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The role of mass-transport complexes (MTCs) in the initiation and evolution of submarine canyons

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Abstract

The offshore area of the Otway Basin, located within the SE continental margin of Australia, is dominated by a multibranch canyon system where submarine mass-transport complexes (MTCs) are widely distributed. We integrate high-resolution multi-beam bathymetric and seismic reflection data to investigate the importance of regionally distributed MTCs in dictating the evolution of canyon systems. We interpret three regionally distributed MTCs that fail retrogressively and affect almost 70% of the study area. Within the MTCs, we observed seven canyons that initiated from the continental shelf edge and extended to the abyssal plain. Although these canyons share common regional tectonics and oceanography, the scales, morphology, and distribution are distinctly different. This is devoted to the presence of failure-related scarps (i.e. headwall and sidewall scarps) that control the initiation and formation of the canyons. The retrogressive failure mechanisms of MTCs have created a series of the headwall and lateral scarps on the continental shelf and slope regions. In the continental shelf, where terrestrial input (i.e. fluvial systems) is absent, the origin of the canyons is related to the local failure events and the contour current activities occurring near the pre-existing, massive headwall scarps (c. 120 m high, 3km long). The occurrence of these local failures has provided the necessary sediment input for subsequent gravity-driven, downslope sediment flows. In the continental slope region, the widespread scarps can capture gravity flows initiated from the continental shelf, developing an area of flow convergence, which greatly widens and deepens the canyon system. The gradual diversion and convergence through MTCs related scarps have facilitated the canyon confluence process, which has fundamentally changed the

28 canyoning process. Thus, we conclude that the retrogressive failure mechanism of MTCs has a
29 direct contribution to the initiation, distribution, and evolution of the canyons, especially in areas
30 where fluvial input is missing. Moreover, the retrogressive failure mechanism is responsible for the
31 canyon deepening and confluence process, which can greatly facilitate the delivery of sediment
32 into deep oceans.

33 1. Introduction

34 Submarine canyons are defined as steep-sided V- or U-shaped valleys that are cutting into the
35 seabed, extending from the continental shelf to the continental slope areas, with numerous
36 tributaries entering from both sides (Shepard et al., 1966; Twichell and Roberts, 1982; Obelcz et
37 al., 2014). Canyons are complex geomorphology features formed by erosion from sediment gravity
38 flows occurring near the continental margins (Shepard, 1972; Canals et al., 2006; Harris and
39 Whiteway, 2011). Canyons are often associated with sand-rich gravity flows and submarine fans
40 are thus considered as modern analogues for deepwater hydrocarbon reservoirs (Stow and Mayall,
41 2000; Weimer and Slatt, 2004). Mass-transport complexes (MTCs) are gravity-driven shear failure
42 deposits resulting from creep, spread, slide, slump and debris flow processes (Posamentier and
43 Martinsen, 2011; Wu et al., 2021). MTCs can be extremely erosive, thus containing large volumes
44 of sediments, with single deposits covering areas of $>100 \text{ km}^2$ and volumes $>10,000 \text{ km}^3$ (Frey
45 Martinez et al., 2005; Moscardelli and Wood, 2016; Nugraha et al., 2019). MTCs normally fail
46 retrogressively (i.e. backstepping slope failures), the emplacement of MTCs can leave a series of
47 giant slide scars (c.2-5 km wide) on the continental slope areas (Figure 1a, 1b; i.e. Williams, 2016;
48 Li et al., 2017). Both MTCs and canyons can transfer large amounts of sediments between the
49 continental shelf and abyssal plain environments, they are considered as important sediment
50 transportation conduits in deepwater settings (McAdoo et al., 2000; Popescu et al., 2004; Antobreh
51 and Krastel, 2006; Lee et al., 2007; Urgeles and Camerlenghi, 2013).

