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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 km² 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[®] 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

104 **GEOLOGICAL SETTING**

105 **Lithostratigraphy**

106 The study area is located on the northwest flank of the Storegga Slide, at a latitude of
107 around 64°N on the mid-Norwegian margin, where the continental slope rises in two
108 directions, both northeastward and southeastward (Fig. 1a). Based on Exploration Well
109 6403/6-1, the lithostratigraphy of our study area can be divided into a breakup sequence
110 (below horizon H6 in Fig. 1d) and several post-breakup units above (Jing et al., 2020). The
111 breakup sequence was not deformed by slope instability processes. In contrast, post-breakup
112 units between horizons H6 and H1 were deformed, eroded and evacuated by recurrent slope
113 failures (Figs. 1c and 1d). These post-breakup strata are stratigraphically equivalent to the
114 Brygge, Kai and Naust formations (Fig. 1d).

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

127 2008; Camerlenghi and Pini, 2009; Sawyer et al., 2009; Mesri and Huvaj-Sarihan, 2012;
128 Conti et al., 2014).

129

130 **MTCs near the Storegga area**

131 The structure of MTCs can be recorded by the seismic character and kinematic
132 indicators they present, such as grooves, scarps, fractures and slide blocks (Bull et al., 2009a;
133 Alves, 2015). In the Storegga area, multiple MTCs overlapped each other along with the
134 occurrence of the Storegga Slide complex, including the Slide W, Slide S, Slide R and the
135 Storegga Slide (Bryn et al., 2003; Solheim et al., 2005b) (Figs. 1a, 1c and 1d). Higher on the
136 continental slope, bathymetric and seismic data image several MTCs with slide blocks,
137 correlating with Slides S and R, formed above gentle glide planes with gradients of less than
138 2° (Gauer et al., 2005; Micallef et al., 2007; Bull et al., 2009b) (Figs. 1c and 1d). At least two
139 types of seismic facies have been observed in these MTCs: a) chaotic to transparent facies
140 with grooves and flow-like features denoting greater transport distances, and b) discontinuous
141 stratified facies comprising slide blocks whose movement was relative limited (Gauer et al.,
142 2005; Solheim et al., 2005a; Micallef et al., 2009; Sawyer et al., 2009).

143

144 ***Slide W***

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

151 et al., 2022). Except for slide blocks along their sidewalls, these MTCs comprise transparent
152 to chaotic seismic facies (Riis et al., 2005; Lawrence and Cartwright, 2010; Omosanya et al.,
153 2022). On the northwest flank of the Storegga Slide, three craters are observed cutting into
154 the Brygge Formation (C1 to C3 in Omosanya et al., 2022). In study area, these Slide W
155 MTCs have been eroded and removed by subsequent slope failure events, leaving an ‘L’-
156 shaped ramp on the modern seafloor (Jing et al., 2020, 2022) (Figs. 1b and 1c).

157

158 *Slides S and R*

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

168

169 *Storegga Slide*

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

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

181

182 **Development of MTCs Comprising Slide Blocks**

183 MTCs with closely spaced and tilted coherent blocks are observed on bathymetric and
184 seismic data all over the mid-Norwegian margin, and also near the Storegga Slide, generating
185 a rugged seafloor (Solheim et al., 2005a; Micallef et al., 2007). Below these blocks, seismic
186 and sediment core data reveal a layer-parallel glide plane that propagates at present into intact
187 layers on the upper continental slope after lateral support was lost by the undercutting of the
188 lower continental slope (Locat et al., 2016; Giona Bucci et al., 2022). These layers comprise
189 soft marine clays interbedded with (harder) glacial deposits, resulting in weak layers with
190 lower shear strengths, higher sensitivity and excess pore pressures when compared to the
191 confining strata (L'Heureux et al., 2012; Ogata et al., 2014; Locat et al., 2016; Gatter et al.,
192 2021; Wu et al., 2022).

193 Propagating glide planes can eventually disrupt the overlying strata to form local
194 fractures and slabs on the upper continental slope (Laberg et al., 2013; Zhang et al., 2021).
195 These slabs can then be softened, fractured and fragmented by high dip-angle fractures,
196 ending up as a series of laterally spread blocks on a gentle submarine slope (Micallef et al.,
197 2007; Baeten et al., 2014; Wu et al., 2021). Due to internal softening, deformation and
198 sediment liquefaction, the size of these blocks often decreases with their transporting

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

201

202 **RESULTS**

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

204 The northwestward transport of Storegga Slide has been recorded by seafloor grooves
205 near the slide scar and intervals with discontinuous to chaotic seismic reflections (Haflidason
206 et al., 2004) (Figs. 1a and 1d). Detailed bathymetric and structure maps reveal the northwest
207 flank of the Storegga Slide (study area) as dipping to the southwest, with multiple small-scale
208 failures post-dating the Storegga Slide and five distinct terraces delimited by scarps - terraces
209 1 to 5 and scarps S1 to S6 (Figs. 1b and 1d). Structural relief varies significantly on these
210 terraces, from the smooth seafloor in Terrace 5 to the rugged 'L'-shaped Terrace 1
211 undercutting through scarps S1 to S3 (Figs. 1b and 1c).

212 In this study area, MTC 1 is recognized in the lower continental slope to fills ooze
213 evacuation structures (craters) below, perhaps as a result of focused fluid flow and sediment
214 density reversal during Slide W (Riis et al., 2005; Lawrence and Cartwright, 2010; Omosanya
215 et al., 2022). Above MTC 1, MTC 2 can be distinguished by its glide plane (Horizon H2) that
216 eroded the top of MTC 1, where a group of NW-striking furrows is recorded in Terrace 2
217 with a sinuosity approaching 1.01 (Horizon H2; Figs. 1d, 2a, 3d, and 4). Towards the
218 seafloor, a group of NW-striking grooves observed on both the relief and variance maps of
219 Terrace 2 reveals a similar location and geometry to the glide-plane furrows below (Figs. 3a,
220 3d and 4). Seafloor grooves and underlying furrows have identical orientations and length, as
221 well as the same location and geometry (Figs. 4c and 4d), representing the significant
222 differential compaction within MTC 2.

223 Apart from these seafloor grooves representing glide plane furrows, discrete
224 northwestward channels are recorded in MTC 2 by their differing variance and amplitude
225 value on the seafloor, correlating to the transport of MTCs derived from the upper continental
226 slope during the main Storegga Slide (Haflidason et al., 2004; 2005) (see Figs. 2c, 2d, 3b and
227 3c). These channels have an average sinuosity of 1.18 in Terrace 2, crossing the relatively
228 straight grooves (Figs. 3b, 3c, 4c and 5). Beyond the 5km wide 'L'-shaped ramp, the channels
229 in the southeast side upper slope reveal gently curved features with sinuosity about 1.02
230 (Figs. 2 and 5). The multiple grooves and sediment waves observed inside the turbidite
231 channels differentiate them from debris channels, which contain chaotic strata with high
232 variance coefficients (Fig. 2d).

233

234 **MTCs with Slide Blocks**

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

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

247 propagation of glide planes through stratigraphic weak layers (Gauer et al., 2005; Kvalstad et
248 al., 2005) (Fig. 7). These layer-parallel glide planes remove the support to overlying
249 consolidated strata where internal friction angle could up to 20-30 degree, resulting in the
250 generation of unstable slabs and subsequent fragmentation by steep (around 70-degree)
251 fractures, forming laterally spread square-shaped blocks (Micallef et al., 2007; Wu et al.,
252 2022).

253

254 *Slide S Blocks in Terrace 4*

255 Blocks in Slide S were translated above discrete glide planes identified at different
256 stratigraphic levels (see ‘shift point’ in Fig. 7c). Above these glide planes, most blocks are
257 curved on variance time slices (Fig. 6c). Blocks are 1000-2000 m apart and up to 80 ms tall
258 (Fig. 7). Their length (L) varies from 800 m to 3600 m, while their width (W) ranges from
259 200 m to 600 m (Fig. 9). These slide blocks become larger downslope, where an eroded and
260 irregular megablock is recognized (Figs. 6c and 7b). Moreover, a series of en echelon cracks
261 are found to cut through Unit 1 on the back of the headwall scarp where the slide blocks
262 originated from (Figs. 7b and 8a). The width of these cracks reaches only a few tens of
263 meters, while their length ranges from 1 km to 5 km. Between these sub-parallel cracks and
264 headwall scarps, incipient blocks and slabs are also identified (Fig. 8a).

