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1 Long-term slope instability induced by the reactivation of  
2 Mass Transport Complexes: An underestimated geohazard on  
3 the Norwegian continental margin

4  
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13

14    **ABSTRACT**

15           Submarine landslides are significant geohazards, capable of displacing large volumes  
16 of sediment from continental margins to deposit mass-transport complexes (MTCs) and  
17 generate offshore tsunamis. However, the reactivation of MTCs after their initial failure has  
18 long been overlooked. By analysing high-quality three-dimensional seismic reflection data  
19 and seismic attribute maps, as well as comparing the geometry of different MTCs, we  
20 investigate the development of long-term slope instability and its hazardous consequences on  
21 the northwest flank of the Storegga Slide. Our results demonstrate that the reactivation of  
22 MTCs can deform both their inner structure and overlying strata, promoting the formation of  
23 sinuous channels and local slope failures on the seafloor. These findings further reveal the  
24 MTCs that are underconsolidated or comprise slide blocks may remain unstable for a long  
25 time after their initial failure, particularly when affected by slope undercutting and a  
26 corresponding reduction in lateral support. This study shows that MTC-prone sequences are  
27 more likely to comprise regions of continental slopes with long-term instability and recurring  
28 marine geohazards.

29

30    **Keywords:** Storegga Slide; Slope instability; Laterally spread blocks; MTCs' reactivation;  
31    Geohazards.

32

33

## 34 INTRODUCTION

35 Submarine landslides are a major source of seafloor deformation and hazardous  
36 tsunamis, being capable of damaging both subaqueous and coastal infrastructures in single or  
37 multiple events (Harbitz et al., 2006; Talling et al., 2007; Sun et al., 2018a). Previous  
38 research concerning slope instability processes usually separates major and long-term  
39 precondition factors such as high sediment supply, overpressure and slope oversteepening,  
40 from short-term triggers that include earthquakes, volcanism and human activity (Leynaud et  
41 al., 2009; Urlaub and Hjelstuen, 2020). A comprehensive evaluation of submarine landslide  
42 likelihood, landslide distribution, preconditioning factors and any episodic triggers is  
43 therefore crucial to a complete assessment of long-term slope instability (Masson et al., 2006;  
44 Leynaud et al., 2009).

45 Mass transport deposits (MTDs) and mass transport complexes (MTCs) are terms  
46 used interchangeably in the literature, representing distinct phenomena, scales of analysis,  
47 and degrees of instability (Alves et al., 2022). Mass movements in nature can be generalized  
48 into a term representing a wide spectrum of deposits, the so-called mass transport complexes  
49 (MTCs), particularly when their strata are clearly associated in space and time (Pickering and  
50 Hiscott, 2015). Single failure events eroding parts of a continental slope and depositing  
51 discrete intervals of failed, convoluted beds, are usually referred to as mass transport deposits  
52 (MTDs) (Wang et al., 2017; Shanmugam, 2021). Thus, MTCs are usually thicker and  
53 represent long-lasting slope failure when compared with the more episodic, discrete MTDs  
54 (Alves, 2015).

55 MTCs can develop for several millions of years and are usually recognized via the  
56 interpretation of seismic and borehole data and outcrop expression in both marine  
57 environments and exhumed orogenic belts (Solheim et al., 2005a; Pini et al., 2012; Ogata et  
58 al., 2019b). They can be several thousands of cubic kilometers in volume, presenting varied

59 internal kinematic indicators and heterogeneous internal structures (Bull et al., 2009a;  
60 Urgeles and Camerlenghi, 2013; Dalla Valle et al., 2015; Moscardelli and Wood, 2016;  
61 Omosanya, 2018; Ogata et al., 2019a). After both MTCs and MTDs are deposited,  
62 differential compaction processes in their interior can further influence the overlying slope  
63 morphology by generating local depressions and fractures near the seafloor (Alves, 2010).

64 Despite their significance in the geological record, MTCs have seldom been  
65 considered in the literature to be the sources, or triggers, of further slope instability. This  
66 most likely owes to the limited resolution of seismic reflection data, which could not clearly  
67 differentiate MTCs' reactivation from 'syn-failure' depositional features and structures.  
68 Nevertheless, the reservoir and seal potentials of MTCs have attracted the energy industry's  
69 interest in the past few years, raising important concerns regarding the instability and  
70 geohazard potential of large swathes of continental margins in which they occur (Alves et al.,  
71 2014, 2022; Cox et al., 2020).

72 In this study, high-resolution three-dimensional seismic reflection data are used to  
73 characterize slope instability in the understudied northwest flank of Storegga Slide on the  
74 Norwegian margin, where submarine landslides have occurred during the Quaternary  
75 glaciation period (Bryn et al., 2003; Solheim et al., 2005) (Fig. 1a and 1b). Geochronological  
76 and bathymetric data have previously highlighted the significance of long-term slope  
77 instability in other parts of the Storegga area by recognizing multiple slide scarps and  
78 channels in MTCs (Haflidason et al., 2004, 2005). This research further identifies a series of  
79 post-failure features associated with MTCs. It shows that MTCs can deform the seafloor well  
80 after their initial emplacement, highlighting the presence of long-term instability in the areas  
81 where they occur. Together with their triggers and development, this paper shows that the  
82 deposited MTCs could still be unstable in long term and may lead to an underestimation of  
83 subaqueous geohazards.

84

## 85 DATA AND METHODS

86 This work uses time- and depth-migrated 3D seismic data and one exploration well  
87 (6403/6-1) from the mid-Norwegian margin (Fig. 1a). The seismic data cover 263 km<sup>2</sup> of the  
88 northwest flank of the Storegga Slide, over the south Modgunn Arch (gray-shaded area in  
89 Fig. 1a). The summit of this arch was drilled by well 6403/6-1, providing lithostratigraphic  
90 and wireline information such as formation tops, depth and bulk density of drilled strata.  
91 Therefore, relative dates for seismic-stratigraphic units are based, in this work, on seismic-  
92 well ties and published information from the Norwegian margin (Berg et al., 2005; Jing et al.,  
93 2020).

94 Seismic interpretation uses Schlumberger Petrel<sup>®</sup> and includes the compilation of  
95 relevant two-way time (TWT) structural and seismic-attribute maps. In order to visualize the  
96 multiple MTCs and structures identified on seismic, we compute RMS amplitude, TWT  
97 structure and variance maps for key seismic horizons and geological features. TWT structure  
98 maps are computed for the seafloor (horizon H1) and glide planes of interest. Slide scarps,  
99 fractures, slumped strata, and submarine channels are features with high variance and high  
100 RMS amplitude, whereas small-scale MTCs comprise high-relief, low-variance features. The  
101 geometry of channels, furrows and blocks, including their sinuosity, dimensions and  
102 orientations, are also analyzed in this work.

103

## **GEOLOGICAL SETTING**

### **Lithostratigraphy**

The study area is located on the northwest flank of the Storegga Slide, at a latitude of around 64°N on the mid-Norwegian margin, where the continental slope rises in two directions, both northeastward and southeastward (Fig. 1a). Based on Exploration Well 6403/6-1, the lithostratigraphy of our study area can be divided into a breakup sequence (below horizon H6 in Fig. 1d) and several post-breakup units above (Jing et al., 2020). The breakup sequence was not deformed by slope instability processes. In contrast, post-breakup units between horizons H6 and H1 were deformed, eroded and evacuated by recurrent slope failures (Figs. 1c and 1d). These post-breakup strata are stratigraphically equivalent to the Brygge, Kai and Naust formations (Fig. 1d).

The Kai and Brygge formations, upper Eocene to upper Pliocene in age and respectively placed between horizons H4-5 and H5-6 (Fig. 1d), are composed of marine claystone with intervals of sandstone, siltstone, limestone and marl (Dalland, 1988). Biogenic ooze, with relatively high porosity and water content - when compared with clay or sand - predominates in these two formations (Lawrence and Cartwright, 2010). Between horizons H1 and H4, the Naust Formation has accumulated from the Early Pleistocene to the present day, comprising alternating glacial and marine deposits (Bryn et al., 2003). Long-term slope instability in the Naust Formation is document by multiple headwall and lateral scarps, channels, and accompanying MTCs (Bryn et al., 2003; Haflidason et al., 2004, 2005; Kvalstad et al., 2005; Baeten et al., 2014). Importantly, these MTCs are potential unstable in the long term due to their high clay content, which prevents the recovery of shear strength after their deposition and allows additional deformation (Lewis et al., 1998; Dellisanti et al.,

2008; Camerlenghi and Pini, 2009; Sawyer et al., 2009; Mesri and Huvaj-Sarihan, 2012; Conti et al., 2014).

### **MTCs near the Storegga area**

The structure of MTCs can be recorded by the seismic character and kinematic indicators they present, such as grooves, scarps, fractures and slide blocks (Bull et al., 2009a; Alves, 2015). In the Storegga area, multiple MTCs overlapped each other along with the occurrence of the Storegga Slide complex, including the Slide W, Slide S, Slide R and the Storegga Slide (Bryn et al., 2003; Solheim et al., 2005b) (Figs. 1a, 1c and 1d). Higher on the continental slope, bathymetric and seismic data image several MTCs with slide blocks, correlating with Slides S and R, formed above gentle glide planes with gradients of less than 2° (Gauer et al., 2005; Micallef et al., 2007; Bull et al., 2009b) (Figs. 1c and 1d). At least two types of seismic facies have been observed in these MTCs: a) chaotic to transparent facies with grooves and flow-like features denoting greater transport distances, and b) discontinuous stratified facies comprising slide blocks whose movement was relative limited (Gauer et al., 2005; Solheim et al., 2005a; Micallef et al., 2009; Sawyer et al., 2009).

### ***Slide W***

Slide W materializes the oldest failure event of the Storegga Slide complex, having occurred before 1.7 Ma (Bryn et al., 2003; Solheim et al., 2005) (Fig. 1a and 1d). The relief map of its basal glide plane reveals local depressions, previously interpreted as craters or ooze evacuation structures (Riis et al., 2005; Lawrence and Cartwright, 2010). Above the basal glide plane, MTCs with basal striations, inner imbrications and ooze mounds suggest recurrent slope failure during ooze evacuation (Riis et al., 2005; Jing et al., 2022; Omosanya



et al., 2022). Except for slide blocks along their sidewalls, these MTCs comprise transparent to chaotic seismic facies (Riis et al., 2005; Lawrence and Cartwright, 2010; Omosanya et al., 2022). On the northwest flank of the Storegga Slide, three craters are observed cutting into the Brygge Formation (C1 to C3 in Omosanya et al., 2022). In study area, these Slide W MTCs have been eroded and removed by subsequent slope failure events, leaving an ‘L’-shaped ramp on the modern seafloor (Jing et al., 2020, 2022) (Figs. 1b and 1c).

### ***Slides S and R***

Slides S and R occurred in the Storegga area at respectively ~ 0.5 Ma and ~ 0.3 Ma (Berg et al., 2005) (Fig. 1a, 1c and 1d). These two slides comprise debrites and blocks with chaotic to stratified seismic characters (Bryn et al., 2003). In the upper part of these two slides, nearly intact and rotated slide blocks are observed above well-defined glide planes (Bryn et al., 2003; Solheim et al., 2005). Scarp S5 in our study area seems to separate Slides S and R (Fig. 1b, 1c and 1d), but further interpretation indicates that Slide S was capable of triggering the development of Slide R further up on the slope (Bull et al., 2009b). This opens questions about the true relationship between Slides S and R and how their interaction was able to promote long-term slope instability in the study area.

### ***Storegga Slide***

The Storegga Slide, as the most recent slope failure of the Storegga Slide complex, affected a total area of 90,000 km<sup>2</sup> since around 8200 ya (Bryn et al., 2003) (Fig. 1a and 1d). Subsequent structures, such as scars, scarps and MTCs, are exposed on the modern seafloor, denoting variable features such as closely spaced blocks along their headwalls and compressional structures (toe thrusts) on the lower part of the continental slope (Haflidason et

al., 2005; Bull et al., 2009a). Debris and turbidity channels can be recognized as linear structures with particular seismic characters, such as chaotic seismic reflectors with higher variance and amplitude (Haflidason et al., 2004). Seismic data and sediment cores from the northern flank of the Storegga Slide indicate that local slope failure has continued for ~5000 yrs after its main episode (Haflidason et al., 2004, 2005). This observation once more suggests long-term slope instability in the study area.

## **Development of MTCs Comprising Slide Blocks**

MTCs with closely spaced and tilted coherent blocks are observed on bathymetric and seismic data all over the mid-Norwegian margin, and also near the Storegga Slide, generating a rugged seafloor (Solheim et al., 2005a; Micallef et al., 2007). Below these blocks, seismic and sediment core data reveal a layer-parallel glide plane that propagates at present into intact layers on the upper continental slope after lateral support was lost by the undercutting of the lower continental slope (Locat et al., 2016; Giona Bucci et al., 2022). These layers comprise soft marine clays interbedded with (harder) glacial deposits, resulting in weak layers with lower shear strengths, higher sensitivity and excess pore pressures when compared to the confining strata (L'Heureux et al., 2012; Ogata et al., 2014; Locat et al., 2016; Gatter et al., 2021; Wu et al., 2022).

Propagating glide planes can eventually disrupt the overlying strata to form local fractures and slabs on the upper continental slope (Laberg et al., 2013; Zhang et al., 2021). These slabs can then be softened, fractured and fragmented by high dip-angle fractures, ending up as a series of laterally spread blocks on a gentle submarine slope (Micallef et al., 2007; Baeten et al., 2014; Wu et al., 2021). Due to internal softening, deformation and sediment liquefaction, the size of these blocks often decreases with their transporting

distance, before they are completely fragmented and liquefied into debrites and turbidity currents (Bull et al., 2009a; Alves, 2015; Cox et al., 2020).

