch^1 collapsed and the sediments that had been previously deformed by compression where remould filling part of zone S (**Fig. 10C**).

These observations corroborate that the compression zone Ch predates the main failure. Nevertheless, it is uncertain how early this compression took place. Whether this compression zone reflects an early phase of the main movement or a significantly earlier phase? If they were part of the main event, what is the implication for the retrogressive model proposed for Storegga? Further observations, outside of the main study area, are required to constrain the timing of Ch formation.

Other aspect of the evolution of the present-day seabed that is not totally understood and require further study is the timing and nature of Zone B. This blocky deposit is thought to be associated with sediment overbanking of the Storegga main failure, followed by localized slope instability in front of the compression zone.

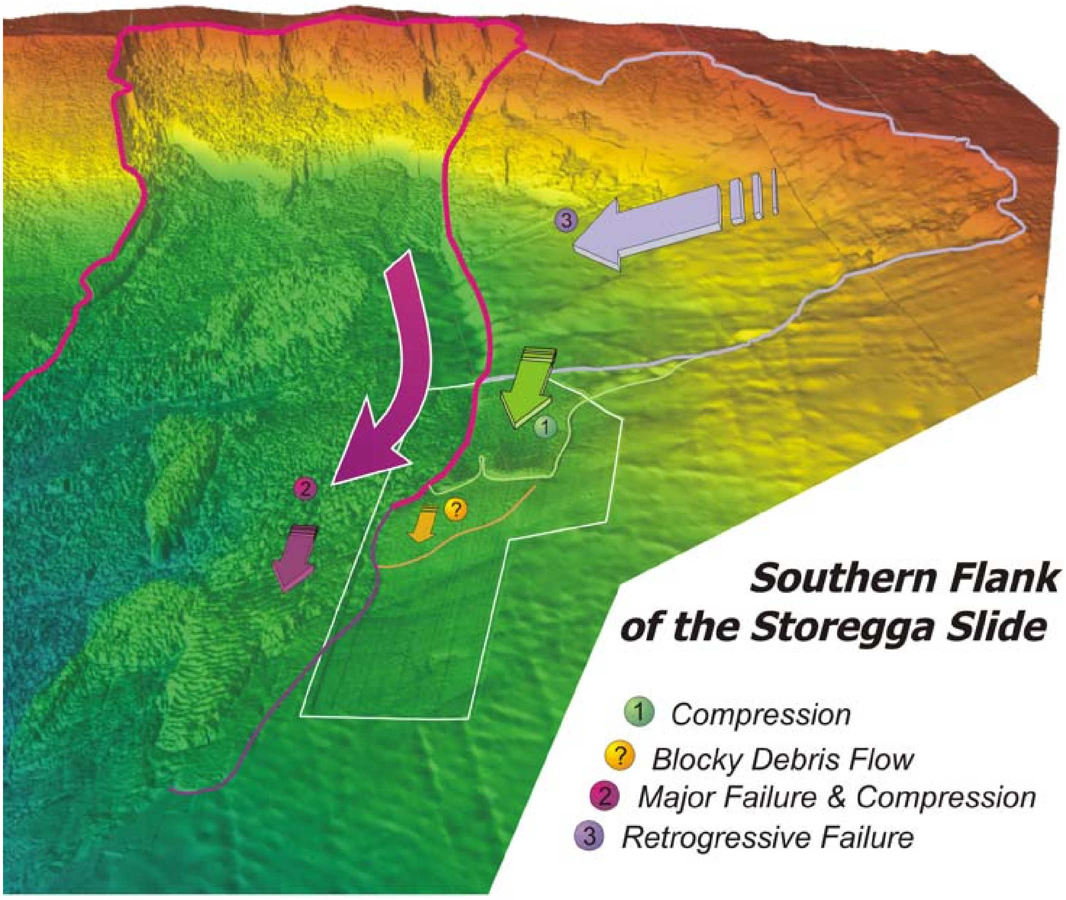


Fig. 9 *– 3D perspective view of the southern flank of the Storegga Slide (Norsk Hydro bathymetry) looking eastward, with suggested chronology for the major events leading to the formation of the present-day morphology.*

5. Summary and Conclusions

3D seismic interpretation followed by geomorphologic analyses on the Southern Holocene Storegga Flank has shown the existence of five distinctive morphological zones in the study area. These zones have been given the informal names of: Zone S - where the slope sediments were remoulded; Zones Cl and Ch (1 and 2) - where the seabed has marked ridges resulting from compression of the sediments; Zone B - dominated by blocky deposits and Zone U - where the NSF sediments are undisturbed. The most prominent feature in this area is the compression zone Ch. This compression zone presents features described as characteristic of *frontally confined submarine landslides*. The base of the deformation lies on top of the Tampen Slide deposits. Although the exact timing of the formation of this compression zone and the other features described in this paper was not determined, a relative chronology has been established and can be summarized in the following way:

1) Tampen slide at 150 ka BP (0.15 Ma)
2) Deposition of Weichselian debris flow sediment from 24 to 13 ka BP; NSF build-up
3) Failure remote from study area to the east; some NSF sediments pushed by impact into compressive structures, formation of compression zone Ch (**Fig. 10A**)
4) Major failure continues downslope, originating Zone S that truncates Zone Ch; formation of compression zone Cl by response to the impact (**Fig. 10B**)
5) Due to lack of lateral support the northern lobe of the compression zone Ch, sub-zone Ch^2, collapsed into the major Storegga erosion area, zone S (**Fig. 10C**)

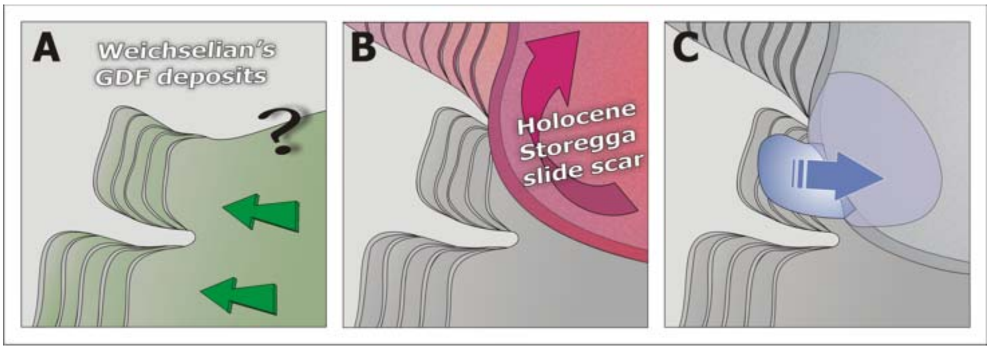


Fig 10 *- Sketch representation of the three main events shaping the seabed in the proximities of Zone* Ch^1*. (A) Formation of compression zone Ch. (B) Main slide, cut of zone Ch and formation of zones S and Cl. (C) Collapse of the sub-zone* Ch^2*.*

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