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

271 7c. Sourced from these scarps, the subsurface channels cross Scarp 4 and terraces 3 and 4,
272 post-dating them after the main Storegga Slide (Figs. 1c, 6a-6b).

273

274 ***Slide R Blocks in Terrace 5***

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

285

286 **DISCUSSION**

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

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

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

299 The presence of undercut areas on the modern seafloor, and stratigraphic data from
300 sediment cores, suggest a southwestward slope failure has partially evacuated MTC 2 through
301 the 'L'-shaped ramp soon after the main Storegga Slide (Haflidason et al., 2005; Micallef et
302 al., 2009) (Figs. 1b and 1c). Slope instability associated with this failure could not be limited
303 to this 'L'-shaped ramp, as the failed MTC 2 is also observed in Terrace 2 (Figs. 2 and 4).
304 The evacuation of MTCs through Terrace 1 (the lower section of 'L'-shaped ramp) also
305 exposed the southwest scarp (S2) of Terrace 2 (Fig. 4). This enhanced the instability of MTC
306 2 in Terrace 2 by reducing its lateral support, and thus contributing to its remobilization.

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

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

316 2) Soon after, a southwestward slope failure sourced from the northwest flank
317 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).

324

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.

344

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.

362

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

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

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

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

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

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

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

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

422

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

424 A distinct feature of Slide S is the presence of larger blocks towards the lower
425 continental slope (Fig. 6c). Indicated by the cracks and incipient slabs on the upper slope
426 (Fig. 8a), these blocks are likely formed from the fragmentation of slabs and progressively
427 spread blocks (Fig. 10e). In contrast to retrogressively spread blocks, which have an
428 evacuated lower slope (Alves, 2015; Zhang et al., 2021), these progressive blocks are
429 laterally supported by slabs until they are fully fragmented (Dong et al., 2017; Debnath,
430 2018). However, accompanied by the formation of cracks in Terrace 5 and slope failures in
431 Terrace 4, recurrent reactivation of Slide S is perhaps related to the undercutting of the lower
432 continental slope. This removal of lower slope support could have triggered the long-term
433 instability of the progressively spread blocks. In comparison, retrogressively spread blocks
434 may not have been reactivated due to the pre-existing evacuation of their lower slope.

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

440 of low-angle extensional fractures. Instead, they led to the formation of high-angle faults
441 during block reactivation, as observed near the exposed scarps S4.1-S4.4 (Figs. 6b, 7c, and
442 10f).

443

444 **IMPLICATIONS**

445 The instability of continental slopes has been assessed in previous work, which gave
446 greater focus to pre-instability scenarios (Leynaud et al., 2009; Urlaub and Hjelstuen, 2020).
447 Monitoring seafloor deformation preceding slope failure requires multiple approaches, such
448 as the use of multibeam, geophysical and geodetic data (Maksymowicz et al., 2017; Urlaub et
449 al., 2018). Based on the mapping of geomorphological features from high-resolution 3D
450 seismic data, this work recognizes the presence of channels, seafloor failure scars and cracks
451 as materializing the reactivation of MTCs near the Storegga Slide. These observations
452 provide evidence for post-slide instability where emplaced MTCs remain unstable well after
453 their failure. These MTCs become the subject of instability, being reactivated to trigger
454 further instability features. Although this kind of seafloor deformation occurs locally near the
455 larger Storegga area, its potential to repeatedly remobilize near-seafloor strata must not be
456 ignored. Considering the wide distribution of MTCs along continental margins, such as the
457 Norwegian margin, Mediterranean Sea, West Africa, South China Sea and east USA
458 (Solheim et al., 2005a; Chaytor et al., 2007; Dalla Valle et al., 2015; Li et al., 2017; Sun et al.,
459 2018b), a re-evaluation of MTCs-driven slope instability is essential to protect submarine
460 infrastructure and coastal populations.

461

462 **CONCLUSIONS**

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

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

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

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

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

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

482

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497

498 **REFERENCES CITED**

- 499 Alves, T.M., 2010, 3D Seismic examples of differential compaction in mass-transport
500 deposits and their effect on post-failure strata: *Marine Geology*, v. 271, p. 212–224,
501 doi:10.1016/j.margeo.2010.02.014.
- 502 Alves, T.M., 2015, Submarine slide blocks and associated soft-sediment deformation in deep-
503 water basins: A review: *Marine and Petroleum Geology*, v. 67, p. 262–285,
504 doi:10.1016/j.marpetgeo.2015.05.010.
- 505 Alves, T.M., Cardona, S., and Rodrigues, M.C.N.L., 2022, Mass transport processes,
506 injectites and styles of sediment remobilization: *Deepwater Sedimentary Systems:
507 Science, Discovery, and Applications*, p. 361–406, doi:10.1016/B978-0-323-91918-
508 0.00013-X.
- 509 Alves, T.M., Kurtev, K., Moore, G.F., and Strasser, M., 2014, Assessing the internal
510 character, reservoir potential, and seal competence of mass-transport deposits using
511 seismic texture: A geophysical and petrophysical approach: *AAPG Bulletin*, v. 98, p.
512 793–824, doi:10.1306/09121313117.
- 513 Baeten, N.J., Laberg, J.S., Vanneste, M., Forsberg, C.F., Kvalstad, T.J., Forwick, M., Vorren,
514 T.O., and Haflidason, H., 2014, Origin of shallow submarine mass movements and their
515 glide planes—Sedimentological and geotechnical analyses from the continental slope off
516 northern Norway: *Journal of Geophysical Research: Earth Surface*, v. 119, p. 2335–
517 2360, doi:10.1002/2013JF003068.
- 518 Berg, K., Solheim, A., and Bryn, P., 2005, The Pleistocene to recent geological development
519 of the Ormen Lange area: *Marine and Petroleum Geology*, v. 22, p. 45–56,
520 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 Cyclicity, *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.

730

731

732 **FIGURE CAPTIONS**

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

748

749 **Figure 2. a)** Seismic profile showing typical turbidite and debris channels on the southeast
750 side upper continental slope. The location of the profile is shown in Figs. 1b and 2b-2d. MTC
751 1 was deposited in association with Slide W, before the Storegga Slide proper (Bryn et al.,
752 2003; Omosanya et al., 2022). **b)** TWT map of the seafloor (Horizon H1). The grooves and
753 sediment waves inside the turbidite channels distinguish them from debris channels, the latter
754 of which present a rugged internal character. Location of the TWT map is shown in Figs. 1b
755 and 1c. **c)** RMS amplitude map of the seafloor (H1). The chaotic facies of strata inside debris
756 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

782 S4 and Terraces 3 and 4. **c)** Variance-slice 50 ms above the basal glide plane (Horizon H3) of
783 laterally spread blocks. In Terrace 4, the size of Slide S blocks increases towards lower slope.
784

785 **Figure 7. a-c)** Selected seismic profiles across Terrace 4. The locations of the profiles are
786 shown in Fig. 6. Slide blocks in Units 1 and 2 are separated by scarp S5. Slide S blocks are
787 located on the lower continental slope (Unit 1) and were draped by a thin interval of
788 contourites. Seismic reflections in these contourites are continuous in the chasms but folded
789 and faulted above discrete slide blocks. The ‘eroded block’ in b) corresponds to the irregular
790 block in Fig. 6c, forming the largest block in Terrace 4. The seafloor scarps S4.1-S4.4 in Fig.
791 6b relate to underlying Slide S blocks 1-4 in c). Discrete glide plane below Slide S blocks
792 shift stratigraphic levels in c). Slide R blocks are located in Terrace 5 and are underlain by
793 incipient Slide S blocks and cracks.