## **RESULTS**

### **Channels in MTCs with Differing Sinuosity Values**

The northwestward transport of Storegga Slide has been recorded by seafloor grooves near the slide scar and intervals with discontinuous to chaotic seismic reflections (Haflidason et al., 2004) (Figs. 1a and 1d). Detailed bathymetric and structure maps reveal the northwest flank of the Storegga Slide (study area) as dipping to the southwest, with multiple small-scale failures post-dating the Storegga Slide and five distinct terraces delimited by scarps - terraces 1 to 5 and scarps S1 to S6 (Figs. 1b and 1d). Structural relief varies significantly on these terraces, from the smooth seafloor in Terrace 5 to the rugged 'L'-shaped Terrace 1 undercutting through scarps S1 to S3 (Figs. 1b and 1c).

In this study area, MTC 1 is recognized in the lower continental slope to fills ooze evacuation structures (craters) below, perhaps as a result of focused fluid flow and sediment density reversal during Slide W (Riis et al., 2005; Lawrence and Cartwright, 2010; Omosanya et al., 2022). Above MTC 1, MTC 2 can be distinguished by its glide plane (Horizon H2) that eroded the top of MTC 1, where a group of NW-striking furrows is recorded in Terrace 2 with a sinuosity approaching 1.01 (Horizon H2; Figs. 1d, 2a, 3d, and 4). Towards the seafloor, a group of NW-striking grooves observed on both the relief and variance maps of Terrace 2 reveals a similar location and geometry to the glide-plane furrows below (Figs. 3a, 3d and 4). Seafloor grooves and underlying furrows have identical orientations and length, as well as the same location and geometry (Figs. 4c and 4d), representing the significant differential compaction within MTC 2.

Apart from these seafloor grooves representing glide plane furrows, discrete northwestward channels are recorded in MTC 2 by their differing variance and amplitude value on the seafloor, correlating to the transport of MTCs derived from the upper continental slope during the main Storegga Slide (Haflidason et al., 2004; 2005) (see Figs. 2c, 2d, 3b and 3c). These channels have an average sinuosity of 1.18 in Terrace 2, crossing the relatively straight grooves (Figs. 3b, 3c, 4c and 5). Beyond the 5km wide 'L'-shaped ramp, the channels in the southeast side upper slope reveal gently curved features with sinuosity about 1.02 (Figs. 2 and 5). The multiple grooves and sediment waves observed inside the turbidite channels differentiate them from debris channels, which contain chaotic strata with high variance coefficients (Fig. 2d).

#### **MTCs with Slide Blocks**

Due to the post-Storegga sediment drape is not voluminous and thick enough to cover failure-related features on the slope, the Storegga Slide scar and correlating MTCs are still exposed on the modern seafloor (Haflidason et al., 2004). Below the smooth seafloor of Terraces 4 and 5 (Fig. 6), two intervals with MTCs are identified as Units 1 and 2 (Figs. 7 and 8). Geochronological data indicate these MTCs, resulted from Slides S and R, can be respectively dated around 0.5 Ma and 0.3 Ma (Solheim et al., 2005) (Figs. 1d and 7). Despite the fact that these two slides encompass hundreds of square kilometres on the Norwegian margin, blocky features are only observed on the gentle north flank of the Storegga Slide, including our study area (Figs. 1 and 6).

In seismic data, slide blocks can be identified as a series of sub-parallel, coherent strata separated by chasms (Micallef et al., 2007) (Fig. 6). The development of these blocks on gentle slopes has been attributed to a reduction in lateral and toe support along with a

propagation of glide planes through stratigraphic weak layers (Gauer et al., 2005; Kvalstad et al., 2005) (Fig. 7). These layer-parallel glide planes remove the support to overlying consolidated strata where internal friction angle could up to 20-30 degree, resulting in the generation of unstable slabs and subsequent fragmentation by steep (around 70-degree) fractures, forming laterally spread square-shaped blocks (Micallef et al., 2007; Wu et al., 2022).

#### ***Slide S Blocks in Terrace 4***

Blocks in Slide S were translated above discrete glide planes identified at different stratigraphic levels (see ‘shift point’ in Fig. 7c). Above these glide planes, most blocks are curved on variance time slices (Fig. 6c). Blocks are 1000-2000 m apart and up to 80 ms tall (Fig. 7). Their length (L) varies from 800 m to 3600 m, while their width (W) ranges from 200 m to 600 m (Fig. 9). These slide blocks become larger downslope, where an eroded and irregular megablock is recognized (Figs. 6c and 7b). Moreover, a series of en echelon cracks are found to cut through Unit 1 on the back of the headwall scarp where the slide blocks originated from (Figs. 7b and 8a). The width of these cracks reaches only a few tens of meters, while their length ranges from 1 km to 5 km. Between these sub-parallel cracks and headwall scarps, incipient blocks and slabs are also identified (Fig. 8a).

Strata in Unit 2 comprise contourite deposits (Figs. 6a and 7c). Seismic reflections are continuous in chasms between Slide S blocks but folded and faulted above these same blocks (see the near-seafloor folds in Fig. 6a, and the faults above block 7 in Fig. 7b). Along the upper part of Terrace 4, these faults terminate at the glide planes of small-scale slumps formed near scarp S5 (Figs. 6b and 7b). On the lower part of Terrace 4, these same faults form scarps on the seafloor, such as the S4.1 – S4.4 above slide blocks 1 to 4 in Figs. 6b and

7c. Sourced from these scarps, the subsurface channels cross Scarp 4 and terraces 3 and 4, post-dating them after the main Storegga Slide (Figs. 1c, 6a-6b).

#### ***Slide R Blocks in Terrace 5***

Slide R blocks are only observed in Terrace 5, occur in Unit 2, and are relatively small (see blocks on both sides of scarp S5 in Fig. 7b). Slide R blocks are closely spaced and up to 80 ms tall (Fig. 7a and 7b). Their length (L) varies from 800 m to 3600 m, with a width (W) from 200 m to 600 m (Figs. 8c, 8d and 9). Longitudinal blocks and chasms close to scarp S6 show a N-S strike, which is perpendicular to the local slope gradient (Fig. 8c). In contrast, blocks close to scarp S5 are more fragmented and strike to the NW (Fig. 8d). Behind scarp S5, a group of en echelon chasms is recognised between Slide R blocks (see ‘chasms in Unit 2’ in Fig. 8b). In contrast to other chasms, these en-echelon chasms are underlain by cracks developing in Unit 1, sharing a similar geometry, location, strike and length (see ‘cracks in Unit 1’ in Fig. 8a).

## **DISCUSSION**

### **Sinuuous Channels Formed by MTCs’ Remobilization**

In MTC 2, groups of channels present a sinuosity ranging from 1.02 in the southeast side upper slope to 1.18 in Terrace 2, where glide plane furrows are observed. These channels may record the transport direction of MTC 2, having developed together with its emplacement. However, the sinuous path they present in Terrace 2 does not correlate with the straight furrows observed on its glide plane, or the later slide complex would have been transported in multiple directions. Therefore, we interpret these sinuous channels to have

developed after the onset of movement in MTC 2, during which the relatively straight furrows on its glide plane were able to erode MTC 1. Moreover, no marked changes of slope geometry, which could have increased the sinuosity of overlying flow, can be observed in MTC 2. This suggests that channels in Terrace 2 were as straight as those on the upper continental slope during their initial development.

The presence of undercut areas on the modern seafloor, and stratigraphic data from sediment cores, suggest a southwestward slope failure has partially evacuated MTC 2 through the 'L'-shaped ramp soon after the main Storegga Slide (Haflidason et al., 2005; Micallef et al., 2009) (Figs. 1b and 1c). Slope instability associated with this failure could not be limited to this 'L'-shaped ramp, as the failed MTC 2 is also observed in Terrace 2 (Figs. 2 and 4). The evacuation of MTCs through Terrace 1 (the lower section of 'L'-shaped ramp) also exposed the southwest scarp (S2) of Terrace 2 (Fig. 4). This enhanced the instability of MTC 2 in Terrace 2 by reducing its lateral support, and thus contributing to its remobilization.

Together with the coexistence of straight channels on southeast side upper continental slope (Fig. 2) and straight glide-plane furrows in Terrace 2 (Fig. 3d), the sinuous channels in Terrace 2 are here related to the remobilization of MTC 2 after its lateral support was removed. This remobilization did not evacuate the entire MTC 2 from Terrace 2 but was enough to deform MTC 2 internally, increasing the sinuosity of pre-existing channels. The development of MTC 2 and accompanying channels followed the sequence of events below:

- 1) MTC 2 was first mobilized during the initial NW transport of Storegga Slide and later deposited along the northwest flank with low-sinuosity internal channels and glide-plane furrows (Figs. 2, 3d, 4d and 10a).

- 2) Soon after, a southwestward slope failure sourced from the northwest flank undercut MTC 2 through a 'L'-shaped ramp, exposing Scarp S2 on the seafloor (Figs. 1b and

318 3a). Due to insufficient lateral support near Terrace 2, the still unconsolidated MTC 2 was  
319 remobilized and began to move over the evacuated ramp, deforming the internal channels  
320 previously formed (Figs. 3b, 3c, 4c and 10b).

321 3) Since then, differential compaction has followed the trace of glide-plane furrows at  
322 the base of MTC 2, forming grooves on the modern seafloor that cross the sinuous channels  
323 formed during the remobilization in the previous stage (Fig. 4c and 10c).

### 325 **Effect of MTCs' Reactivation on Post-failure Strata**

#### 326 ***The Reactivated MTCs (Slide S) Impacts the Development of Slide R***

327 Slide R comprises laterally spread blocks has been thought to remain stable since they  
328 were formed, as no fractures or seafloor cracks can be observed within the overlying strata.  
329 However, the chasms between Slide R blocks (Fig. 8b) and the underlying cracks in Unit 1  
330 (Fig. 8a), with matching geometries to the chasms, indicate a later episode of local extension.

331 The layer-parallel glide planes and overlying square-shaped blocks suggest that the  
332 development of Slide S was accompanied by the propagation of its glide plane upslope,  
333 resulting in a series of extensional cracks in Unit 1 (Figs. 7b and 8a). While the chasms  
334 preserved between Slide R blocks appear to be controlled by the underlying cracks in Slide S,  
335 it is possible that cracks associated with Slide S propagated into Unit 2 as longitudinal  
336 chasms during Slide R movement (see the red dashed line in Figs. 8a and 8b). In addition, the  
337 reactivation of Slide S is attributed to the evacuation of Slide S blocks and subsequent  
338 reduction in lateral support (Bull et al., 2009b). Therefore, our seismic interpretation suggest  
339 that a reactivated Slide S was able to induce the movement of Slide R blocks by reducing  
340 lateral support on the slope via the propagation of their glide plane and by forming  
341 extensional cracks, thus fracturing the overlying MTC. Although the cracks are narrow, the



342 reactivation of the Slide S could be subtle on the upper slope, without significant sediment  
343 transport.

#### 345 *Seafloor Scarps and Slumps Indicate Long-term Instability of MTCs*

346 In Terrace 4, there are two intervals above a basal glide plane, with laterally spread  
347 Slide S blocks and overlying contourites. Small-scale folds above these blocks (Figs. 6a and  
348 7a), channels near scarps S4.1-S4.4, and slumps near S5 (Figs. 6b, 7b and 7c), are features  
349 indicating an unstable Terrace 4. Differential compaction within contourite deposits, resulting  
350 in small folds above blocks, may be responsible for this instability. However, the Storegga  
351 Slide scar and correlating MTCs are exposed on the modern seafloor (Haflidason et al.,  
352 2004), suggesting the post-slide deposition is inconspicuous to enhance a differential  
353 compaction and trigger this slope instability.

354 In parallel, slope undercutting during the main Storegga Slide could have also  
355 increased the instability of Terrace 4 by reducing lateral support along Scarp S4. Faults are  
356 observed below the seafloor MTCs in the lower and upper parts of Terrace 4 (Figs. 7b and  
357 7c), while continuous reflections in the middle of the terrace suggest a relatively stable  
358 contourites interval (Figs. 7a and 7b). Due to these faults and overlying seafloor slope failures  
359 are only located above Slide S blocks (Figs. 7b and 7c), we suggest that these laterally spread  
360 blocks should have been reactivated during the emplacement of Storegga Slide and led to  
361 local slope failure above.

#### 363 **A Model Explaining the Development of Unstable MTCs with Laterally Spread Blocks**

364 Previous studies have suggested that the strike of laterally spread blocks (also named  
365 as ‘spreading blocks’) can be parallel to slide headwalls and perpendicular to their direction

of downslope transport when formed in a retrogressive sequence (Kvalstad et al., 2005; Baeten et al., 2014). These retrogressively spread blocks are fragmented downslope, where they decrease in size via strain softening and intermixing of flows during their downslope transport (Bull et al., 2009a; Cox et al., 2020). Conversely, newly formed (or incipient) slide blocks can be identified on the upper continental slope as intact features with relatively larger sizes due to their limited movement (Micallef et al., 2007). Given that fragmented and rotated blocks are observed on the lower part of Terrace 5 (Figs. 8b, 8c and 8d), the spreading of Slide R blocks can be related to a retrogressive sequence (Bull et al., 2009b), similarly to blocks observed in Slide S, Slide R and within the Storegga Slide.