52 Submarine canyons and MTCs have a close relationship in terms of their spatial distribution,
53 triggering mechanisms, and preconditioning factors (Micallef et al., 2012; Watson et al., 2020). The
54 emplacement of MTCs can represent the early phase of submarine canyon initiation, providing
55 early depressions on the continental slopes that extend to the shelf break (Farre et al., 1983). The

56 continuous downcutting process associated with canyon development can steepen the gradient of
57 canyon sidewalls, which preconditions the intra-canyon MTCs near the canyon walls (i.e. Farre et
58 al., 1983; Green and Uken, 2008). The intra-canyon MTCs occur retrogressively, increasing the
59 canyon's width (i.e. lateral extension; Pratson and Ryan, 1994) and extending the canyon upslope
60 (i.e. headward incision; Farre et al., 1983; He et al., 2014). Most of the published works have
61 focused on constraining local, coeval, intra-canyon MTCs (senus detached MTCs; Moscardelli and
62 Wood, 2008) with the evolution of the canyons (i.e. Green and Uken, 2008; Gong et al., 2011; He
63 et al., 2014; Su et al., 2020). The relationship between canyons with the regional distributed MTCs
64 (i.e. 100s to 100,000s of km²) (senus attached MTCs; Moscardelli and Wood, 2008) that typically
65 fails retrogressively, have largely been overlooked. Relatively little is known on how regionally
66 distributed MTCs, especially how their retrogressive failure mechanism can influence the initiation,
67 evolution, and morphology of submarine canyons. Therefore, this study uses a high-resolution (c.
68 10 m vertical resolution) 3D seismic reflection dataset, integrated with 2D seismic and multi-beam
69 data to analyse the spatial and temporal relations between canyons and regional distributed MTCs
70 in the Otway Basin, southern Australia (Figure 2a, 2b).

71 2. Geological setting

72 2.1 Tectonic

73 The Otway Basin is a broadly NW-SE striking offshore non-volcanic, rift basin located along the SE
74 Australian passive margin (Figure 2). The basin was initiated by late Jurassic to early Palaeogene
75 rifting, during the progressive breakup of southern and eastern Gondwana. After experiencing
76 multistage rifting, thermal subsidence and inversion, the south Australian margin ultimately broke
77 with Antarctica at the end of the Cretaceous (approximately 67 Ma; Willcox and Stagg, 1990;
78 Perincek and Cockshell, 1995; Krassay et al., 2004; Totterdell et al., 2014). Although the detailed
79 history of the separation and final breakup between Australia and Antarctica remains partially
80 studied (Gibson et al., 2013; Holford et al., 2014), the formation of a regionally distributed
81 Maastrichtian unconformity has been attributed to the eventual separation of Australia and
82 Antarctica Plates (Figure 3; Krassay et al., 2004; Holford et al., 2014).

83 2.2 Sedimentology

84 Sedimentary successions in the Otway Basin during Cenozoic has been progressively influenced by
85 marine-related, often calcareous-rich sediments, reflecting an open marine depositional
86 environment (McGowran et al., 2004). The Cenozoic post-rift sedimentation is represented by the
87 Wangerrip Group (late Palaeocene to middle Eocene, mainly siliciclastic rich), the Nirranda Group
88 (middle Eocene to early Oligocene, mainly containing sandstones and marls), the Heytesbury
89 Group (late Oligocene to late Miocene, mainly contains marls and limestones), and the Whalers
90 Bluff Formation (WBF; Pliocene-Recent, mainly contains a mixed siliciclastic-carbonate sediments)
91 (Figure 3a; Dickinson et al., 2002; Krassay et al., 2004; Holford et al., 2014). Our study interval lies
92 in the WBF formation at a time when the study area was in a passive continental margin setting. In
93 the continental slope area, thick, localised sediments deposited in the Pliocene-recent succession
94 represent marine clastic sediments deposited in the submarine canyons (Figure 3b, 3c) (Tassone et
95 al., 2011).

96 *2.3 Oceanography*

97 Two shelf break currents dominate the current day ocean circulation in the study area (Duran et
98 al., 2020): (i) the eastward-flowing South Australia Current (SAC) and (ii) the south-eastward-
99 flowing Zeehan Current (ZC) (Figure 2b). The South Australia Current is a eastward flow with high
100 salinity, high velocity (0.5 m/s), it is flowing down to 300 m water depth (Duran et al., 2020). The
101 Zeehan Current is fed by the South Australian Current, it is a poleward current with low salinity,
102 and high current velocity (0.4 m/s), flowing down to 300 m water depth (Ridgway, 2007).

103 As the fluvial activity is limited in the study area (McGowran et al., 2004), the mounded seismic
104 facies (sub-parallel to wavy, low- to high amplitude, internal truncations) in the WBF Formation
105 have a clear indication of the contour current activity (Figure 3b, 3c; i.e. Nugraha et al., 2018). The
106 modern canyons show a clear eastward lateral migration compare to the buried Pliocene canyons
107 in the continental shelf region (Figure 3c). These observations all indicate the overall eastward shelf
108 break parallel currents (SAC and LC) affect the sedimentary processes in the continental shelf
109 region.