794

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

803

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

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

809

810 **Figure 10.** Schematic diagrams summarizing the development of MTCs in the study area. **a-c)**
811 the unconsolidated MTC can be remobilized by slope undercutting and a reduction in lateral
812 support. **Stage 1:** During the main phase of Storegga Slide, massive sediments are removed
813 from the southeast side upper continental slope and transported northwestward as MTC 2. Its
814 glide plane eroded the top of the pre-existing MTC 1, generating a group of glide-plane
815 furrows with low sinuosity. Flow channels, such as turbidity and debris, were also developed
816 at this time. **Stage 2:** A local slope failure is sourced on the northwest flank of the Storegga
817 Slide, evacuating the MTCs around Terrace 2. Due to a reduction in its lateral support, the
818 unconsolidated MTC 2 was remobilized, causing its internal channels to become more
819 sinuous. **Stage 3:** Differential compaction in MTC 2 is controlled by structures (furrows) on
820 its glide plane, resulting in the formation of a group of straight grooves on the modern
821 seafloor, which cross-cut the previously formed channels. **d-f)** the instability of laterally
822 spread Slide S blocks was increased and triggered by slope undercutting. **Stage 1:** Together
823 with slide blocks retrogressively spread during Slide S (in Unit 1), the glide plane of the latter
824 slide propagated to the upper continental slope and fragmented the overlying strata. Incipient
825 slabs were generated between the evacuated scarp on the lower continental slope and seafloor
826 cracks on upper slope. **Stage 2:** During the downslope movement of slabs, laterally spread
827 blocks are generated from both their lower and upper boundaries, generating both
828 retrogressively and progressively spread blocks. Compared to the retrogressively spread
829 blocks, these progressive blocks are supported by slabs on the lower continental slope, near
830 which younger and larger blocks are located. **Stage 3:** Recurrent slope undercutting removed
831 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