Contrasting with the Slide R blocks in Terrace 5, Slide S blocks in Terrace 4 are larger towards the lower continental slope (Figs. 6c, 7 and 9). As block size cannot increase during their downslope transport, rather decreasing by strain softening and fragmentation, the large blocks observed in the lower part of Terrace 4 suggest they were remarkably large when first formed. While the smaller blocks, such as block 7 in Figs. 6c and 7b, along the headwall of Terrace 4, hint at a smaller initial size. As the size of laterally spread blocks on gentle slopes is determined by the physical properties of the failed strata, abrupt lithological changes are expected to have significantly changed the strength of Unit 1 as well as the size of Slide S blocks along Terrace 4 (Puzrin et al., 2017) (Fig. 6c). However, the similar height of blocks and dip angles of their bounding fractures suggest a relatively homogeneous strength in the strata composing Unit 1 (Micallef et al., 2007; Wu et al., 2021). Hence, the smaller blocks in the upper part of Terrace 4 may not represent their initial size, but result from later fragmentation after their initial development.

Following slope undercutting, glide plane propagation in an upslope direction can induce the lateral spreading of slide blocks, as observed in Slide R and the Storegga Slide per se (Micallef et al., 2007a; Solheim et al., 2005). Such a glide plane can propagate much

beyond a slide's headwall to fragment the overlying strata into slabs, as those observed in Unit 1 (Baeten et al., 2014; Zhang et al., 2021) (Figs. 7b and 8a). Failed slabs are large and irregular, but maintaining a coherent inner structure until they are fragmented into series of blocks during their downslope transport (Micallef et al., 2007; Dey et al., 2016). Numerical simulations further suggest that, during the fragmentation of moving slabs, blocks can spread from both its lower and upper boundaries (Debnath, 2018; Zhang et al., 2021).

Laterally spread blocks generated from the lower boundary of a slab may also form retrogressively as they use a fully evacuated lower slope to accommodate their movement (Alves, 2015; Zhang et al., 2021) (see the 'retrogressive model' in Fig. 10d). Laterally spread blocks detached from the upper boundary of a slab develop progressively and are partially supported by the moving slab, limiting their transport (Dong et al., 2017; Debnath, 2018; Zhang et al., 2021) (see the 'progressive model' in Fig. 10e). Hence, sliding slabs are transient features before being fully fragmented into series of retrogressively and progressively spread blocks on the lower and upper parts of submarine slopes, respectively (Dong et al., 2017; Debnath, 2018). Together with the extensional cracks and smaller blocks along the headwall of Slide S (Scarp 5 in Figs. 6c and 8a), the large and irregular block close to scarp S4 could have formed one of the failed slabs, while the other blocks in Terrace 4 could be progressively spread from moving slabs, in an event comprising, at least, two stages:

1) The north flank of the Storegga area was undercut by Slide S and a glide plane propagated towards the upper slope at the same time. On the lower slope, blocks were laterally spread from evacuated scarps in a retrogressive sequence, showing a reduction in size with transporting distance and rotation (blocks in Fig. 10d). On the upper slope, the propagation of glide plane eventually breakup overlying strata, resulting in extensional cracks and incipient slabs (cracks and slabs in Figs. 8a and 10d). Similar features are identified on the north flank and headwall region of Storegga Slide (Solheim et al., 2005).

2) Together with the downslope transport of slabs and retrogressively spread blocks from their lower scarps, blocks were also progressively spread from their upper scarps at the same time, generating new and large Slide S blocks in the lower part of Terrace 4 (Figs. 6c, 7 and 10e). These progressive blocks were supported by slabs from the lower slope, thus preventing further transportation and maintaining their instability until slope undercutting removes this lateral support.

### **Slope Undercutting As a Trigger of Blocky MTCs' Reactivation**

A distinct feature of Slide S is the presence of larger blocks towards the lower continental slope (Fig. 6c). Indicated by the cracks and incipient slabs on the upper slope (Fig. 8a), these blocks are likely formed from the fragmentation of slabs and progressively spread blocks (Fig. 10e). In contrast to retrogressively spread blocks, which have an evacuated lower slope (Alves, 2015; Zhang et al., 2021), these progressive blocks are laterally supported by slabs until they are fully fragmented (Dong et al., 2017; Debnath, 2018). However, accompanied by the formation of cracks in Terrace 5 and slope failures in Terrace 4, recurrent reactivation of Slide S is perhaps related to the undercutting of the lower continental slope. This removal of lower slope support could have triggered the long-term instability of the progressively spread blocks. In comparison, retrogressively spread blocks may not have been reactivated due to the pre-existing evacuation of their lower slope.

Another important aspect concerns the lithification of Slide S blocks prior to their initial development, which led to more consolidated material in Slide S than in the contourites that drape it. This greater consolidation contrasts with the reduced shear strength of the underlying marine clay that forms Slide S glide plane. Consequently, Slide S blocks are the most consolidated features of Units 1 and 2 in Terrace 4, hindering the development

of low-angle extensional fractures. Instead, they led to the formation of high-angle faults during block reactivation, as observed near the exposed scarps S4.1-S4.4 (Figs. 6b, 7c, and 10f).

## **IMPLICATIONS**

The instability of continental slopes has been assessed in previous work, which gave greater focus to pre-instability scenarios (Leynaud et al., 2009; Urlaub and Hjelstuen, 2020). Monitoring seafloor deformation preceding slope failure requires multiple approaches, such as the use of multibeam, geophysical and geodetic data (Maksymowicz et al., 2017; Urlaub et al., 2018). Based on the mapping of geomorphological features from high-resolution 3D seismic data, this work recognizes the presence of channels, seafloor failure scars and cracks as materializing the reactivation of MTCs near the Storegga Slide. These observations provide evidence for post-slide instability where emplaced MTCs remain unstable well after their failure. These MTCs become the subject of instability, being reactivated to trigger further instability features. Although this kind of seafloor deformation occurs locally near the larger Storegga area, its potential to repeatedly remobilize near-seafloor strata must not be ignored. Considering the wide distribution of MTCs along continental margins, such as the Norwegian margin, Mediterranean Sea, West Africa, South China Sea and east USA (Solheim et al., 2005a; Chaytor et al., 2007; Dalla Valle et al., 2015; Li et al., 2017; Sun et al., 2018b), a re-evaluation of MTCs-driven slope instability is essential to protect submarine infrastructure and coastal populations.

## CONCLUSIONS

This study identifies key features marking the post-depositional reactivation of mass transport complexes (MTCs) and shows them to be underestimated marine geohazards on the Norwegian margin. Long-term slope instability was promoted by the presence of underconsolidated MTCs and laterally spread blocks. Key conclusions of this work can be summarized as follows:

a) The remobilization of unconsolidated MTCs can be recorded by the increased sinuosity of channels that developed during the initial transport of MTCs from upper continental slope.

b) Reactivated MTCs with laterally spread blocks can cause seafloor fractures and scarps, accompanied by slumps and channels crossing the slide scar.

c) Indicated by the cracks and incipient slabs on the upper continental slope and larger blocks on the lower slope, blocks are suggested to be progressively spread from moving slabs, leaving unstable MTCs with supports from lower slope.

d) The instability of MTCs may be maintained for millions of years, and is most frequently triggered by slope undercutting, making them hitherto underestimated geohazards.

As a consequence, this study demonstrates that pre-existing MTCs can be a significant preconditioning factor for long-term slope instability on continental slopes. Slope undercutting develops self-sustaining areas with recurrent slope failure, as that documented in this work on the northwest flank of the Storegga Slide.

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The seismic data (Survey MC3DMGS2002, acquired in 2002 by PGS) that support the findings are available from the Norwegian University of Science and Technology (NTNU) or DISKOS. Restrictions apply to the availability of these data, which were used under license for this study. Data are available with permission of NTNU. For access to the data through NTNU, contact: Knut Back <knut.reitan.backe@ntnu.no>.

## REFERENCES CITED

- Alves, T.M., 2010, 3D Seismic examples of differential compaction in mass-transport deposits and their effect on post-failure strata: *Marine Geology*, v. 271, p. 212–224, doi:10.1016/j.margeo.2010.02.014.
- Alves, T.M., 2015, Submarine slide blocks and associated soft-sediment deformation in deep-water basins: A review: *Marine and Petroleum Geology*, v. 67, p. 262–285, doi:10.1016/j.marpetgeo.2015.05.010.
- Alves, T.M., Cardona, S., and Rodrigues, M.C.N.L., 2022, Mass transport processes, injectites and styles of sediment remobilization: *Deepwater Sedimentary Systems: Science, Discovery, and Applications*, p. 361–406, doi:10.1016/B978-0-323-91918-0.00013-X.
- Alves, T.M., Kurtev, K., Moore, G.F., and Strasser, M., 2014, Assessing the internal character, reservoir potential, and seal competence of mass-transport deposits using seismic texture: A geophysical and petrophysical approach: *AAPG Bulletin*, v. 98, p. 793–824, doi:10.1306/09121313117.
- Baeten, N.J., Laberg, J.S., Vanneste, M., Forsberg, C.F., Kvalstad, T.J., Forwick, M., Vorren, T.O., and Haflidason, H., 2014, Origin of shallow submarine mass movements and their glide planes—Sedimentological and geotechnical analyses from the continental slope off northern Norway: *Journal of Geophysical Research: Earth Surface*, v. 119, p. 2335–2360, doi:10.1002/2013JF003068.
- Berg, K., Solheim, A., and Bryn, P., 2005, The Pleistocene to recent geological development of the Ormen Lange area: *Marine and Petroleum Geology*, v. 22, p. 45–56, doi:10.1016/j.marpetgeo.2004.10.009.



521 Bryn, P., Solheim, A., Berg, K., Lien, R., Forsberg, C.F., Haflidason, H., Ottesen, D., and  
 522 Rise, L., 2003, The Storegga Slide Complex; Repeated Large Scale Sliding in Response  
 523 to Climatic Cyclicality, *in* p. 215–222, doi:10.1007/978-94-010-0093-2\_24.

524 Bugge, T., Belderson, R.H., and Kenyon, N.H., 1988, The Storegga slide: Philosophical  
 525 Transactions - Royal Society, Series A, v. 325, p. 357–388, doi:10.1098/rsta.1988.0055.

526 Bull, S., Cartwright, J., and Huuse, M., 2009a, A review of kinematic indicators from mass-  
 527 transport complexes using 3D seismic data: *Marine and Petroleum Geology*, v. 26, p.  
 528 1132–1151, doi:10.1016/j.marpetgeo.2008.09.011.

529 Bull, S., Cartwright, J., and Huuse, M., 2009b, A subsurface evacuation model for submarine  
 530 slope failure: *Basin Research*, v. 21, p. 433–443, doi:10.1111/j.1365-  
 531 2117.2008.00390.x.

532 Camerlenghi, A., and Pini, G.A., 2009, Mud volcanoes, olistostromes and Argille scagliose in  
 533 the Mediterranean region: *Sedimentology*, v. 56, p. 319–365, doi:10.1111/j.1365-  
 534 3091.2008.01016.x.

535 Chaytor, J.D., Twichell, D.C., Brink, U.S. Ten, Buczkowski, B.J., and Andrews, B.D., 2007,  
 536 Revisiting Submarine Mass Movements Along The U.S. Atlantic Continental Margin:  
 537 Implications For Tsunami Hazards, *in* *Submarine Mass Movements and Their*  
 538 *Consequences*, Dordrecht, Springer Netherlands, p. 395–403, doi:10.1007/978-1-4020-  
 539 6512-5\_41.

540 Conti, S., Fontana, D., Lucente, C.C., and Pini, G.A., 2014, Relationships between seep-  
 541 carbonates, mud volcanism and basin geometry in the Late Miocene of the northern  
 542 Apennines of Italy: The Montardone mélange: *International Journal of Earth Sciences*,  
 543 v. 103, p. 281–295, doi:10.1007/s00531-013-0928-y.

544 Cox, D.R., Huuse, M., Newton, A.M.W., Gannon, P., and Clayburn, J., 2020, Slip sliding  
 545 away: Enigma of large sandy blocks within a gas-bearing mass transport deposit,  
 546 offshore northwestern Greenland: AAPG Bulletin, v. 104, p. 1011–1043,  
 547 doi:10.1306/10031919011.

548 Dalla Valle, G., Gamberi, F., Foglini, F., and Trincardi, F., 2015, The Gondola Slide: A mass  
 549 transport complex controlled by margin topography (South-Western Adriatic Margin,  
 550 Mediterranean Sea): Marine Geology, v. 366, p. 97–113,  
 551 doi:10.1016/j.margeo.2015.05.001.

552 Dalland, A., 1988, A lithostratigraphic scheme for the Mesozoic and Cenozoic succession  
 553 offshore Norway north of 62° N: Norw. Petrol. Dir. Bull.,.

554 Debnath, B., 2018, Modelling of downslope displacement of failed soil blocks originating  
 555 from submarine landslides:, <http://research.library.mun.ca/id/eprint/13399>.

556 Dellisanti, F., Pini, G.A., Tateo, F., and Baudin, F., 2008, The role of tectonic shear strain on  
 557 the illitization mechanism of mixed-layers illite-smectite. A case study from a fault zone  
 558 in the Northern Apennines, Italy: International Journal of Earth Sciences, v. 97, p. 601–  
 559 616, doi:10.1007/s00531-007-0180-4.

560 Dey, R., Hawlader, B.C., Phillips, R., and Soga, K., 2016, Numerical modelling of submarine  
 561 landslides with sensitive clay layers: Geotechnique, v. 66, p. 454–468,  
 562 doi:10.1680/jgeot.15.P.111.

563 Dong, Y., Wang, D., and Randolph, M.F., 2017, Runout of Submarine Landslide Simulated  
 564 with Material Point Method: Procedia Engineering, v. 175, p. 357–364,  
 565 doi:10.1016/j.proeng.2017.01.045.