110 **3. Dataset and Methodology**

111 *3.1 Multibeam Dataset*

112 The multi-beam echosounder bathymetry data is provided by Geoscience Australia
113 (<https://portal.ga.gov.au/persona/marine>), covering an area of c. 12,000 km² (Figure 4a). The
114 lateral resolution of the data is 50 × 50 m, it enables the identification and interpretation of seafloor
115 morphology and associated canyons and MTCs, especially in areas absent of seismic-reflection data
116 (Figure 4a).

117 *3.2 Seismic Dataset*

118 The 3D pre-stack time migrated (PSTM) seismic-reflection data were acquired by Santos in 2002,
119 located in the vicinity of Portland, offshore SE Australia (Figure 2b). The survey covers an area of c.
120 360 km² with a bin spacing of 25 m × 12.5 m (inline × crossline), and a dominant frequency of 50
121 Hz at the seabed. We estimate that the spatial resolution of the seismic data, given an average
122 velocity of the near seabed sediment derived from the seismic report (1824 m/s), is c. 9 m. The 3D
123 seismic data are zero-phase, and presented in SEG normal polarity with an increase in acoustic
124 impedance expressed as a positive amplitude.

125 *3.3 Methodology*

126 The seismic-stratigraphic framework is correlated with Holford et al. (2014) work in the adjacent
127 area. Seismic and multi-beam data are used to map MTC and canyon related features. The key
128 morphometric parameters of the canyons (i.e. canyon width and height) are quantitatively
129 measured and discussed to reveal the sedimentary processes involved in the canyon origin and
130 evolution. In this study, the canyon width is defined as the distance between the canyon shoulders.
131 The canyon height is defined as the depth from the canyon shoulder to the canyon base.

132 **4. Result**

133 *4.1 Morphology of the study area*

134 The study area spans from the continental shelf, to slope, to abyssal plain environment (Figure 4a).
135 The morphology of the study area is characterised as having a narrow (c. 7km) and steep slope
136 (Figure 4a). The continental shelf area dips from 0.4° to 1° with an average water depth of 250 m
137 (Figure 4a). The continental slope area is characterised by a relatively gentle slope of c. 10° in the
138 upper section, to a steep slope gradient of c. 30° near the lower section, with water depths ranging
139 from 600 m to 1500 m, respectively (Figure 4a). The multi-beam and seismic data reveal several

140 canyons initiated from the continental shelf region, spanning the continental slope, and ultimately
141 terminating in the abyssal plain (Figure 4a). The topographic profiles extracted from the multi-
142 beam data showed dramatic differences in the across-canyon margin morphology (Figure 4b). The
143 width of canyons increases along with the dip of the slope, with canyons converging at the abyssal
144 plain (Figure 4b, 4c).

145 *4.2 MTCs and canyons*

146 Three MTCs (MTC-1, MTC-2, and MTC-3) have been interpreted in the study area (Figure 5a, 5b).
147 Seismic data reveals several distinctive NNW-SSE oriented extensional scarps, and NE-SW oriented
148 lateral extensional scarps near the shelf-edge, and within the slope and abyssal plain (Figure 5b).
149 The arcuate NNW-SSE dipping extensional scarps are interpreted as MTC headwall scarps that mark
150 the updip part of an MTC, where extensional deformation dominates (Figure 5b; i.e. Bull et al.,
151 2009). The NE-SW dipping lateral scarps are interpreted as MTCs lateral margins that separate
152 deformed sediments (MTCs) from the undeformed seabed (Figure 5b; i.e. Frey Martinez et al., 2005;
153 Bull et al., 2009). Based on the orientation of headwall scarps and lateral margins, the MTCs are
154 predominately transported subparallel to the dip direction of the slope.

155 Seven major canyons (canyon 1-7) spanning from continental shelf to abyssal plain are observed
156 within the MTC influenced area (Figure 5a, 5b). They are oriented NNW-SSW on the continental
157 slope, sub-parallel to the dip direction of the slope. Canyon-1-3 and Canyon-7 are initiated from
158 shelf edge headwall scarps with clear landward incision features, while Canyon-4-6 are restricted
159 in the continental slope (Figure 5b). As the study area is disconnected to the modern fluvial system
160 (Leach and Wallace, 2001), which indicates a limited sediment input at or near the canyon heads.
161 The canyons are thus relatively sediment starved as compared to canyons connected with direct
162 fluvial input (e.g. the Type 1 canyons from Jobe et al., 2011).