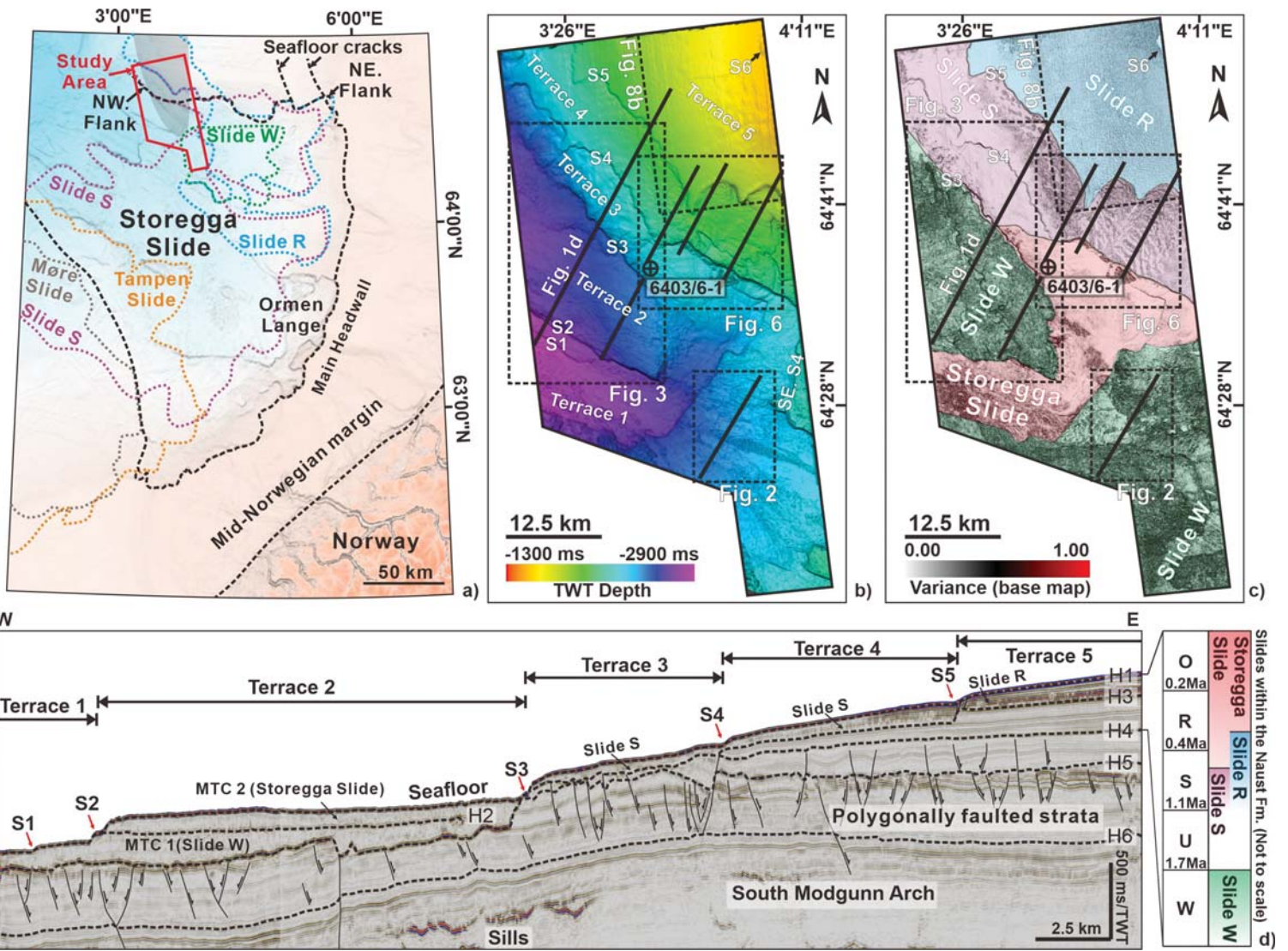


Figure 2

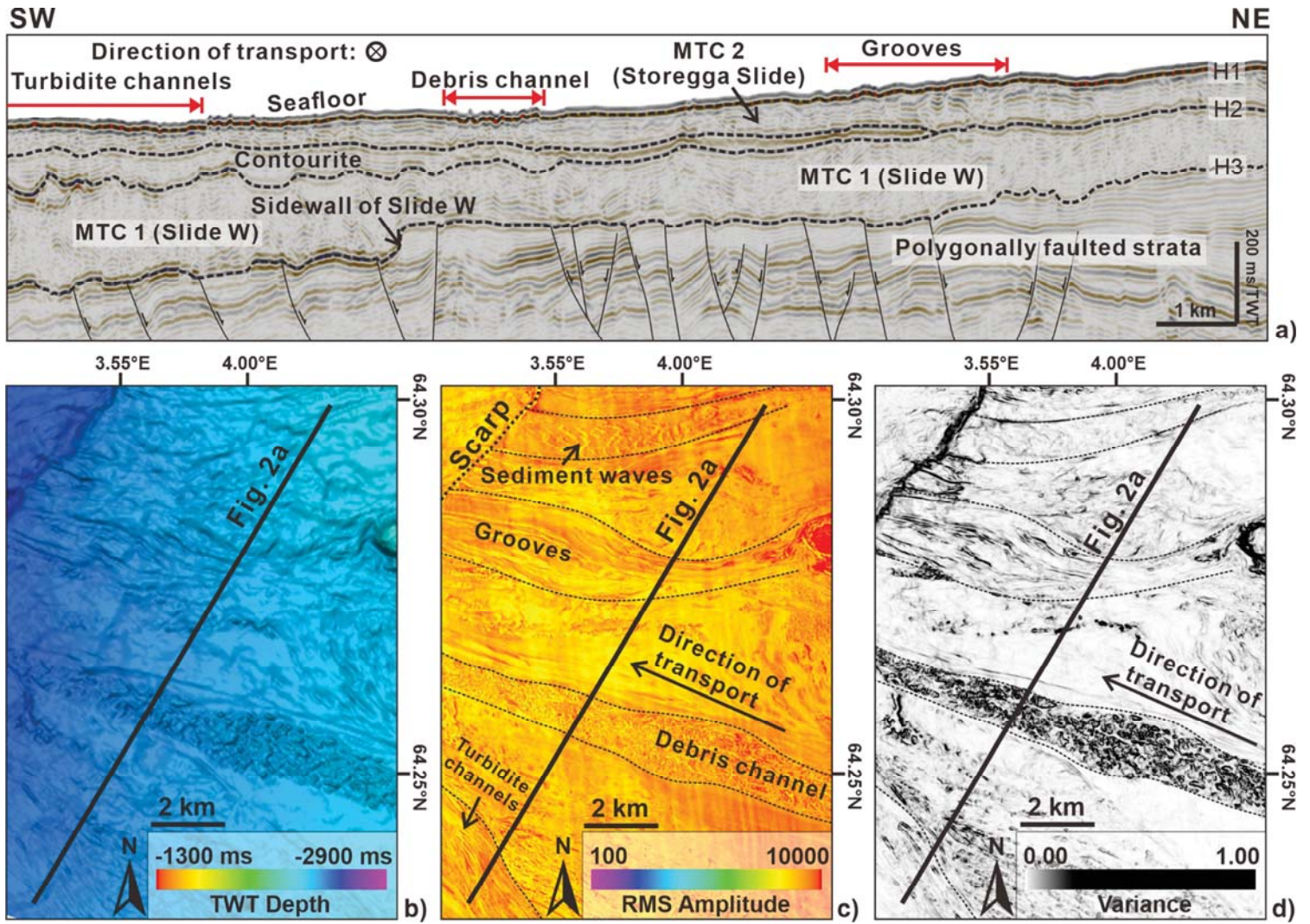


Figure 3