566 Gatter, R., Clare, M.A., Kuhlmann, J., and Huhn, K., 2021, Characterisation of weak layers,  
 567 physical controls on their global distribution and their role in submarine landslide

568 formation: *Earth-Science Reviews*, v. 223, p. 103845,  
569 doi:10.1016/j.earscirev.2021.103845.

570 Gauer, P., Kvalstad, T.J., Forsberg, C.F., Bryn, P., and Berg, K., 2005, The last phase of the  
571 Storegga Slide: Simulation of retrogressive slide dynamics and comparison with slide-  
572 scar morphology: *Marine and Petroleum Geology*, v. 22, p. 171–178,  
573 doi:10.1016/j.marpetgeo.2004.10.004.

574 GEBCO Bathymetric Compilation Group 2020, 2020, GEBCO\_2020 Grid:,  
575 doi:10.5285/a29c5465-b138-234d-e053-6c86abc040b9.

576 Giona Bucci, M., Micallef, A., Urlaub, M., Mountjoy, J., and Barrett, R., 2022, A global  
577 review of subaqueous spreading and its morphological and sedimentological  
578 characteristics: A database for highlighting the current state of the art: *Geomorphology*,  
579 v. 414, p. 108397, doi:10.1016/j.geomorph.2022.108397.

580 Haflidason, H., Lien, R., Sejrup, H.P., Forsberg, C.F., and Bryn, P., 2005, The dating and  
581 morphometry of the Storegga Slide: *Marine and Petroleum Geology*, v. 22, p. 123–136,  
582 doi:10.1016/j.marpetgeo.2004.10.008.

583 Haflidason, H., Sejrup, H.P., Nygård, A., Mienert, J., Bryn, P., Lien, R., Forsberg, C.F., Berg,  
584 K., and Masson, D., 2004, The Storegga Slide: Architecture, geometry and slide  
585 development: *Marine Geology*, v. 213, p. 201–234, doi:10.1016/j.margeo.2004.10.007.

586 Harbitz, C.B., Løvholt, F., Pedersen, G., and Masson, D.G., 2006, Mechanisms of tsunami  
587 generation by submarine landslides: A short review: *Norsk Geologisk Tidsskrift*, v. 86,  
588 p. 255–264.

589 Jing, S., Alves, T., and Omosanya, K.O., 2022, Styles of slope instability on a Quaternary  
590 sub-arctic continental margin: The northwest flank of the Storegga Slide: *Marine*  
591 *Geology*, v. 454, p. 106933, doi:10.1016/j.margeo.2022.106933.

592 Jing, S., Alves, T.M., Omosanya, K.O., Hales, T.C., and Ze, T., 2020, Tectonic evolution of  
 593 strike-slip zones on continental margins and their impact on the development of  
 594 submarine landslides (Storegga Slide, northeast Atlantic): Bulletin of the Geological  
 595 Society of America, v. 132, p. 2397–2414, doi:10.1130/B35421.1.

596 Kvalstad, T.J., Andresen, L., Forsberg, C.F., Berg, K., Bryn, P., and Wangen, M., 2005, The  
 597 Storegga slide: Evaluation of triggering sources and slide mechanics: Marine and  
 598 Petroleum Geology, v. 22, p. 245–256, doi:10.1016/j.marpetgeo.2004.10.019.

599 L’Heureux, J.-S. et al., 2012, Identification of Weak Layers and Their Role for the Stability  
 600 of Slopes at Finneidfjord, Northern Norway, *in* Submarine Mass Movements and Their  
 601 Consequences, Dordrecht, Springer Netherlands, p. 321–330, doi:10.1007/978-94-007-  
 602 2162-3\_29.

603 Laberg, J.S., Baeten, N.J., Lågstad, P., Forwick, M., and Vorren, T.O., 2013, Formation of a  
 604 large submarine crack during the final stage of retrogressive mass wasting on the  
 605 continental slope offshore northern Norway: Marine Geology, v. 346, p. 73–78,  
 606 doi:10.1016/j.margeo.2013.08.008.

607 Lawrence, G.W.M., and Cartwright, J.A., 2010, The stratigraphic and geographic distribution  
 608 of giant craters and remobilised sediment mounds on the mid Norway margin, and their  
 609 relation to long term fluid flow: Marine and Petroleum Geology, v. 27, p. 733–747,  
 610 doi:10.1016/j.marpetgeo.2009.10.012.

611 Lewis, K.B., Collot, J.Y., and Lallemand, S.E., 1998, The dammed Hikurangi Trough: A  
 612 channel-fed trench blocked by subducting seamounts and their wake avalanches (New  
 613 Zealand-France GeodyNZ Project): Basin Research, v. 10, p. 441–468,  
 614 doi:10.1046/j.1365-2117.1998.00080.x.

615 Leynaud, D., Mienert, J., and Vanneste, M., 2009, Submarine mass movements on glaciated  
 616 and non-glaciated European continental margins: A review of triggering mechanisms  
 617 and preconditions to failure: *Marine and Petroleum Geology*, v. 26, p. 618–632,  
 618 doi:10.1016/j.marpetgeo.2008.02.008.

619 Li, W. et al., 2017, Morphology, age and sediment dynamics of the upper headwall of the  
 620 Sahara Slide Complex, Northwest Africa: Evidence for a large Late Holocene failure:  
 621 *Marine Geology*, v. 393, p. 109–123, doi:10.1016/j.margeo.2016.11.013.

622 Locat, J., Leroueil, S., Locat, A., and Lee, H., 2016, Weak layers: Their definition and  
 623 classification from a geotechnical perspective, *in* *Submarine Mass Movements and Their*  
 624 *Consequences*, 6th International Symposium, Springer, p. 3–12, doi:10.1007/978-3-319-  
 625 00972-8\_1.

626 Maksymowicz, A., Chadwell, C.D., Ruiz, J., Tréhu, A.M., and Weinrebe, W., 2017,  
 627 Coseismic seafloor deformation in the trench region during the Mw8 . 8 Maule  
 628 megathrust earthquake: , p. 1–8, doi:10.1038/srep45918.

629 Masson, D.G., Harbitz, C.B., Wynn, R.B., Pedersen, G., and Løvholt, F., 2006, Submarine  
 630 landslides: Processes, triggers and hazard prediction: *Philosophical Transactions of the*  
 631 *Royal Society A: Mathematical, Physical and Engineering Sciences*, v. 364, p. 2009–  
 632 2039, doi:10.1098/rsta.2006.1810.

633 Mesri, G., and Huvaj-Sarihan, N., 2012, Residual Shear Strength Measured by Laboratory  
 634 Tests and Mobilized in Landslides: *Journal of Geotechnical and Geoenvironmental*  
 635 *Engineering*, v. 138, p. 585–593, doi:10.1061/(asce)gt.1943-5606.0000624.

636 Micallef, A., Masson, D.G., Berndt, C., and Stow, D.A.V., 2009, Development and mass  
 637 movement processes of the north-eastern Storegga Slide: *Quaternary Science Reviews*,  
 638 v. 28, p. 433–448, doi:10.1016/j.quascirev.2008.09.026.

639 Micallef, A., Masson, D.G., Berndt, C., and Stow, D.A.V., 2007, Morphology and mechanics  
640 of submarine spreading: A case study from the Storegga Slide: *Journal of Geophysical*  
641 *Research: Earth Surface*, v. 112, p. 1–21, doi:10.1029/2006JF000739.

642 Mienert, J., Vanneste, M., Haflidason, H., and Bünz, S., 2010, Norwegian margin outer shelf  
643 cracking: A consequence of climate-induced gas hydrate dissociation? *International*  
644 *Journal of Earth Sciences*, v. 99, p. 207–225, doi:10.1007/s00531-010-0536-z.

645 Moscardelli, L., and Wood, L., 2016, Morphometry of mass-transport deposits as a predictive  
646 tool: *Bulletin of the Geological Society of America*, v. 128, p. 47–80,  
647 doi:10.1130/B31221.1.

648 Nugraha, H.D., Jackson, C.A.-L., Johnson, H.D., Hodgson, D.M., and Clare, M.A., 2022,  
649 Extreme erosion by submarine slides: *Geology*, v. XX, p. 1–5, doi:10.1130/g50164.1.

650 Ogata, K., Festa, A., Pini, G.A., and Alonso, J.L., 2019a, Submarine Landslide Deposits in  
651 Orogenic Belts: , p. 1–26, doi:10.1002/9781119500513.ch1.

652 Ogata, K., Festa, A., Pini, G.A., Pogačnik, and Lucente, C.C., 2019b, Substrate deformation  
653 and incorporation in sedimentary mélanges (olistostromes): Examples from the northern  
654 Apennines (Italy) and northwestern Dinarides (Slovenia): *Gondwana Research*, v. 74, p.  
655 101–125, doi:10.1016/j.gr.2019.03.001.

656 Ogata, K., Mountjoy, J.J., Pini, G.A., Festa, A., and Tinterri, R., 2014, Shear zone  
657 liquefaction in mass transport deposit emplacement: A multi-scale integration of seismic  
658 reflection and outcrop data: *Marine Geology*, v. 356, p. 50–64,  
659 doi:10.1016/j.margeo.2014.05.001.

660 Omosanya, K.O., 2018, Episodic fluid flow as a trigger for Miocene-Pliocene slope  
661 instability on the Utgard High, Norwegian Sea: *Basin Research*, v. 30, p. 942–964,  
662 doi:10.1111/bre.12288.

663 Omosanya, K.O., Duffaut, K., Alves, T.M., Eruteya, O.E., Johansen, S.E., and Waldmann,  
 664 N., 2022, Giant paleo-seafloor craters and mass wasting associated with magma-induced  
 665 uplift of the upper crust: *Scientific Reports*, v. 12, p. 4392, doi:10.1038/s41598-022-  
 666 08205-0.

667 Pickering, K.T., and Hiscott, R.N., 2015, *Deep marine systems: processes, deposits,*  
 668 *environments, tectonics and sedimentation:* John Wiley & Sons.

669 Pini, G.A., Ogata, K., Camerlenghi, A., Festa, A., Lucente, C.C., and Codegone, G., 2012,  
 670 *Sedimentary mélanges and fossil mass- Transport complexes: A key for better*  
 671 *understanding submarine mass movements? Submarine Mass Movements and Their*  
 672 *Consequences - 5th International Symposium*, p. 585–594, doi:10.1007/978-94-007-  
 673 2162-3\_52.

674 Puzrin, A.M., Gray, T.E., and Hill, A.J., 2017, Retrogressive shear band propagation and  
 675 spreading failure criteria for submarine landslides: *Geotechnique*, v. 67, p. 95–105,  
 676 doi:10.1680/jgeot.15.P.078.

677 Reiche, S., Hjelstuen, B.O., and Haflidason, H., 2011, High-resolution seismic stratigraphy,  
 678 sedimentary processes and the origin of seabed cracks and pockmarks at Nyegga, mid-  
 679 Norwegian margin: *Marine Geology*, v. 284, p. 28–39,  
 680 doi:10.1016/j.margeo.2011.03.006.

681 Riis, F., Berg, K., Cartwright, J., Eidvin, T., and Hansch, K., 2005, Formation of large, crater-  
 682 like evacuation structures in ooze sediments in the Norwegian Sea. Possible implications  
 683 for the development of the Storegga Slide: *Marine and Petroleum Geology*, v. 22, p.  
 684 257–273, doi:10.1016/j.marpetgeo.2004.10.023.

685 Sawyer, D.E., Flemings, P.B., Dugan, B., and Germaine, J.T., 2009, Retrogressive failures  
686 recorded in mass transport deposits in the Ursa Basin, Northern Gulf of Mexico: *Journal*  
687 *of Geophysical Research: Solid Earth*, v. 114, p. 1–20, doi:10.1029/2008JB006159.

688 Shanmugam, G., 2021, Deep-Water Processes and Deposits: 965–1009 p., doi:10.1016/b978-  
689 0-12-409548-9.12541-2.

690 Solheim, A., Berg, K., Forsberg, C.F., and Bryn, P., 2005a, The Storegga Slide complex:  
691 Repetitive large scale sliding with similar cause and development: *Marine and*  
692 *Petroleum Geology*, v. 22, p. 97–107, doi:10.1016/j.marpetgeo.2004.10.013.

693 Solheim, A., Bryn, P., Sejrup, H.P., Mienert, J., and Berg, K., 2005b, Ormen Lange - An  
694 integrated study for the safe development of a deep-water gas field within the Storegga  
695 Slide Complex, NE Atlantic continental margin; executive summary: *Marine and*  
696 *Petroleum Geology*, v. 22, p. 1–9, doi:10.1016/j.marpetgeo.2004.10.001.

697 Sun, Q., Alves, T.M., Lu, X., Chen, C., and Xie, X., 2018a, True Volumes of Slope Failure  
698 Estimated From a Quaternary Mass-Transport Deposit in the Northern South China Sea:  
699 *Geophysical Research Letters*, v. 45, p. 2642–2651, doi:10.1002/2017GL076484.

700 Sun, Q., Cartwright, J., Xie, X., Lu, X., Yuan, S., and Chen, C., 2018b, Reconstruction of  
701 repeated Quaternary slope failures in the northern South China Sea: *Marine Geology*, v.  
702 401, p. 17–35, doi:10.1016/j.margeo.2018.04.009.

703 Talling, P.J. et al., 2007, Onset of submarine debris flow deposition far from original giant  
704 landslide: *Nature*, v. 450, p. 541–544, doi:10.1038/nature06313.