163 *4.3 MTC-1*

164 In MTC-1, multiple headwall scarps (HS-1 to HS-5) and their associated lateral margins are observed
165 from the map view and the correlated seismic sections (Figure 6a, Figure 7a). Headwall scarps are
166 recognised as upward concaved lineation with scallop-shaped geometry (Figure 6b). In the seismic
167 dip section, the headwalls are nested in a terraced style, showing a truncated reflector that cuts
168 through upslope sediments (Figure 7a). The heights and angles of the scarps vary considerably
169 throughout MTC-1, with the highest (c. 170 m) and steepest (c. 40°) HS-5 occurring in the upper

170 part of MTC-1 (Figure 7b). The other four headwall scarps (HS-4 to HS-1) are comparatively smaller
171 and gentler than HS-5, with similar morphology and distributed in the central part of the MTC-1
172 (Figure 7b-d). The middle part of MTC-1 has a hummocky seabed expression in map view and
173 contains chaotic and blocky seismic facies in seismic section (Figure 6b, 7a). A clear basal shear
174 surface with a gentle gradient (c. 3°) that separates the underlying layered seismic facies from the
175 overlying chaotic seismic facies has been observed below the HS-4 and HS-1 (Figure 7a). The
176 chaotic and blocky facies accumulated downdip to the HS-4 and HS-1, showing a wedge-shaped
177 geometry in seismic section (Figure 7a, 7c) and a fan shaped geometry in plain view (Figure 6b).
178 The presence of the backstepping stair shape geometry, the relative flat basal shear surface, and
179 the deposition of chaotic seismic facies near the distal part of HS-4 and HS-1, suggests that the
180 initial failure started at the lowermost part of MTC-1 and propagated retrogressively towards the
181 upper slope area. We thus interpret multiple headwall scarps (HS-1 - HS-5) resulting from multiple
182 retrogressive failure events, such as recorded in the Storegga slide and other MTCs (i.e. Bryn et al.,
183 2005; Sawyer et al., 2009; Badhani et al., 2020). The occurrence of retrogressive failure has resulted
184 in linear to sinuous depression features in plan-view (Figure 6b), and small-scale faults or fractures
185 in seismic cross-section (see headwall scarps in Figure 7b-d).

186 *4.4 Canyons in MTC-1*

187 In the upper section of MTC-1, the canyon system comprises three tributaries (Canyon-1 to Canyon-
188 3; Figure 6b, 7b). They are originally initiated from the scarps near the shelf edge (Figure 5).
189 Canyon-1 and -2 are developed in the NE part of MTC-1, while Canyon-3 is in the NW part (Figure
190 6b). Canyon 1-3 have more pronounced seabed erosion than MTC-1. Near the HS-5, clear seabed
191 incision and truncations can be observed in the seismic sections that image the canyons (Figure
192 7b). Canyons 1-3 have a linear geometry in map view. The cross-sectional geometry of canyons is
193 generally U-shaped, with a gently sloping base surface (c. 1°) and steep canyon sidewalls (c. 60°)
194 (Figure 7b, 7c). Canyons 1-3 trend downslope from the continental shelf towards the HS-5 of MTC-
195 1 and converge near the HS-3 (the confluence point; Figure 6b), and ultimately converging into a
196 broad canyon after passing through HS-2, at a water depth 1522 m to 1595 m (Figure 6b, 7d).
197 Numerous crescentic bedforms and axial incisions are observed along the axis of Canyon 1-3
198 (Figure 6b). In the pre-confluence region (abyssal plain area), the Canyons 1-3 ranges from c. 100
199 m to c. 670 m wide and c. 20 m to 134 m high (Figure 7e, 7f). In the post-confluence area, the width

200 increases from c.370 m to c.1140 m, which is 2-3 times wider than that of in the pre-confluence
201 region (Figure 7e). The canyon height increases from c. 90 m to c. 140 m in the post-confluence
202 area, slightly larger than the canyons in the pre-confluence area (Figure 7f).