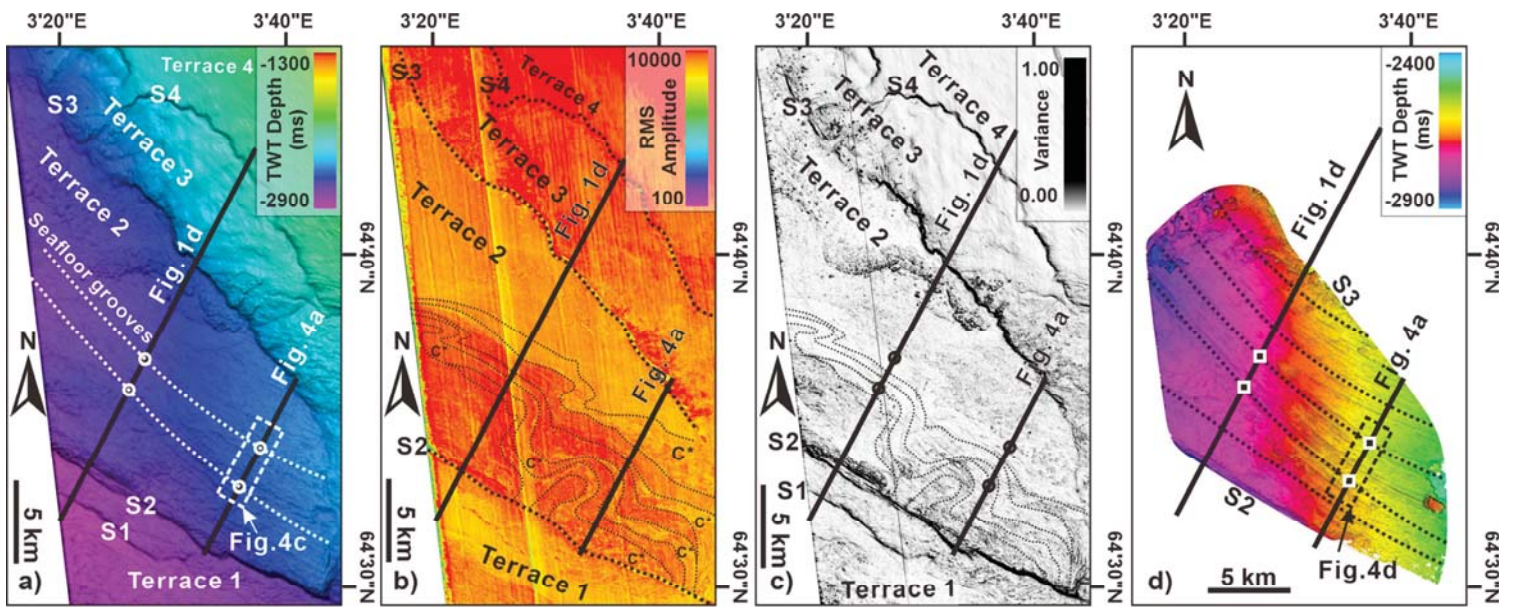


Figure 4

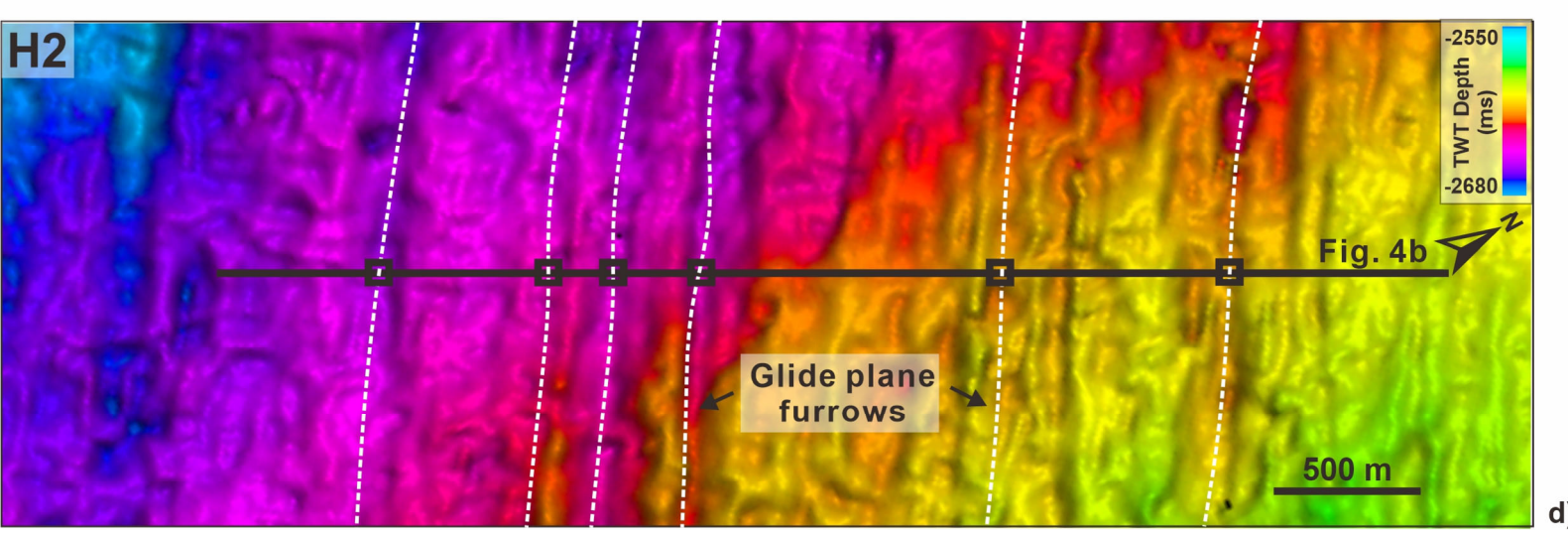
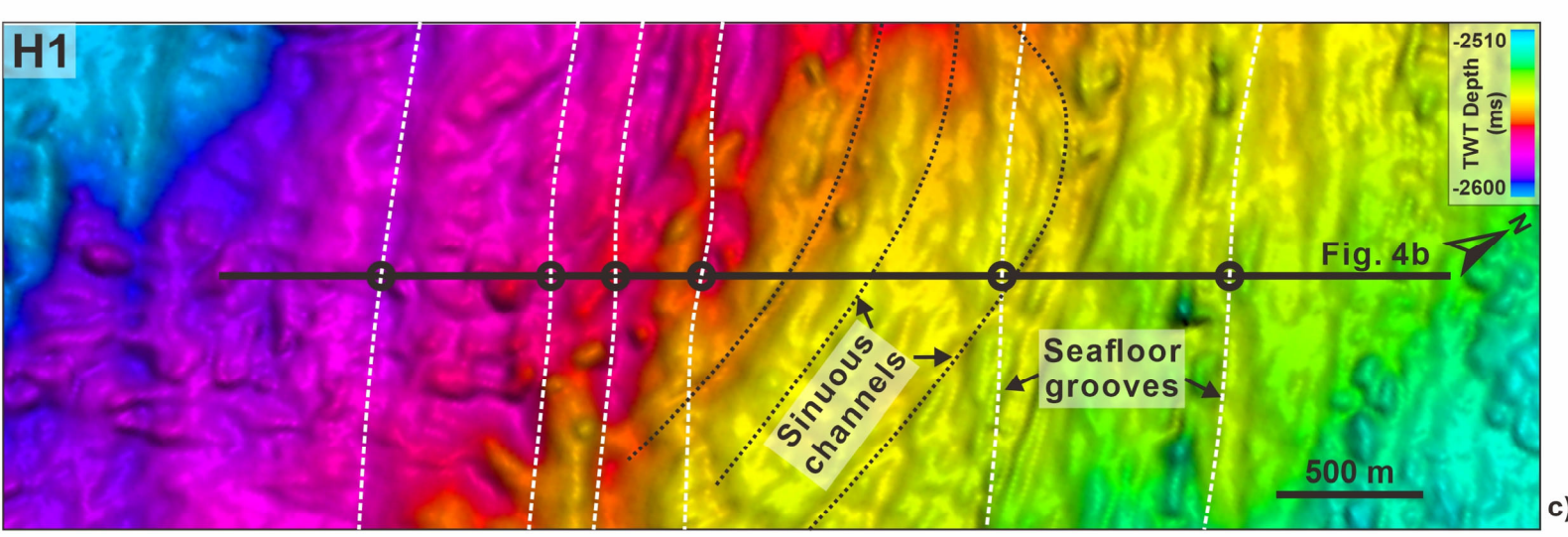