705 Urgeles, R., and Camerlenghi, A., 2013, Submarine landslides of the Mediterranean Sea:  
706 Trigger mechanisms, dynamics, and frequency-magnitude distribution: *Journal of*  
707 *Geophysical Research: Earth Surface*, v. 118, p. 2600–2618,  
708 doi:10.1002/2013JF002720.



- 709 Urlaub, M., and Hjelstuen, B.O., 2020, A numerical investigation of excess pore pressures  
710 and continental slope stability in response to ice-sheet dynamics: Geological Society  
711 Special Publication, v. 500, p. 255–266, doi:10.1144/SP500-2019-185.
- 712 Urlaub, M., Petersen, F., Gross, F., Bonforte, A., Puglisi, G., Guglielmino, F., Krastel, S.,  
713 Lange, D., and Kopp, H., 2018, Gravitational collapse of Mount Etna’s southeastern  
714 flank: Science Advances, v. 4, p. 1–8, doi:10.1126/sciadv.aat9700.
- 715 Wang, X., Wang, Y., He, M., Chen, W., Zhuo, H., Gao, S., Wang, M., and Zhou, J., 2017,  
716 Genesis and evolution of the mass transport deposits in the middle segment of the Pearl  
717 River canyon, South China Sea: Insights from 3D seismic data: Marine and Petroleum  
718 Geology, v. 88, p. 555–574, doi:10.1016/j.marpetgeo.2017.08.036.
- 719 Wu, N., Jackson, C.A.-L., Clare, M.A., Hodgson, D., Nugraha, H.D., Steventon, M., and  
720 Zhong, F.G., 2022, Diagenetic priming of submarine landslides in ooze-rich substrates:,  
721 doi:<https://doi.org/10.31223/X50P9Q>.
- 722 Wu, N., Jackson, C.A.L., Johnson, H.D., Hodgson, D.M., Clare, M.A., Nugraha, H.D., and  
723 Li, W., 2021, The formation and implications of giant blocks and fluid escape structures  
724 in submarine lateral spreads: Basin Research, v. 33, p. 1711–1730,  
725 doi:10.1111/bre.12532.
- 726 Zhang, W., Klein, B., Randolph, M.F., and Puzrin, A.M., 2021, Upslope Failure Mechanisms  
727 and Criteria in Submarine Landslides: Shear Band Propagation, Slab Failure and  
728 Retrogression: Journal of Geophysical Research: Solid Earth, v. 126, p. 1–29,  
729 doi:10.1029/2021JB022041.

## FIGURE CAPTIONS

**Figure 1.** **a)** Location of study area on the northwest flank of the Storegga Slide, mid-Norwegian margin, highlighting the distribution of the Storegga Slide complex (Solheim et al., 2005a) and seafloor cracks (Mienert et al., 2010; Reiche et al., 2011). Map is modified from GEBCO Bathymetric Compilation Group (2020). The gray-shaded area represents the location of south Modgunn Arch. **b)** Detailed two-way time (tw) map of the seafloor, as extracted from seismic data. The seismic profiles and key areas discussed in this work are highlighted by the black lines and rectangles. **c)** Relationship amongst the Storegga Slide complex covering the variance map of basal glide plane (H3) in study area, including slides W, S, R, and the Storegga Slide (Solheim et al., 2005a). **d)** Seismic profile crossing all the slope terraces in the study area with schematic slide stratigraphy in the Naust Formation (Naust Fm.). Location is shown in Figs. 1b and 1c. Horizon H1: seafloor; Horizon H2: inner glide plane between MTCs 1 and 2; Horizon H3: basal glide plane of the Storegga Slide complex; Horizon H4: top of Kai Formation; Horizon H5: top of Brygge Formation; Horizon H6: base of the post-breakup units, remaining intact during the Storegga Slide complex. S1-S6: slope scarps separating terraces.

**Figure 2.** **a)** Seismic profile showing typical turbidite and debris channels on the southeast side upper continental slope. The location of the profile is shown in Figs. 1b and 2b-2d. MTC 1 was deposited in association with Slide W, before the Storegga Slide proper (Bryn et al., 2003; Omosanya et al., 2022). **b)** TWT map of the seafloor (Horizon H1). The grooves and sediment waves inside the turbidite channels distinguish them from debris channels, the latter of which present a rugged internal character. Location of the TWT map is shown in Figs. 1b and 1c. **c)** RMS amplitude map of the seafloor (H1). The chaotic facies of strata inside debris channels contrasts with that of turbidite channels, which are smoother and show lineations in

757 them. **d)** Variance map of the seafloor (Horizon H1). The chaotic and high variance of debris  
758 channels are indicative of their presence on the seafloor.

759  
760 **Figure 3. a)** TWT map of the seafloor (Horizon H1). A group of NW-SE grooves is observed  
761 on the seafloor and marked by a white dashed line. **b-c)** RMS amplitude and Variance maps  
762 of the seafloor (H1). Submarine channels are shown as linear features with higher RMS  
763 amplitude and variance values. **d)** TWT map of the inner glide plane (Horizon H2) between  
764 MTCs 1 and 2 in Fig. 4. A group of glide-plane furrows is marked by black dashed lines. The  
765 detail of grooves and furrows can be observed in Fig. 4. The location of the maps is shown in  
766 Figs. 1b and 1c.

767  
768 **Figure 4. a-b)** Seismic profile crossing Terrace 2. Seafloor grooves are marked by black  
769 circles, and the glide plane furrows are highlighted by rectangles. The location of the seismic  
770 profile is shown in Fig. 3d; **c)** and **d)** Relief maps of the seafloor (horizon H1) and the glide  
771 plane of MTC 2 (horizon H2). The distribution of grooves and furrows are documented as  
772 local depressions on the seafloor and glide plane, sharing the same location and geometry.  
773 The channels shown in Figs. 3b and 3c can also be observed in c) as linear depressions.

774  
775 **Figure 5.** Sinuosity of channels and furrows in study area. The channels on southeast side  
776 upper continental slope and glide-plane furrows reveal a very low sinuosity between 1.01 and  
777 1.02, whereas the channels in Terrace 2 show an average sinuosity of 1.18.

778  
779 **Figure 6. a-b)** TWT and variance maps of the seafloor (Horizon H1). The location of the  
780 maps is shown in Figs. 1b and 1c. Multiple local folds contributed to the formation of a  
781 rugged Terrace 4. Channels (C\*) and slumps are sourced from seafloor scarps crossing scarp

S4 and Terraces 3 and 4. **c)** Variance-slice 50 ms above the basal glide plane (Horizon H3) of laterally spread blocks. In Terrace 4, the size of Slide S blocks increases towards lower slope.

**Figure 7. a-c)** Selected seismic profiles across Terrace 4. The locations of the profiles are shown in Fig. 6. Slide blocks in Units 1 and 2 are separated by scarp S5. Slide S blocks are located on the lower continental slope (Unit 1) and were draped by a thin interval of contourites. Seismic reflections in these contourites are continuous in the chasms but folded and faulted above discrete slide blocks. The ‘eroded block’ in b) corresponds to the irregular block in Fig. 6c, forming the largest block in Terrace 4. The seafloor scarps S4.1-S4.4 in Fig. 6b relate to underlying Slide S blocks 1-4 in c). Discrete glide plane below Slide S blocks shift stratigraphic levels in c). Slide R blocks are located in Terrace 5 and are underlain by incipient Slide S blocks and cracks.

**Figure 8. a)** Variance maps of the basal glide plane of Slide R blocks (Horizon H3). A group of extensional cracks are located in Unit 1 on the northeast side upper continental slope, as observed in Fig. 7b. **b)** Variance map of a time-slice 50 ms above the basal glide plane of Slide R blocks (Horizon H3-50ms). Cracks in Unit 1 can be recognized as longitudinal chasms in the overlying Unit 2. **c-d)** Comparison between Slide R blocks on the upper and lower continental slope. The two areas are marked in Fig. 8b. On the upper continental slope in c), longitudinal blocks with a dominant North-South strike are shown as narrow, low-variance features. Slide blocks on the lower continental slope are rotated and relatively small.

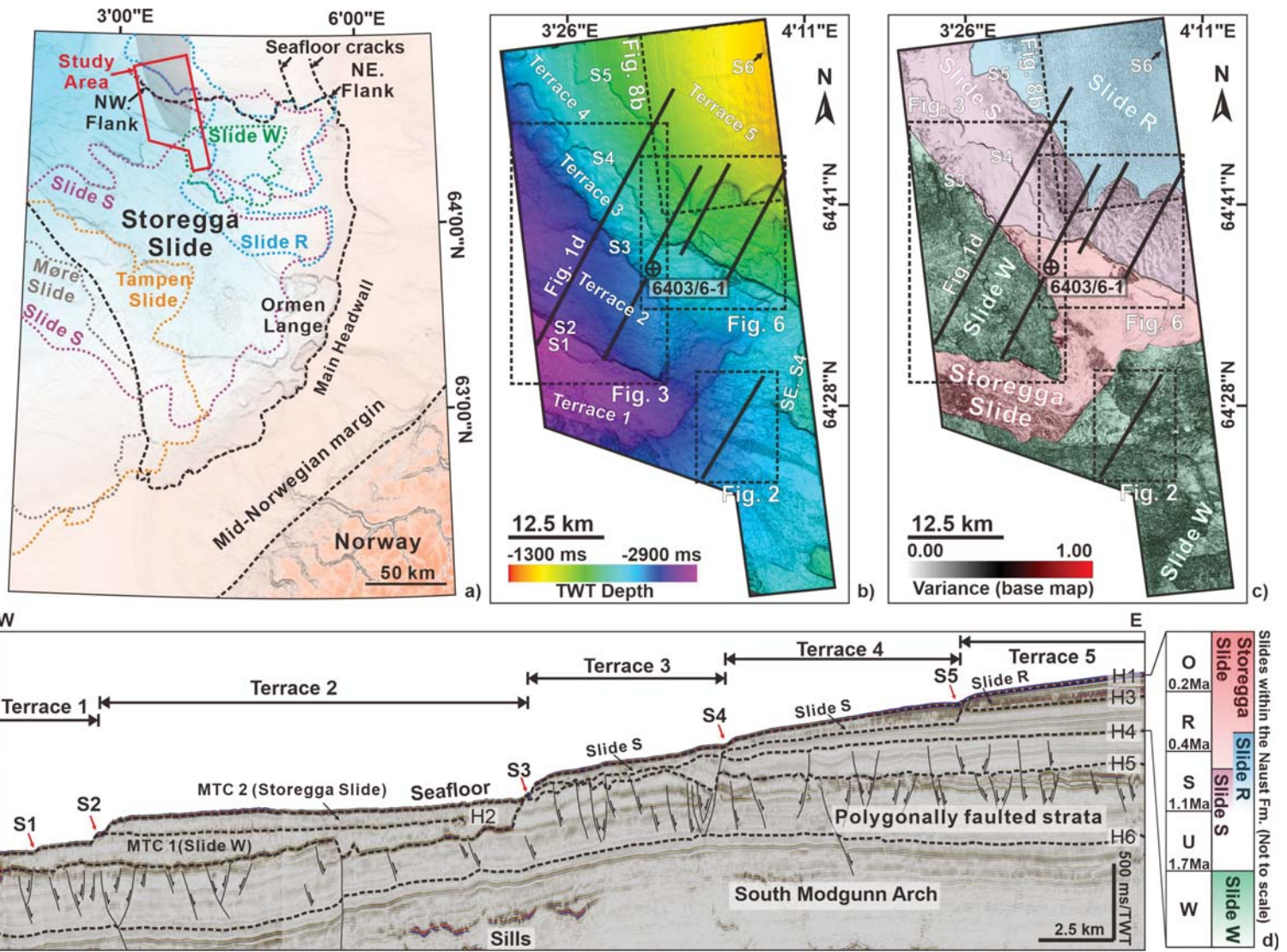
**Figure 9.** Geometric data for blocks in Slides S and R. Slide S blocks are larger in Terrace 4, where they are 1739 m long and 403 m wide on average, with a positive correlation shown on the graph. Slide R blocks in Terrace 5 are 248 m long and 98 m wide on average, showing no

clear correlation on the graphs. The ‘eroded block’ in Fig. 5b was excluded from our analysis, as justified in this work.

**Figure 10.** Schematic diagrams summarizing the development of MTCs in the study area. **a-c)** the unconsolidated MTC can be remobilized by slope undercutting and a reduction in lateral support. **Stage 1:** During the main phase of Storegga Slide, massive sediments are removed from the southeast side upper continental slope and transported northwestward as MTC 2. Its glide plane eroded the top of the pre-existing MTC 1, generating a group of glide-plane furrows with low sinuosity. Flow channels, such as turbidity and debris, were also developed at this time. **Stage 2:** A local slope failure is sourced on the northwest flank of the Storegga Slide, evacuating the MTCs around Terrace 2. Due to a reduction in its lateral support, the unconsolidated MTC 2 was remobilized, causing its internal channels to become more sinuous. **Stage 3:** Differential compaction in MTC 2 is controlled by structures (furrows) on its glide plane, resulting in the formation of a group of straight grooves on the modern seafloor, which cross-cut the previously formed channels. **d-f)** the instability of laterally spread Slide S blocks was increased and triggered by slope undercutting. **Stage 1:** Together with slide blocks retrogressively spread during Slide S (in Unit 1), the glide plane of the latter slide propagated to the upper continental slope and fragmented the overlying strata. Incipient slabs were generated between the evacuated scarp on the lower continental slope and seafloor cracks on upper slope. **Stage 2:** During the downslope movement of slabs, laterally spread blocks are generated from both their lower and upper boundaries, generating both retrogressively and progressively spread blocks. Compared to the retrogressively spread blocks, these progressive blocks are supported by slabs on the lower continental slope, near which younger and larger blocks are located. **Stage 3:** Recurrent slope undercutting removed lateral support to deposited MTCs that include progressive blocks, triggering the reactivation

832 of Slide S blocks, which were supported during Stage 2. Stage 3 deformation is documented  
833 as seafloor faults, scarps and slumps overlying blocks.