203 This stratigraphic relationship between canyons and MTC-1 indicate that the deposition of the
204 MTC-1 occurred prior to the initiation of canyons. The crescentic bedforms are possibly associated
205 with supercritical currents (i.e. Zhong et al., 2015), suggesting gravity flows are still being initiated,
206 and canyons are remaining active as a sediment pathway today. Quantitative analyses of the
207 canyons indicate a strong correlation exists between the canyon width/height with distance along
208 the different MTC-1 headwall scarps. The sharp increase of the canyon's width and depth after the
209 confluence point (near the HS-3) indicate headwall scarps has played a key role in dictating the
210 canyon morphology and erosivity. We thus indicate the topography within MTC-1 was established
211 as a function of topographic confinement imposed by the backstep headwall scarps. The existence
212 of the headwall scarps can facilitate the canyon widening and deepening process.

213 *4.5 MTC-2 and MTC-3*

214 MTC-2 was deposited at the west of the MTC-1 (Figure 5b). MTC-2 has an E-dipping main headwall
215 scarp located in the lower slope setting, a south-dipping western lateral margin, and its eastern
216 lateral margin has been eroded by the MTC-1 (Figure 8a, 8b). MTC-2 contains four internal headwall
217 scarps (HS-1 to HS-4; Figure 8b) and associated lateral margins. Along the proximal part of the
218 western lateral margin, the sidewall displays up to at least three levels of local retrogressive failures
219 that make the west lateral margin complexed (Figure 8b). The cross-cutting relationship between
220 MTC-1 and MTC-2 reveals MTC-2 occurred after the MTC-1. Similar to MTC-1, the multi-headwall
221 scarps are the result of the retrogressive failure events associated with the emplacement of MTC-
222 2. MTC-3 was deposited in the west of the study area (Figure 5b). Distinctive NNW-ESE dipping
223 headwall scarps can be only identified near the upper boundary of the MTC-3 (Figure 8b). Scarps
224 in MTC-3 are significantly less than those in the MTC-1 and MTC-2 (Figure 8b).

225 *4.6 Canyons in MTC-2*

226 Two canyons (Canyon-4 and Canyon-5) that initiated from the lower slope setting, incised across
227 MTC-2, with a little (c. <50 m height) bathymetric expression in plain view (Figure 8a, 8b). The
228 morphology of Canyon-4 is only visible in map view near the lower slope, and it loses surface
229 expression at the location of HS-4 (Figure 8b). Upslope from the Canyon-5 head, two channels are

230 observed from map view (Figure 8b). The morphology of Canyon-5 meanders around the headwall
231 scarps within MTC-2, being initially WNW-SE strike at the location of HS-4 and HS-3, shifting to SE
232 at the site of HS-2, and shifting again to an abrupt SW bend at HS-1 (Figure 8b). After passing
233 through HS-1, Canyon-5 is oriented southward (Figure 8b). Seismic profiles of canyon-5 reveal a U-
234 shaped erosional feature, and the cross-sectional morphology keeps constant along the canyon-5's
235 pathway (Figure 9a-c). The width and height of canyon-5 have a constant variation compared to
236 Canyon-1 (Figure 9d). The upper reach of canyon-5 has a deeper incision and width that can reach
237 76 m and 565 m, respectively. In the abyssal plain, the width of canyon-5 decreases from 565 m to
238 c. 370 m, and increases to 750 m after passing through HS-3 (Figure 9d). The width of Canyon-5
239 drops sharply to 343 m after passing through HS-1. The height of the Canyon-5 constantly
240 decreases from c. 58 m near the HS-4 to c. 44 m near the HS-1 (Figure 9d). In summary, from the
241 HS-4 to HS-1, the Canyon-5 becomes narrower and less incised.

242 Limited distribution of Canyon-4 indicates that the canyon incision has been isolated to the lower
243 slope. The rapid shifting of Canyon-5 pathway indicates the presence of headwall scarps can
244 influence and divert the canyon transport direction. Canyon-5 has a clear backstep (landward)
245 incision and relates to a shelf edge headwall by channels, and this might suggest Canyon-5 is still
246 active during the Holocene. We suggest with the headward incision associated with canyon-5, once
247 the canyon head connects to shelf-edge headwall scarps, it will grow into a 'mature' stage akin to
248 the canyons in MTC-1.