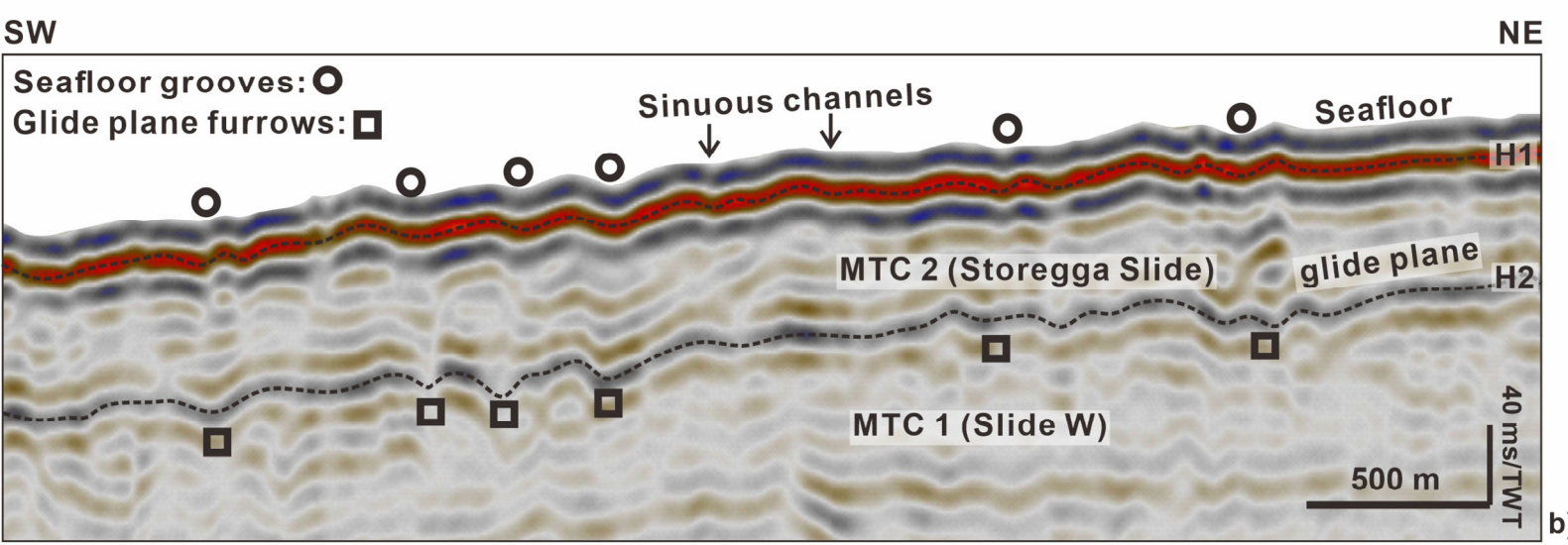
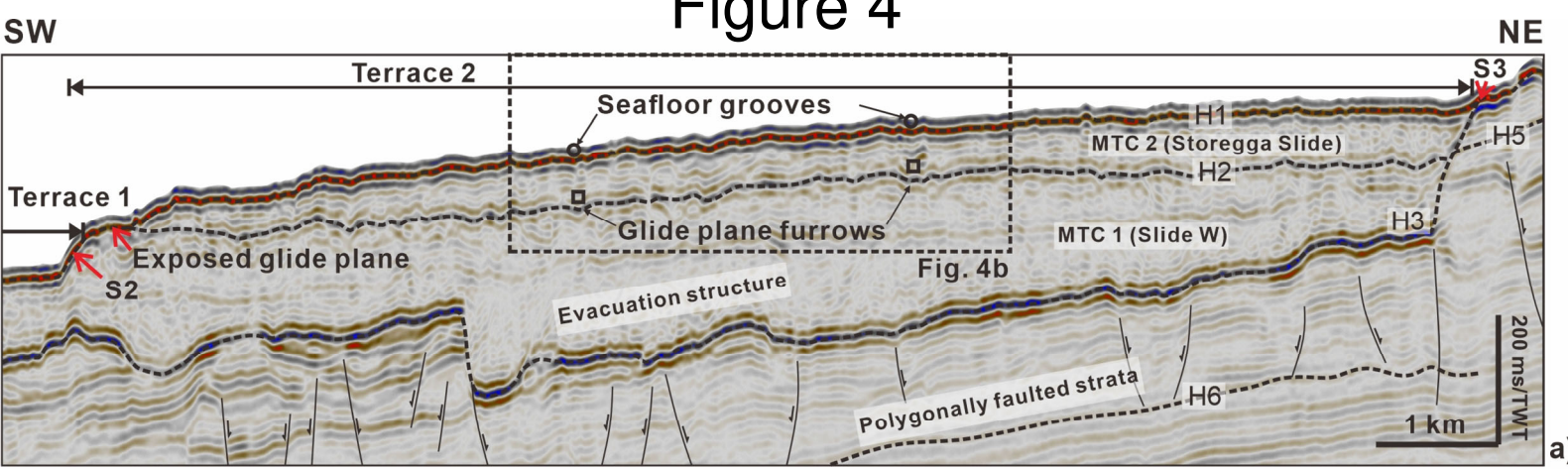
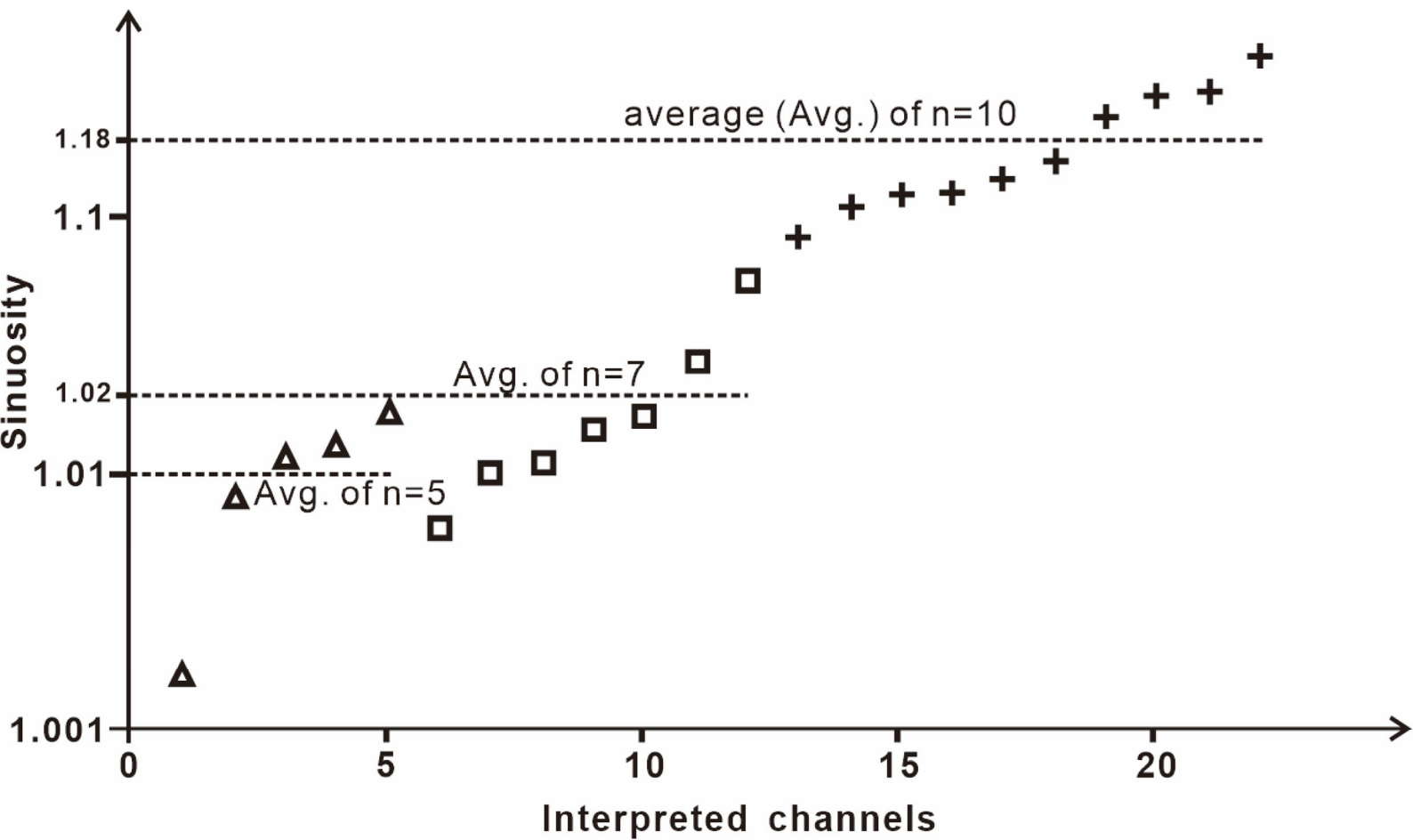