# Figure 1





# Figure 2

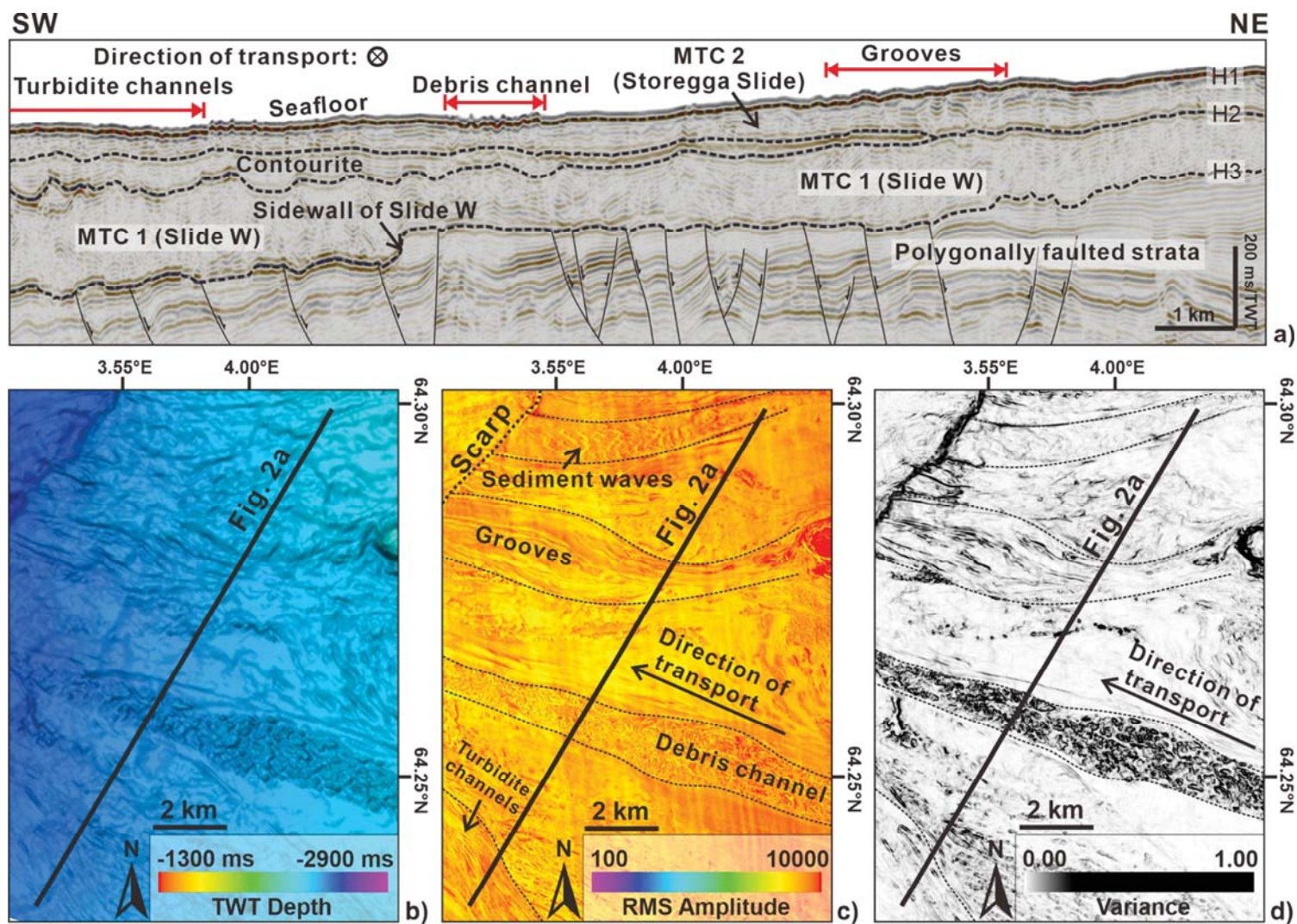
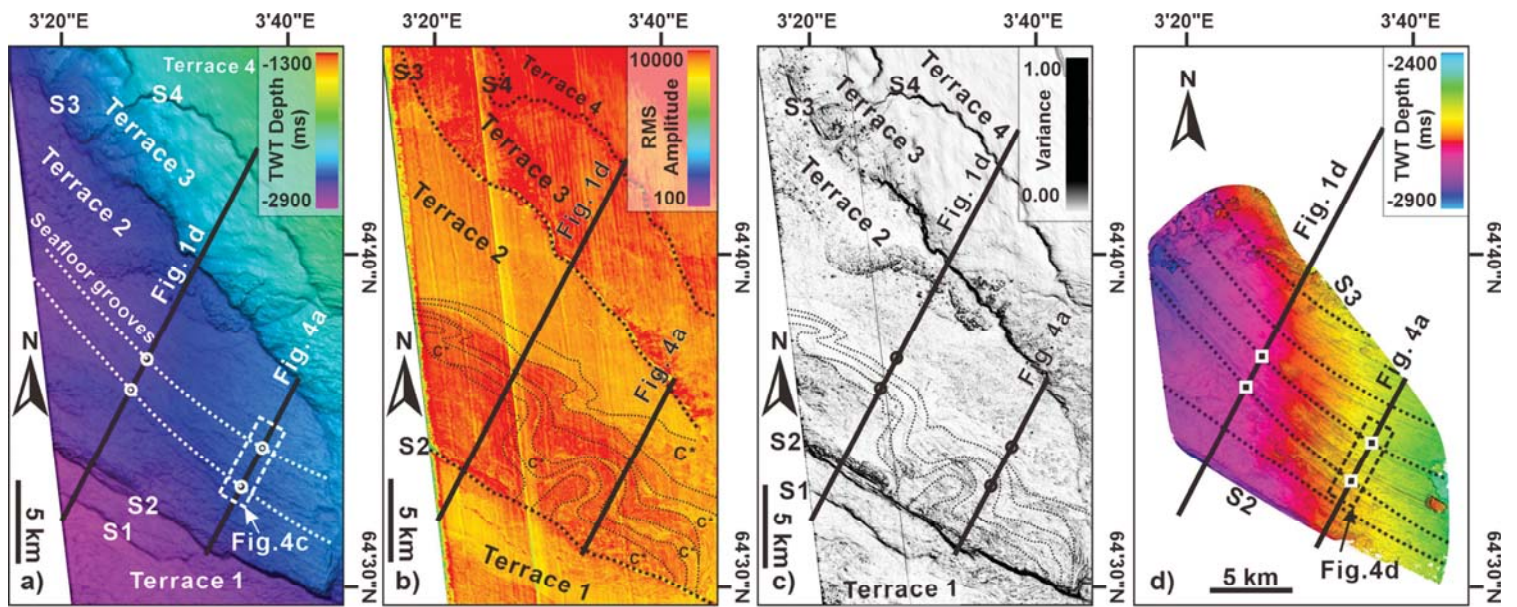


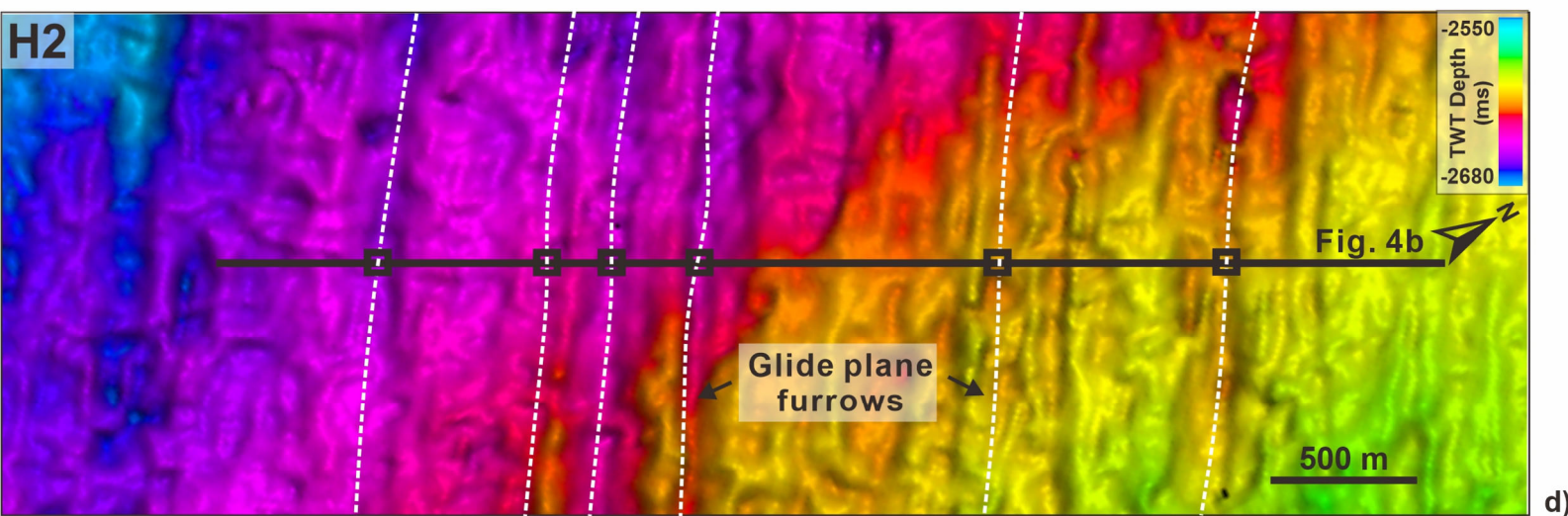
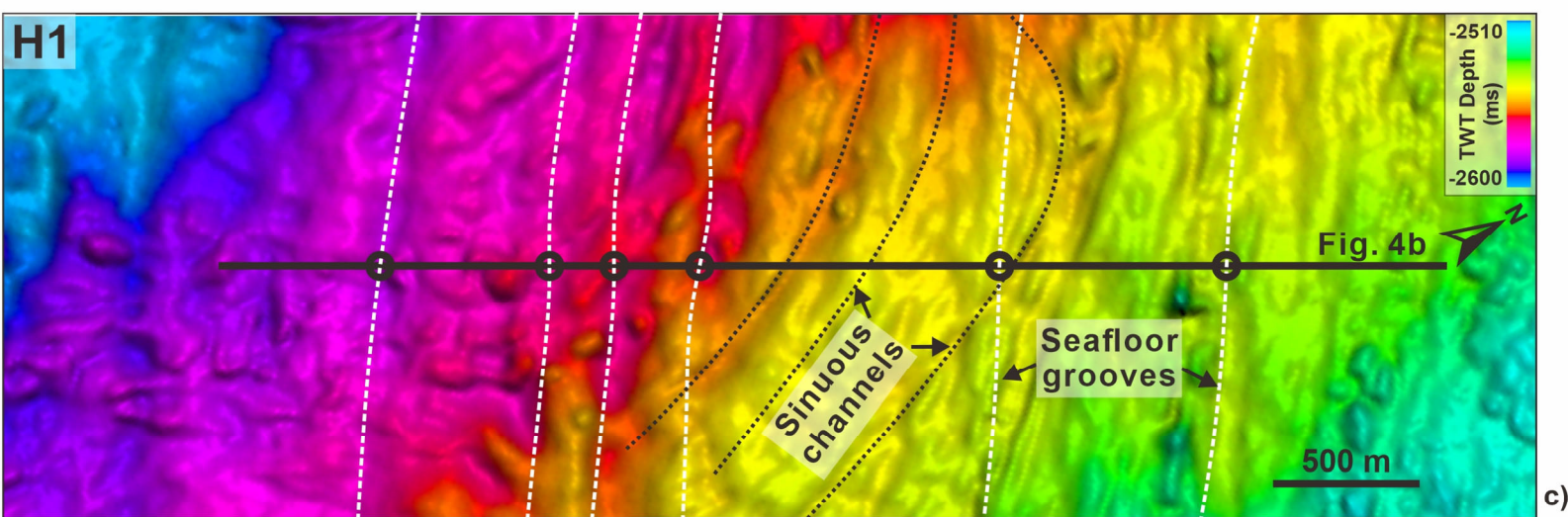
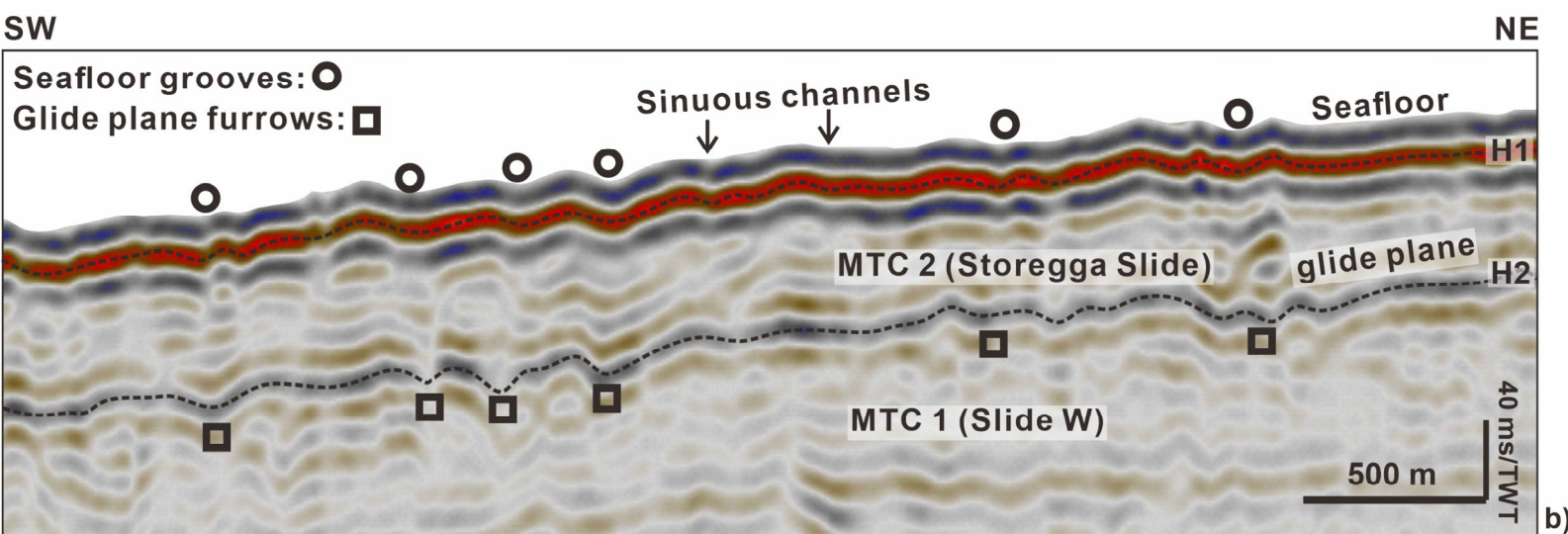
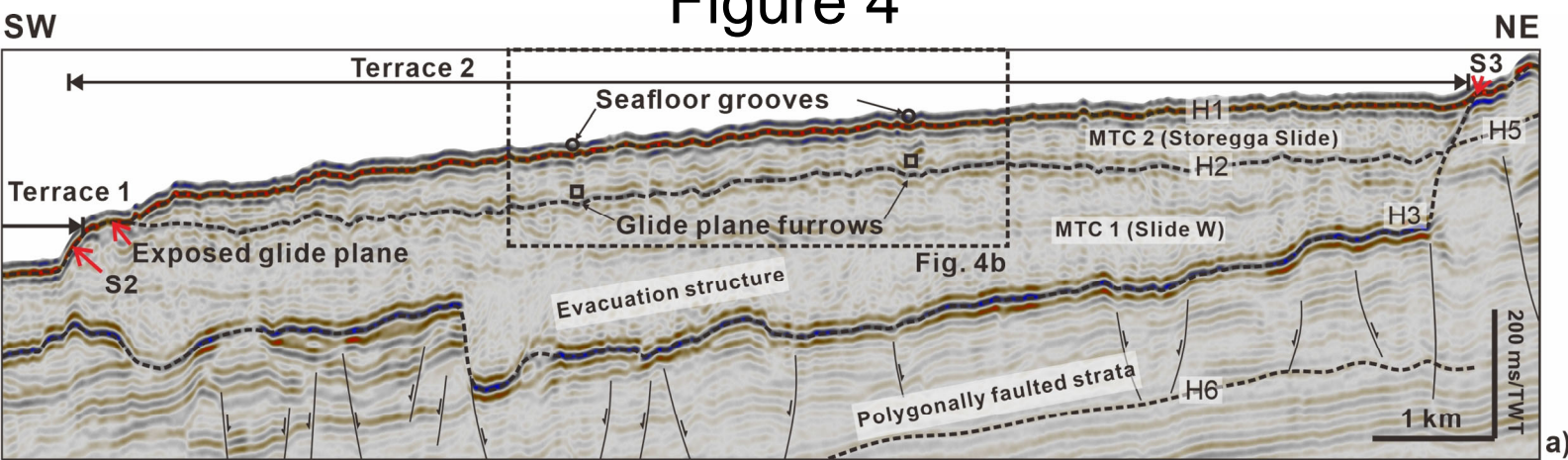