249 *4.6 Canyons in MTC-3*

250 Two canyons (Canyon-6 and Canyon-7) are observed in MTC-3. The morphology of Canyon-6 is only
251 visible close to the lower slope (Figure 8b, Figure 10b). Farther downslope, the Canyon-6 lose its
252 morphology in map view, and there is no visible canyon form in the seismic section as well (Figure
253 10c). The canyon-7 has a tripartite, concave head that cut c.7 km landward into the shelf (Figure
254 8b). The cross-sectional geometry of canyon-7 shows a clear V-shaped incision. However, this V-
255 shaped downcutting geometry is only constrained in the lower slope region (Figure 10a, 10b). The
256 width and the height of canyon-7 are constantly low in the abyssal plain, ranging from c. 120 m to
257 175 m and c. 20 m to 50 m, respectively (Figure 10d).

258 Canyon-6 and Canyon-7 have a broad flat canyon floor, with less apparent signs of incised channels,
259 which might indicate that the flow contributes to the formation of canyons that have been largely

260 displaced due to the absence of headwall scarps. Moreover, due to the absence of the scarps,
261 Canyon-6 and Canyon-7 show a low sinuosity and a subparallel pathway. No major canyon diverting,
262 nor converging has been observed in the MTC-3 region (Figure 8b).

263 5. Discussion

264 *5.1 Origin of the canyons*

265 The study area has a low sediment supply and is characterised by disconnection to modern fluvial
266 systems (Leach and Wallace, 2001). Canyons in the study area are thus sediment starved compared
267 to canyons connected to fluvial input in other areas. Similar canyons that being isolated from major
268 river input, with linear morphology of low sinuosity, have been documented from other margins
269 (termed as Type II canyon; sensu Jobe et al., 2011). The initiation of the type II canyons are
270 connected to the local failures near the continental margins or continental slopes, which is
271 independent of sediment input (i.e. river feed) and sea-level fluctuation (i.e. Normandeau et al.,
272 2014). Other triggers, such as the constructions and modification by turbidity and bottom currents
273 near the canyon heads, have also been suggested to the initiation of the type II canyons (i.e. Jobe
274 et al., 2011).

275 In this study, the morphology of the canyon heads is strictly constrained within the headwall scarps
276 near the shelf edge (Figure 11a, 11b). The spatial relation between the shelf-edge headwall scarps
277 and canyon heads suggests the initiation of canyons are closely related to these pre-existing, steep
278 shelf-edge headwall scarps. Moreover, as the bottom current is active near the shelf-edge area, the
279 movement of the bottom current along the topographically low scarps may induce local turbulence
280 and produce down canyon sediment transportation (i.e. Fenner et al., 1971; Warratz et al., 2019).
281 Thus, we suggest that the canyon systems in the study area are initiated by a combination of
282 multistage retrogressive failure events and contour current activity near the pre-existing headwall
283 scarps (Figure 11c). Although the study area lacks river-sourced sediments, canyon heads can
284 capture sediment from local failure events associated with gravity flows that erode the seabed and
285 form canyons downslope (Figure 11d) (see also similar process from Atlantic canyons; Twichell and
286 Roberts, 1982). Other factors, such as hurricanes, typhoons and tidal currents occurring in the
287 continental shelf area, may also contribute to the canyon initiation (Shepard et al., 1974; Sequeiros

288 et al., 2019). The emplacement of the hurricanes and typhoons can trigger waves and currents,
289 thus resuspending and carrying sediment. These processes will directly play a role in initiating the
290 turbidity currents, which bring the sediments into the canyon heads and enhance the canyoning
291 process (Sequeiros et al., 2019). Tidal currents can act as an efficient force for reworking and
292 carrying sediments in submarine settings (Shepard et al., 1974). Tidal currents can thus transport
293 sediments into the canyon heads area, especially at places where river input is missing.

294 *5.2 Role of retrogressive failure mechanism on canyon evolution*

295 The headwall scarp of MTCs play an essential role in capturing turbidity currents and facilitating
296 turbidity channelization in submarine settings, as proved by examples from previous seismic- and
297 outcrop-based studies (Loncke et al., 2009; Alves and Cartwright, 2010; Ito, 2013; Qin et al., 2017;
298 Li et al., 2020). The three MTCs presented in this study have indicated the spatial variation of
299 canyon morphology is linked with the MTCs morphometric characteristics. Here, we attempt to
300 define the possible mechanical influences of MTCs imposed on the canyon evolution in the
301 following section.