Figure 5



Key:

- ▲ Glide plane furrows below MTC 2 (Figs. 3d and 4d), n=5
- + Sinuous channels in MTC 2 (Figs. 3b-3c and 4c), n=10
- Straight channels in MTC 2 (Figs. 2b-2d), n=7

Figure 6

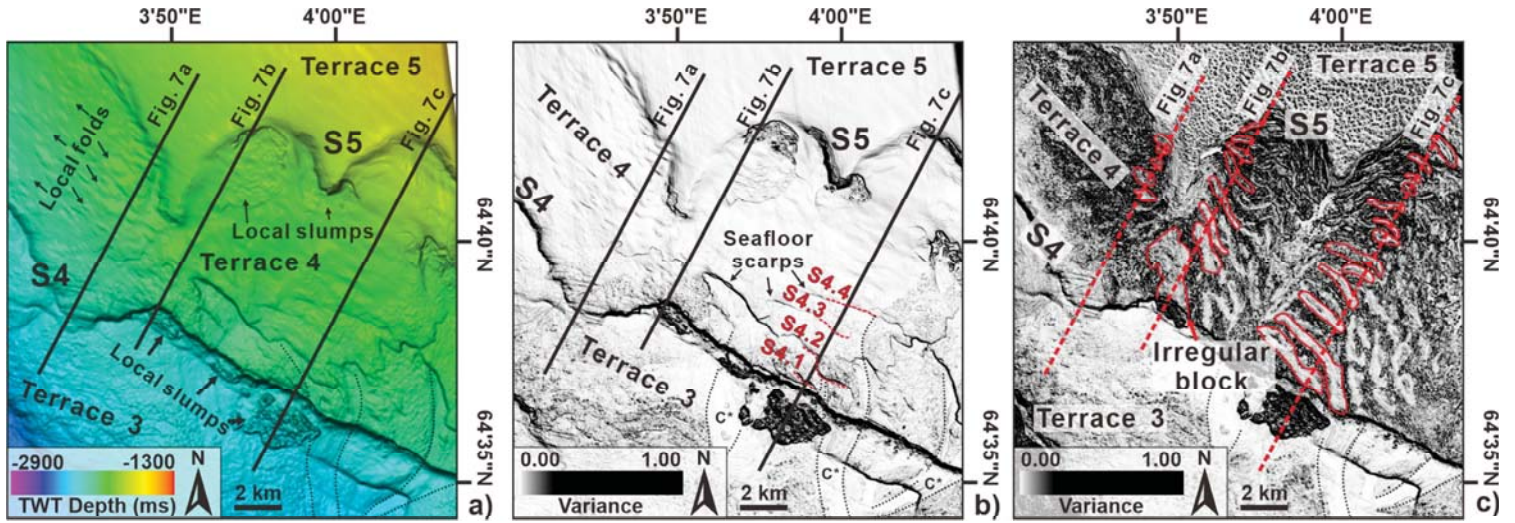


Figure 7

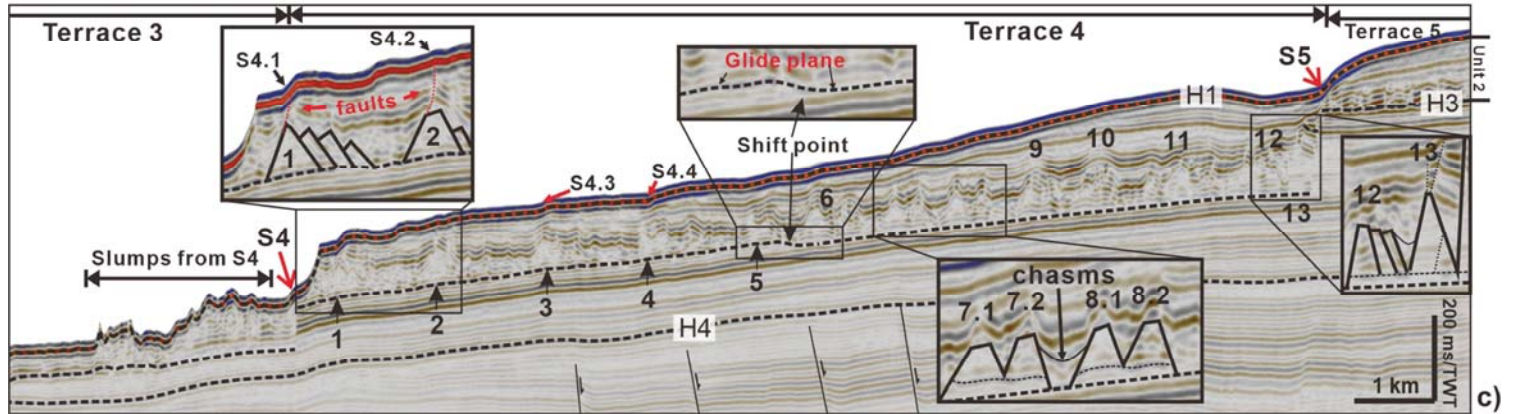
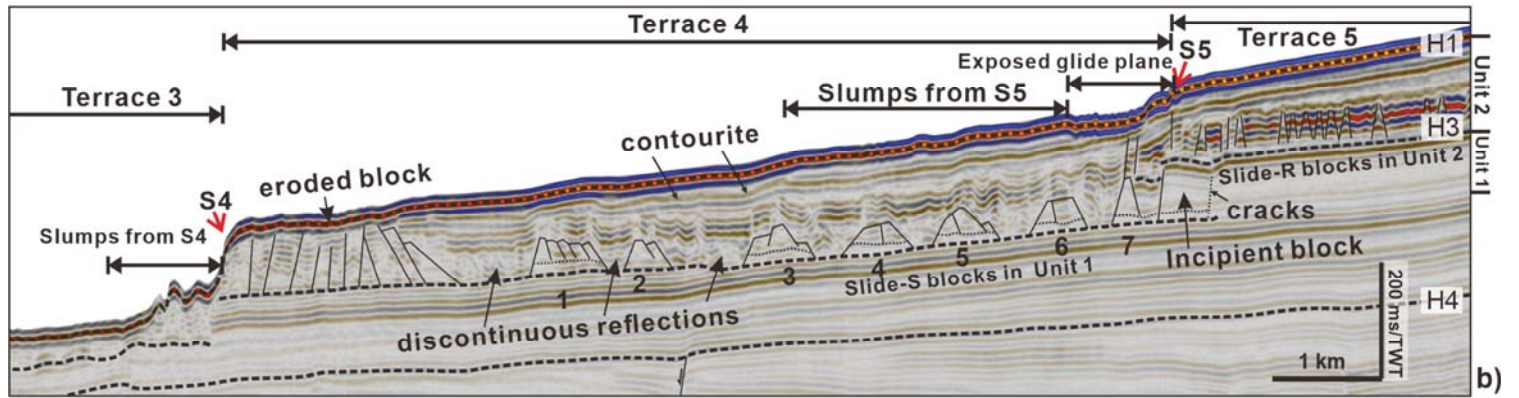
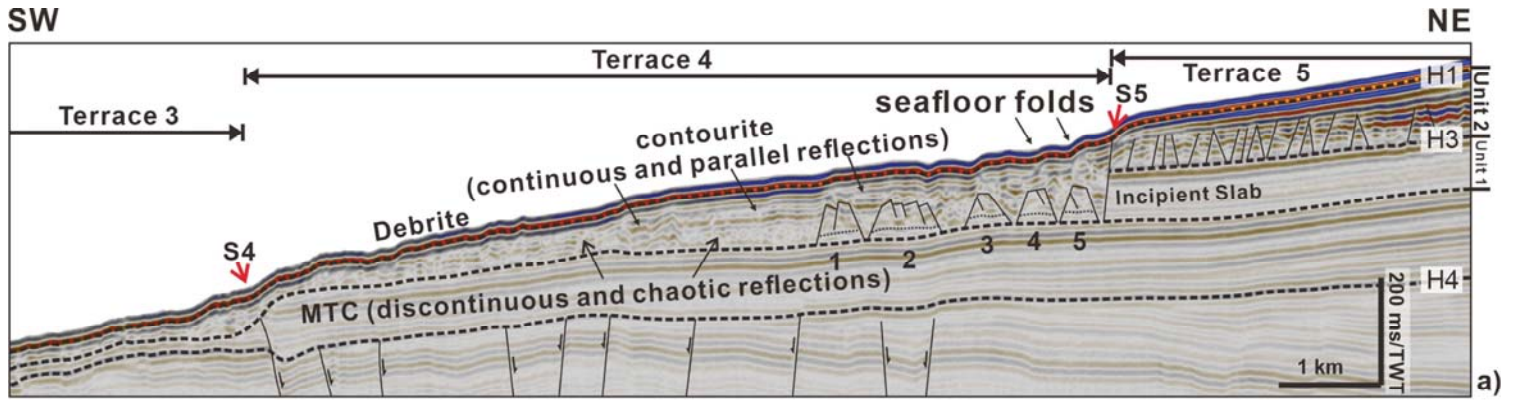
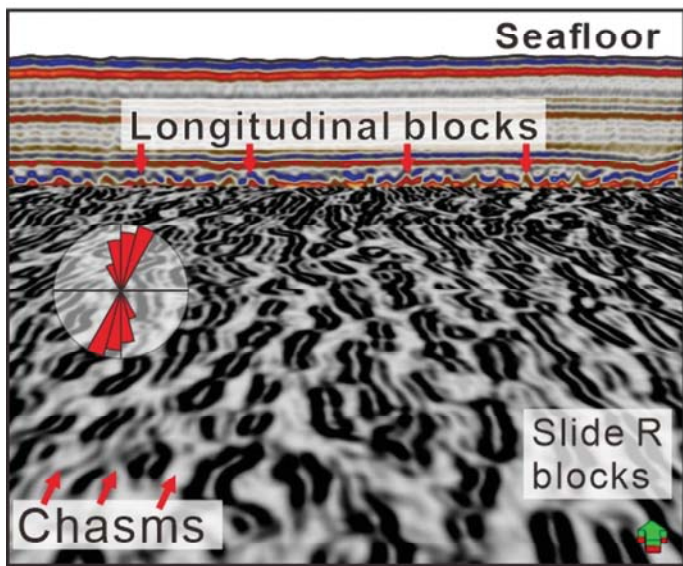
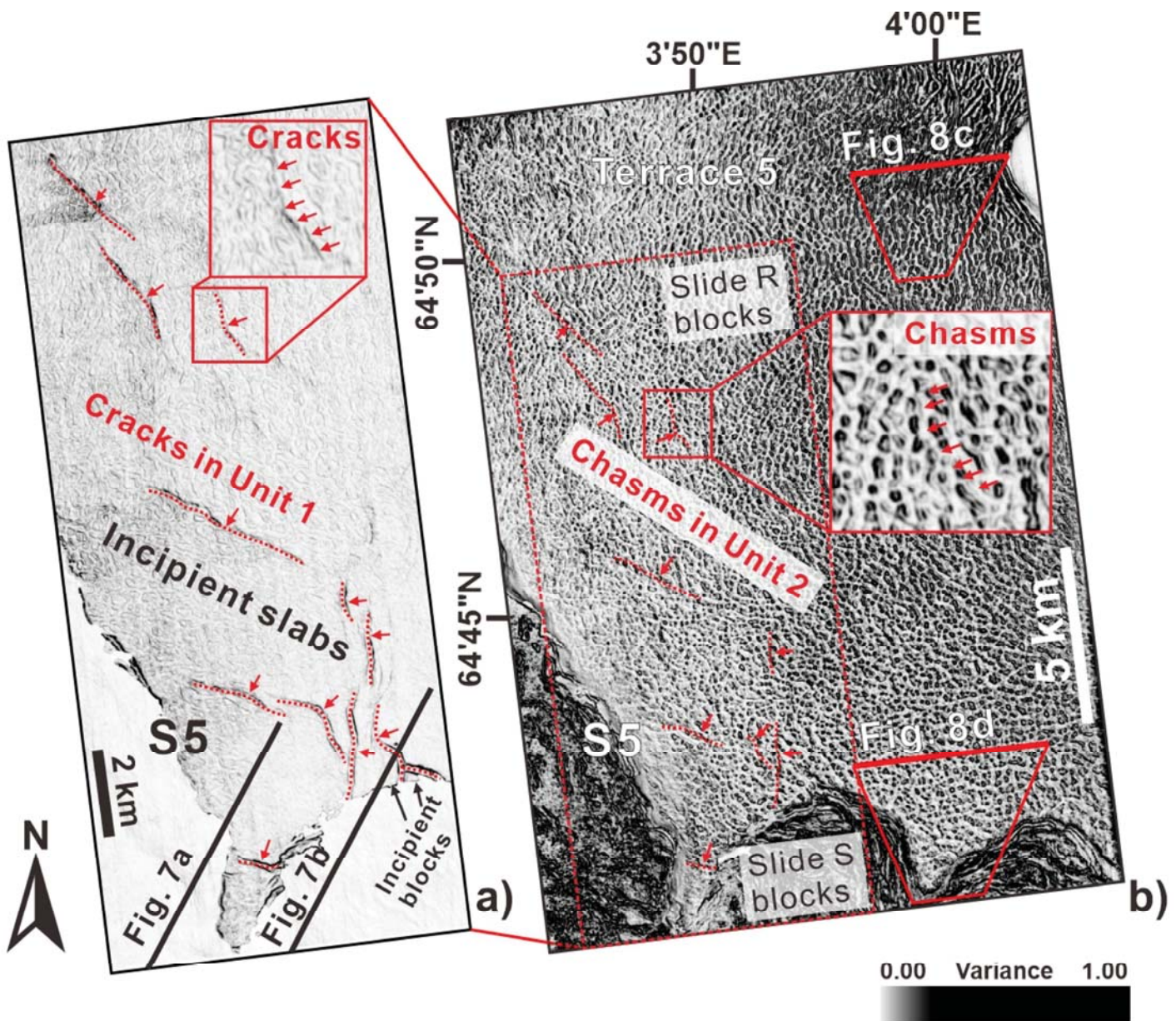
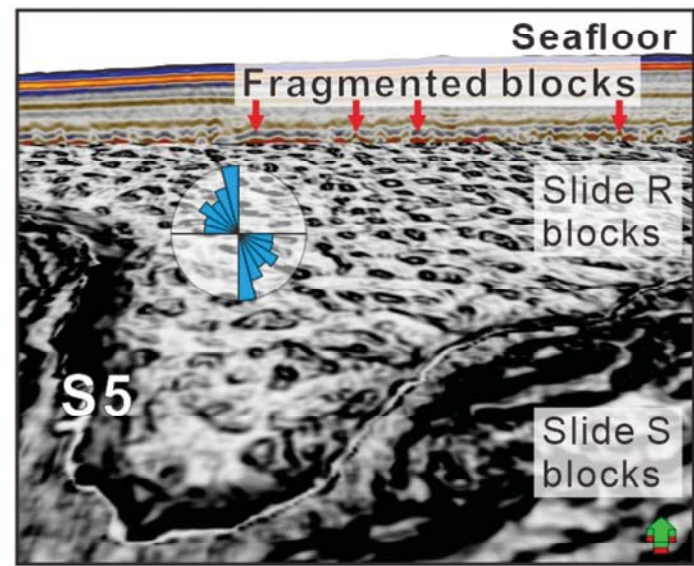


Figure 8



c)



d)