Figure 3





# Figure 4



# Figure 5

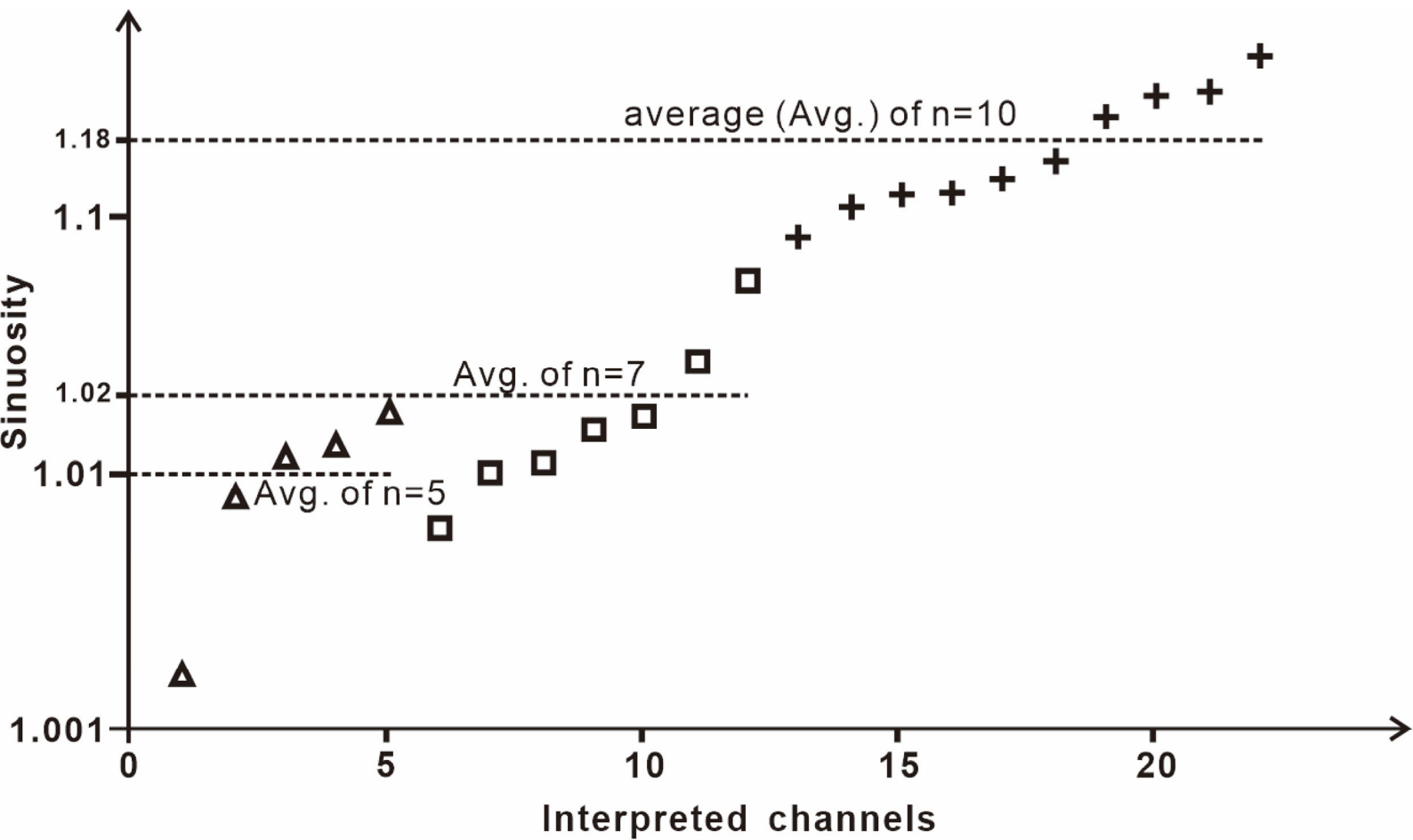
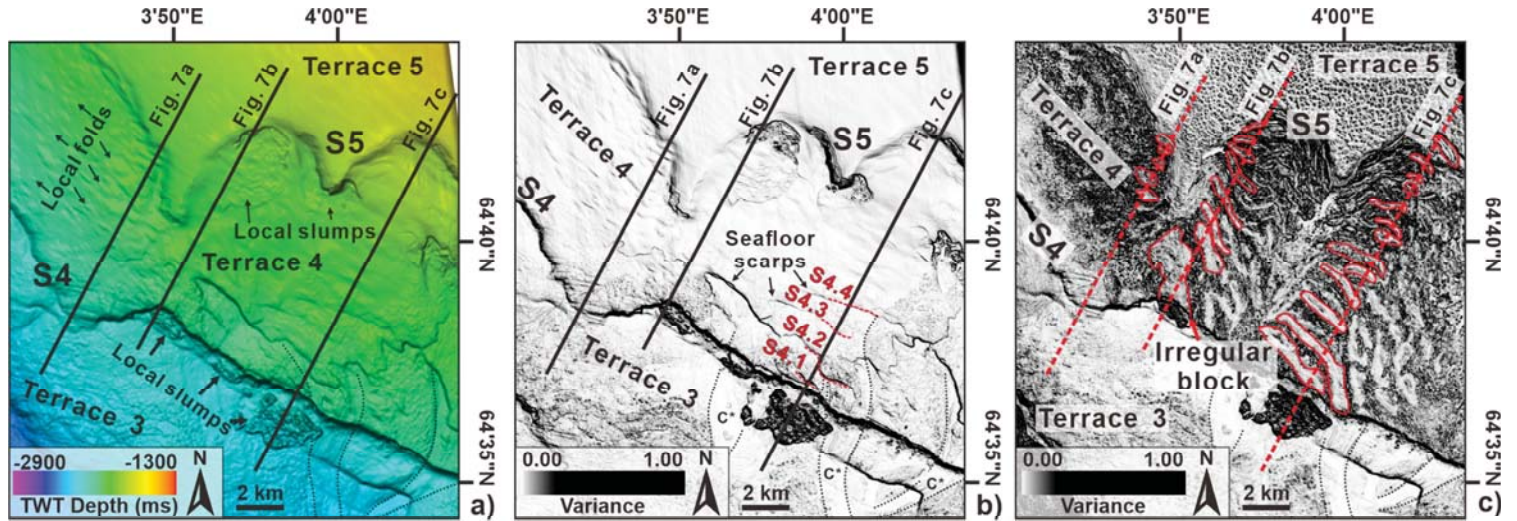