302 The retrogressive failure events associated with MTC-1 have left a pronounced negative seafloor
303 space that greatly changed the slope morphology and created a series of localised seafloor
304 'ponding' accommodations along the pathway of submarine canyon systems. The gravity-driven
305 downslope processes are sensitive to the slope gradient variations, preferentially deposited where
306 the gradient varies the most (Kneller et al., 2016). The varied hierarchies of headwall scarps can
307 therefore trap or divert subsequent turbidity currents and facilitate canyon systems' incision and
308 development. Though the headwall scarps within MTC-2 does not widen nor deepen canyons that
309 are transported through, they do play an essential role in changing the canyon direction. Compared
310 to MTC-1 and MTC-2, MTC-3 has provided a good opposite example. Within MTC-3, due to the lack
311 of internal headwall scarps, thus lack of ability to trap or capture the turbidity currents flow
312 through. Even the Canyon-6 has connected to the shelf-edge headwall scarps, the scale of the
313 canyon is still small compared to canyons in the other two MTCs. Therefore, we indicate the
314 retrogressive failure mechanism of MTCs is responsible for canyon deepening and confluence
315 process, which can greatly influence the morphology of the canyons.

316 *5.3 Other factors that may influence the evolution of the canyon*

317 The evolution of submarine canyons can also be influenced by many other geological factors,

318 including (i) regional tectonics (i.e. regionally distributed faults), which influence the sediments
319 strength, thus the susceptibility to erosion during the formation of canyons (Covault et al., 2007);
320 (ii) the sea-level variation, which can boost sediment input to canyon heads (Vail, 1977;
321 Posamentier et al., 1991); (iii) downslope and along-slope depositional processes (i.e. gravity flows
322 and contourite currents), which erode seafloor and enlarge the scale of submarine canyons
323 (Pratson and Coakley, 1996; He et al., 2014; Miramontes et al., 2020).

324 In this study, tectonics is unlikely to be of significance for canyon development due to the relatively
325 stable nature of the southern Australian continental margin. Recent studies revealed that the
326 canyon process does not necessarily depend on the sea-level rise and fall, as well-developed
327 canyon systems have been identified during the sea-level rise in many submarine settings (i.e. Xu
328 et al., 2010; Paull et al., 2013; Normandeau et al., 2015). In the study area, the modern canyons
329 are contiguous with Pliocene canyon systems, showing similar geometry and slightly eastward
330 migrated distribution pattern. The similarities between buried Pliocene and modern canyons
331 indicate that the location and distribution of modern canyons are an extension of the infilled
332 Pliocene canyon systems. The overall eastward canyon lateral migration during Pliocene-Recent is
333 interpreted as related to an eastward shelf break parallel paleocurrent (i.e. SAC or LC), which is still
334 active near current-day shelf-edge (Godfrey et al., 1986). Moreover, our study suggests that the
335 types of the underlying deposits can also influence the morphology evolution of the canyons. For
336 example, Canyon-1 to Canyon-3 deposit above the slope background deposits (Figure 7b), while
337 Canyon-6 deposits above a buried MTC (Figure 10c). The quantitative analyses reveal that the
338 Canyon-1 to Canyon-3 (immediately above background deposits) are tentatively larger than that of
339 the Canyon-6 (immediately above buried MTCs). This is interpreted as buried MTCs, which are
340 normally more consolidated than undeformed background slope deposits (i.e. Shipp, 2004; Sawyer,
341 2007; Wu et al., 2021). Thus, the erosivity and scale of the Canyon-6 are smaller than other canyons.

342 *5.4 Canyon evolution model*

343 We attempt to build an updated model of canyon formation based on the models by Jobe et al.
344 (2011) and Pratson and Coakley (1996), emphasising the role of headwall scarps associated with
345 the regional distributed MTCs. Our model consists of three phases, MTC deposition, canyon
346 initiation, and canyon transition.