Figure 9

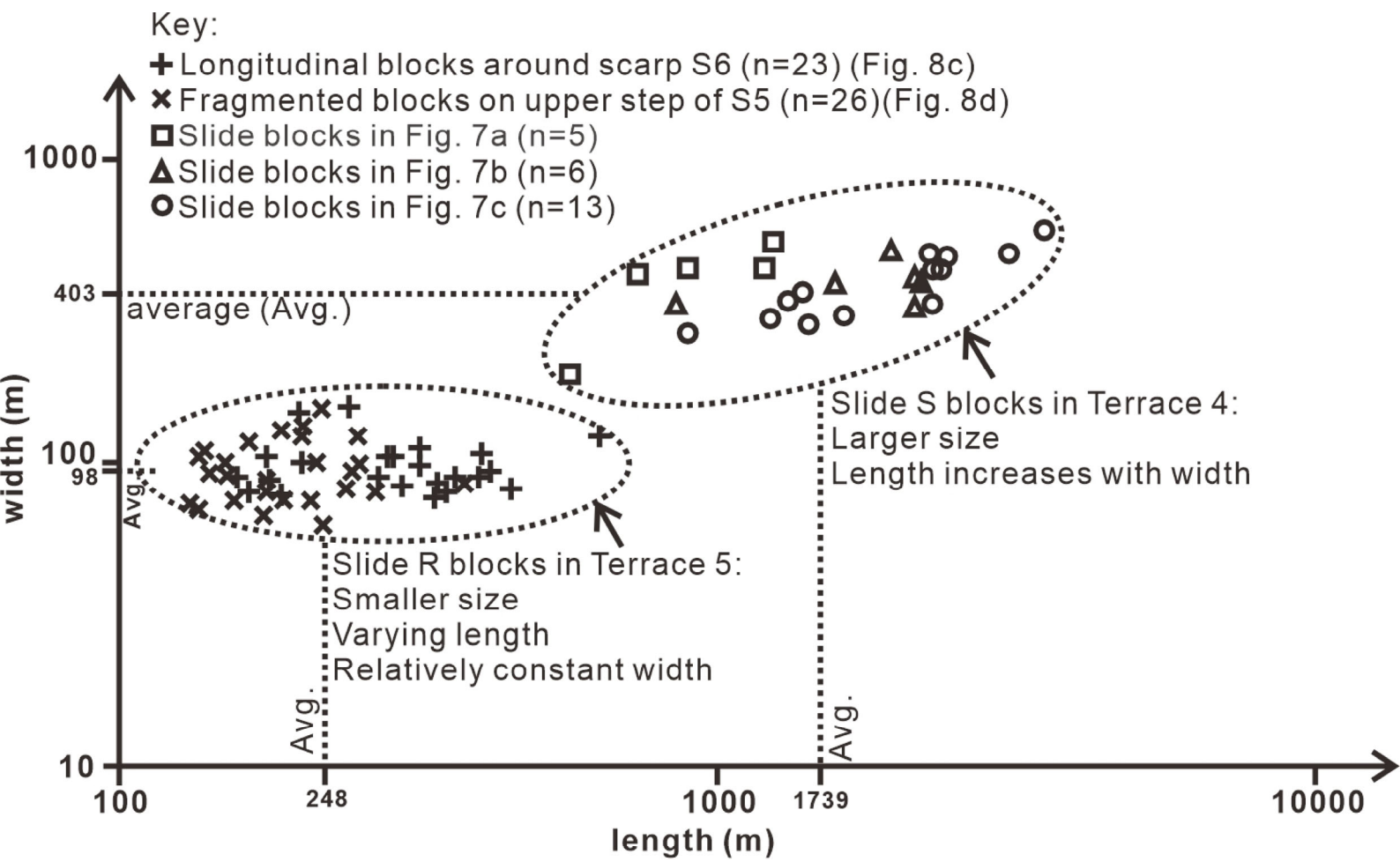
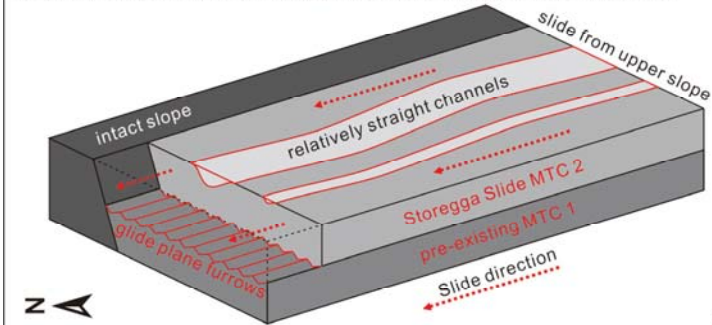


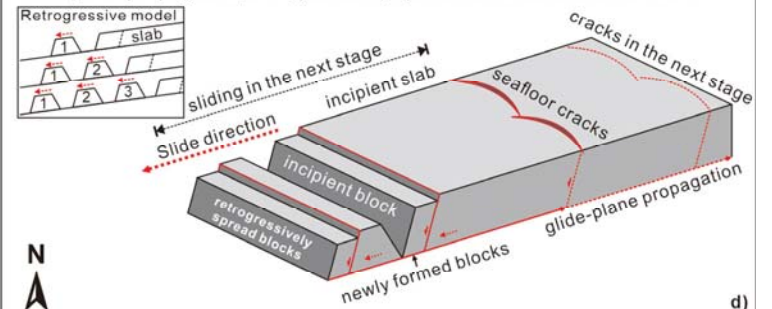
Figure 10

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



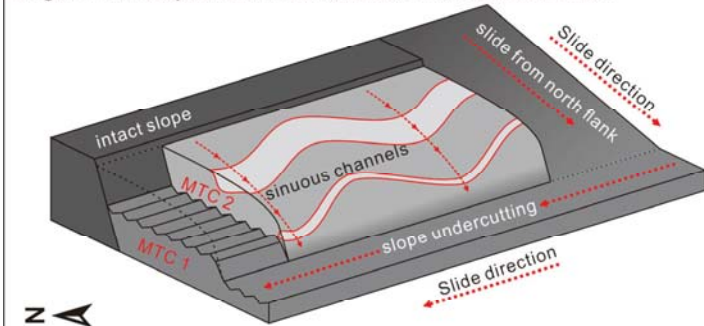
a)

Stage 1: Initiation of Slide S.
Glide-plane propagation, retrogressively spread blocks and slabs in Unit 1



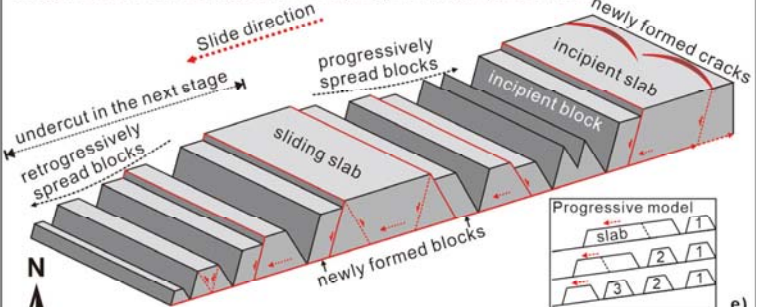
d)

Stage 2: Local slope failure reactivated the unconsolidated MTC 2



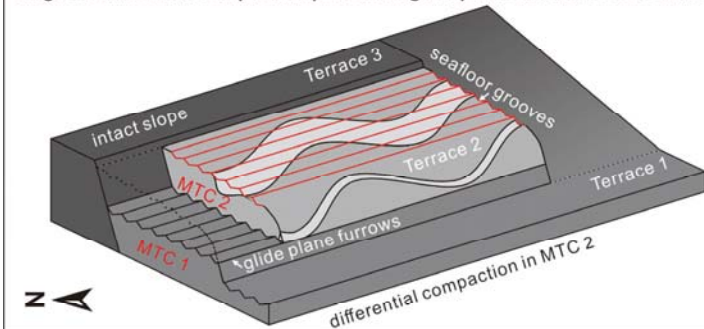
b)

Stage 2: Emplacement of Slide S MTCs.
Fragmentation of sliding slabs with progressively spread blocks



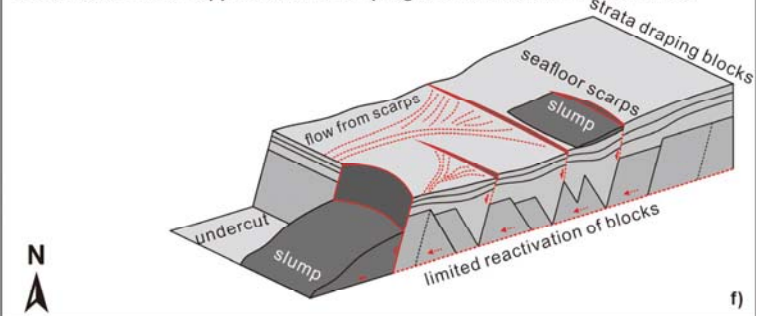
e)

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)