Figure 6



# Figure 7

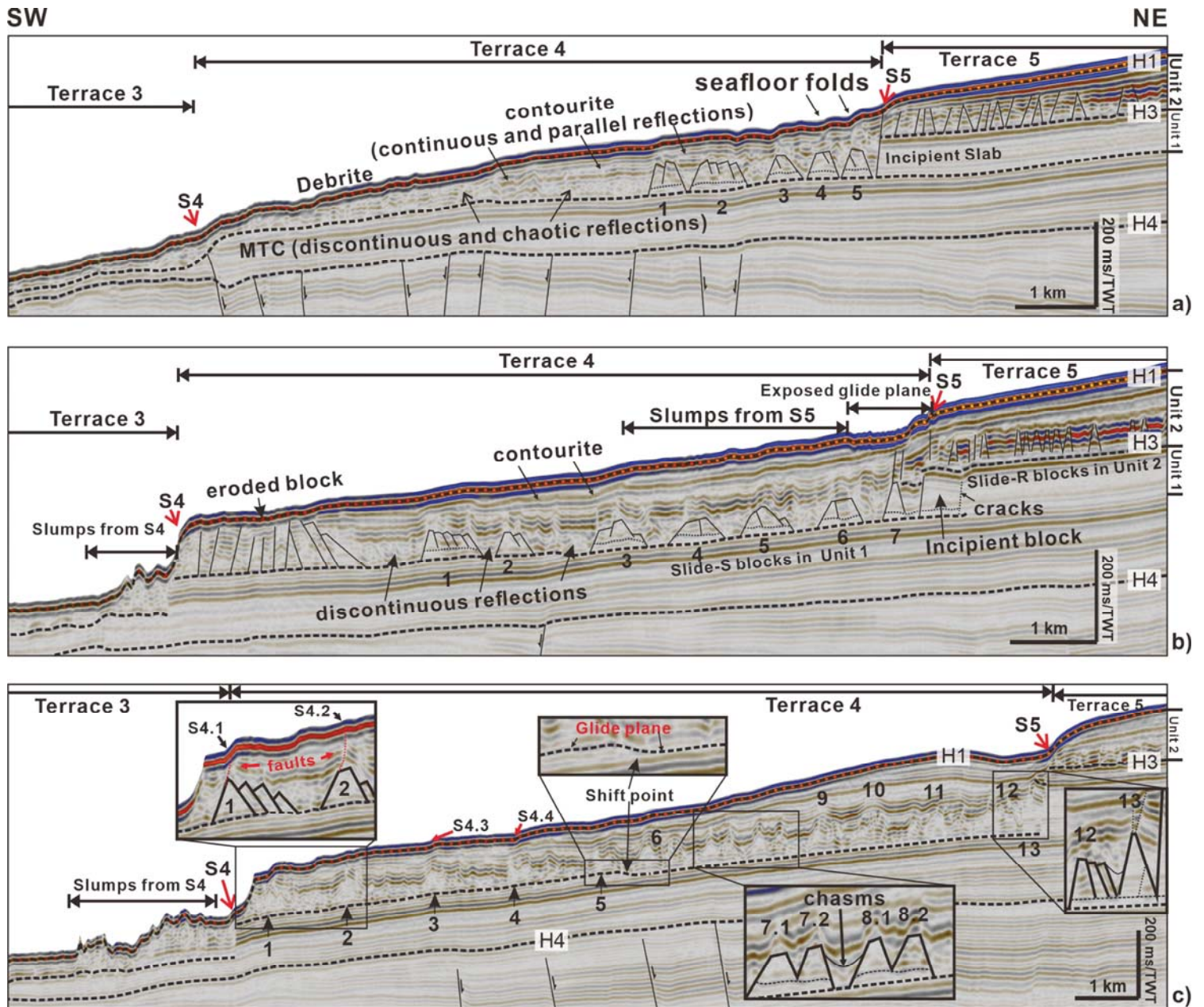
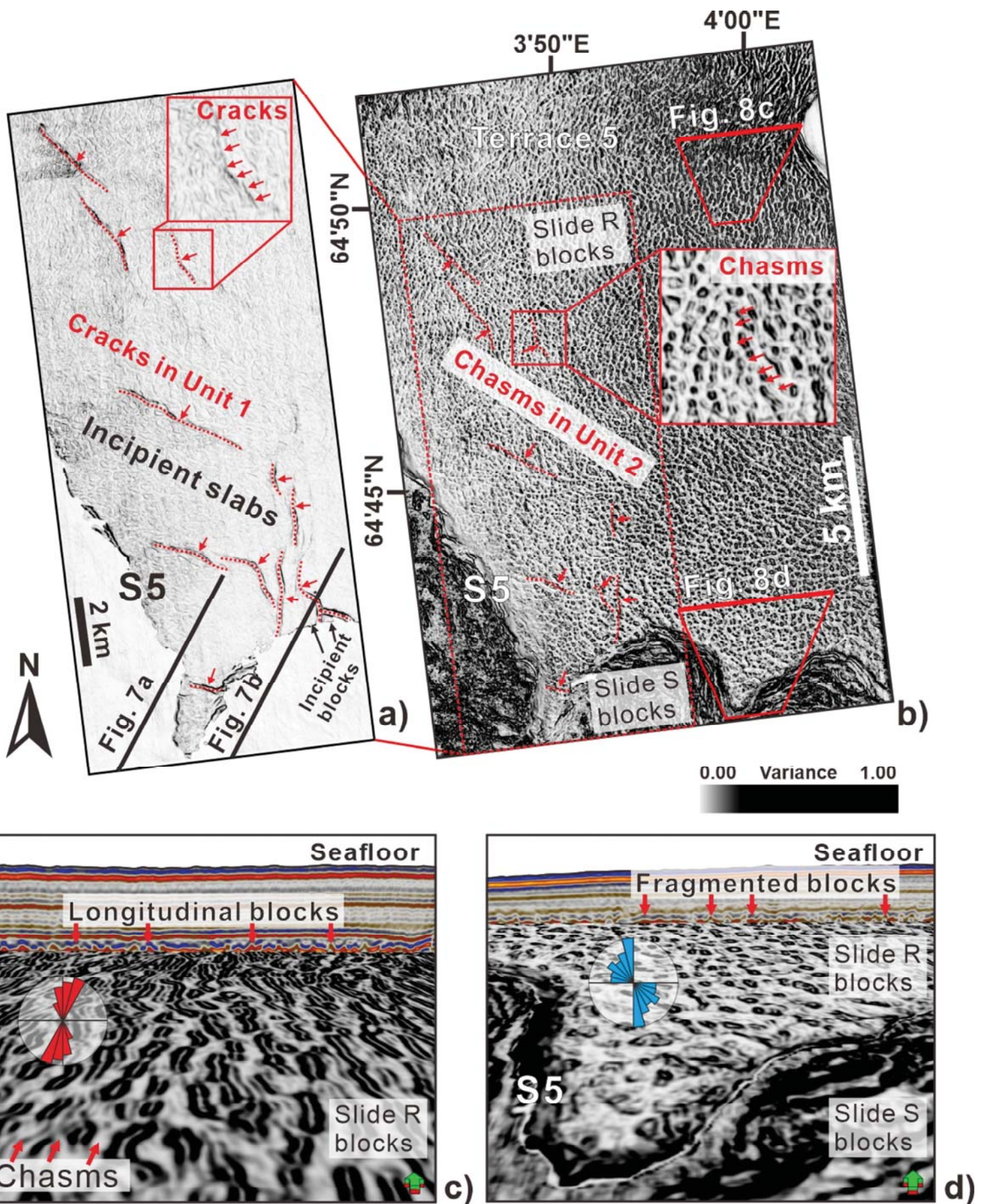
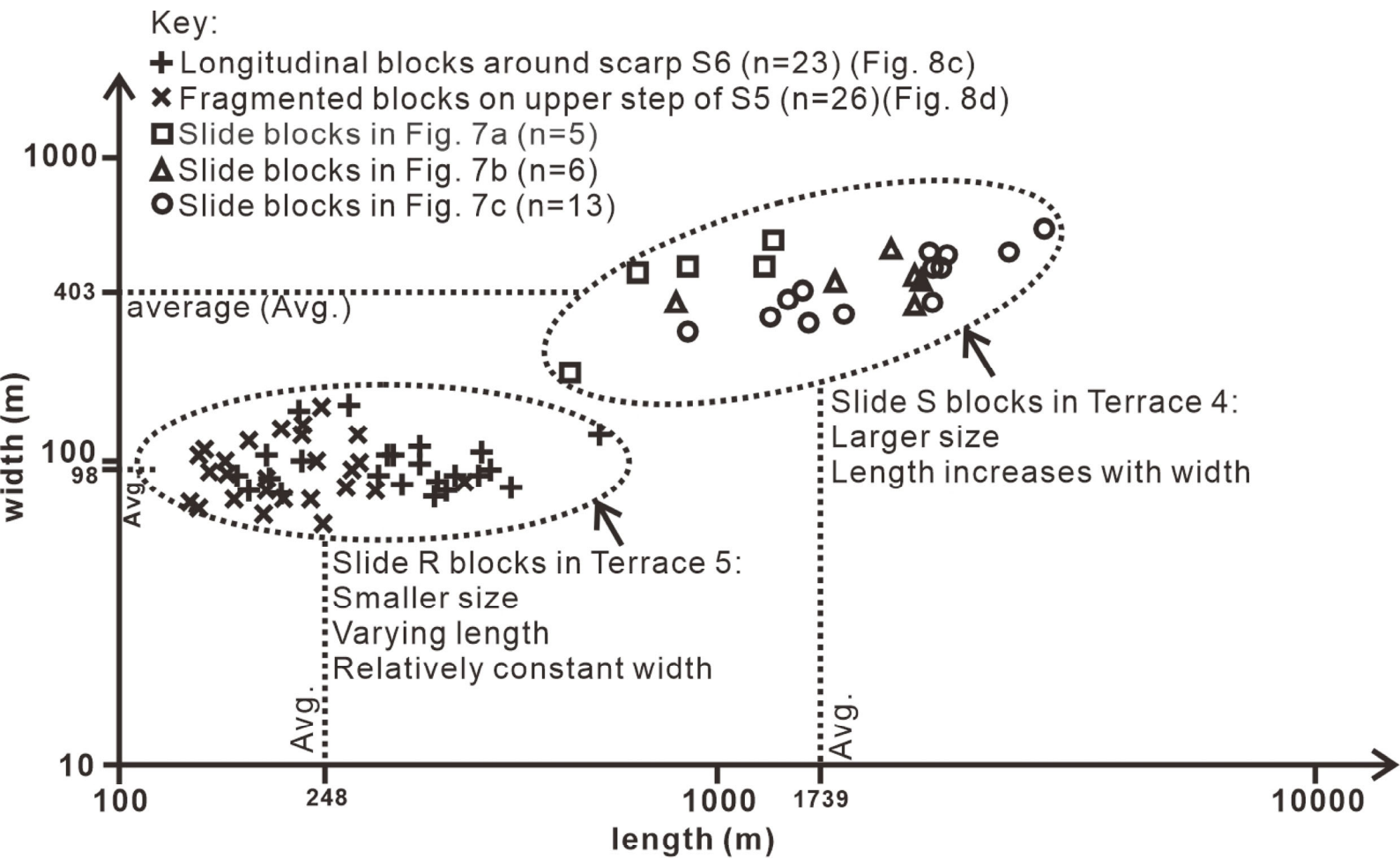




Figure 8



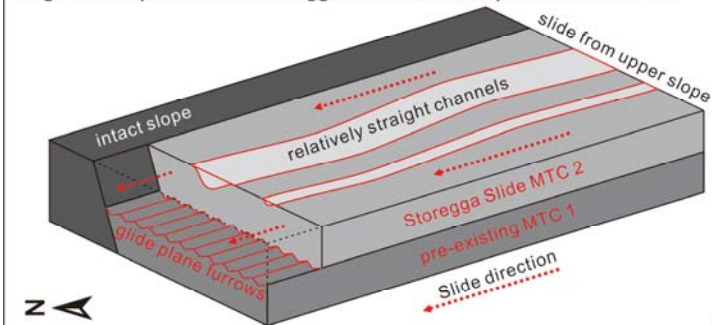
# Figure 9





# Figure 10

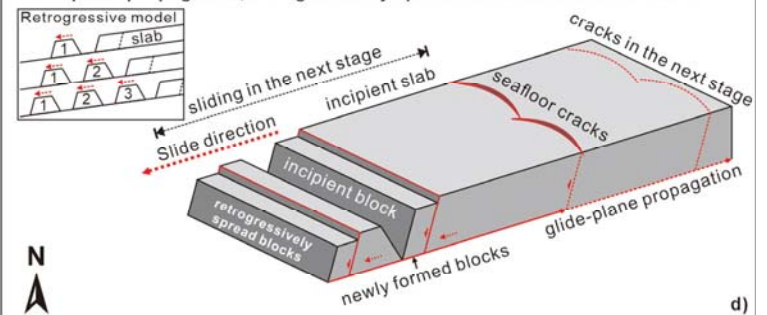
**Stage 1: Main phase of the Storegga Slide and the emplacement of MTC 2**



a)

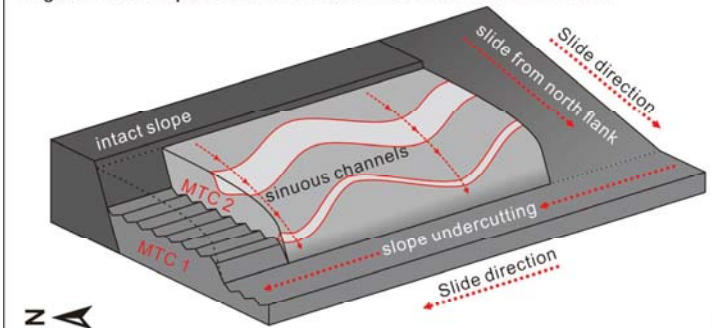
**Stage 1: Initiation of Slide S.**

**Glide-plane propagation, retrogressively spread blocks and slabs in Unit 1**



d)

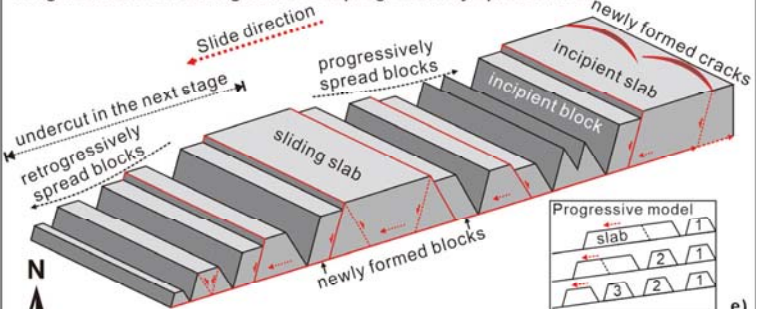
**Stage 2: Local slope failure reactivated the unconsolidated MTC 2**



b)

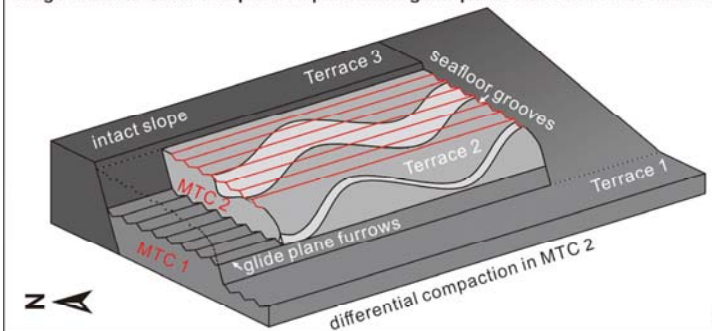
**Stage 2: Emplacement of Slide S MTCs.**

**Fragmentation of sliding slabs with progressively spread blocks**



e)

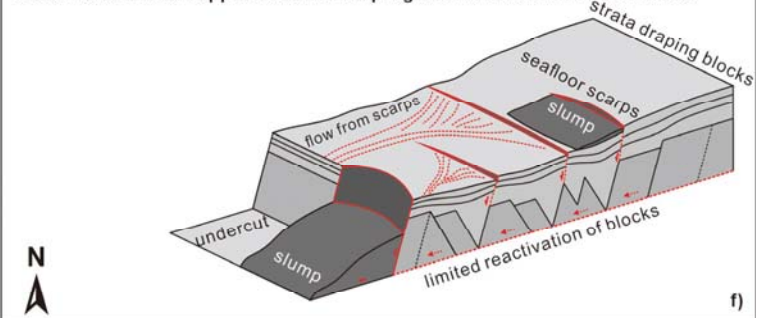
**Stage 3: Differential compaction presented glide plane furrows to the seafloor**



c)

**Stage 3: MTCs' reactivation.**

**Removal of lateral support reactivated progressive blocks in Slide S MTCs**



f)