347 *Phase 1: MTCs deposition*

348 Earthquakes (i.e. Bornhold and Prior, 1989), sediment overloading generated overpressure (i.e.
349 Dugan and Flemings, 2000), or tectonic oversteepening (i.e. Moscardelli et al., 2006) may have
350 triggered the initial failure in the lower slope setting. The initial failure creates an open scarp, that
351 leaves the sediments in the up-dip part unstable. As the gravitational strain accumulates, the
352 sediments that near the initial scarp weaken. A new extensional failure (the second scarp) will
353 occur behind the initial scarp once the sediments become weaker than the along slope gravity-
354 induced stress. The failure process will continue up-dip until the final balance between the shear
355 strength of the slope sediments and the shear stress of the gravitational forces (Sawyer et al., 2009).
356 This retrogressive failure mechanism has left a series of headwall scarps and lateral scarps on the
357 continental shelf and slope settings. The scarp-rich environment represents the initial phase of
358 canyon initiation (Figure 12a).

359 *Phase 2: the initial stage of the canyon system*

360 The failed sediments near the headwall scarps at the shelf edge have led to triangular-shaped
361 canyon heads, that incised into the landward direction (Figure 12b). The failed sediments could
362 excavate the pre-existing headwall scarps and contribute to the initial sediment influx for canyon
363 initiation (see the similar process from Pratson and Coakley, 1996; Puga-Bernabéu et al., 2011).
364 Once the canyon has been initiated, sediments collapse from the canyon sidewalls (canyon flank
365 failures) forms downslope flowing turbidity currents, facilitating the canyoning process. The failure
366 events associated with headwall scarp and canyon sidewalls permitted the delivery of enough
367 material to enable canyon formation and downward incision. Thus, the initiation mechanism for
368 canyons is the failure of sediments at the headwall scarps of the continental shelf and the
369 downslope eroding flows (Figure 12b) (see also similar process documented by: Pratson and Ryan,
370 1994; Pratson and Coakley, 1996; Armitage et al., 2010). Prevailing along-coast, eastward currents
371 may also create local turbulence near the shelf-edge headwall scarps, which further facilitate the
372 formation of flows that carry sediments into the canyon heads.

373 *Phase 3: transitional stage*

374 With the continuous failure near the shelf-edge headwall scarps, the canyon heads gradually
375 establish into triangular or dendritic shapes. These triangular or dendritic shape structures
376 facilitate canyon head capture and funnel larger volumes of sediments into the canyon, and the
377 canyoning process becomes self-propagating (Figure 12b). The failed sediments near the headwall

378 scarps in the continental shelf converged into the channel-shaped conduit that is acting as
379 catchment areas for the canyon evolution. Downward sediment gravity flow generated by the
380 failed sediments can contribute significantly to the ongoing canyon excavation and downslope
381 propagation (Popescu et al., 2004; Baztan et al., 2005). The presence of the headwall scarps on the
382 slope settings provided further acceleration and canyon tributary convergence. The canyons are
383 thus progressively propagating to the far side of the lower slope and abyssal plain.

384 *5.5 Implication*

385 Many studies have shown how submarine MTCs rugose top surface can capture/reroute
386 subsequent sediment pathways based on seismic data (Loncke et al., 2009; Ortiz-Karpf et al., 2015;
387 Qin et al., 2017) and outcrops (Armitage et al., 2009; Jackson and Johnson, 2009; Kneller et al.,
388 2016). These studies are examples of MTCs locates near the shelf edge where the sediment supply
389 is high. The rugose top surfaces developed along the upper surface of MTCs is caused by the
390 presence of the internal rafted blocks. The rugose topography can be healed quickly by subsequent
391 sand-rich turbidity currents or separate failures. Thus, MTCs have a direct influence in the location
392 and distribution of reservoirs and important implications for hydrocarbon exploration.

393 Conversely, our study documents MTCs in low sediment supply margins where large-scale
394 sediment bypass is missing. We showed strong evidence that the emplace of MTCs has played a
395 key role in influencing the morphology evolution of canyon systems. We develop a generic model
396 of the MTCs headwall scarps, as a function of triggering and influencing the morphological
397 evolution of canyons, thus controlling the sediment bypass from the shelf edge to lower slope and
398 further abyssal plain. We indicate the retrogressive failure mechanism can facilitate long-distance
399 sediment transportation within canyon systems, and it may be a common and important process
400 in a submarine setting where modern river systems are absent.

401 **5. Conclusion**

402 This study uses multi-beam bathymetry and seismic reflection data to document how the
403 retrogressive failure mechanism of MTCs and related headwall scarps have influenced the origin,
404 geometry, and distribution of canyons in a sediment starved submarine setting. In summary: (i) the
405 emplacement of MTCs have left multi-scaled headwall scarps and lateral margins on the

406 continental margin and slope area, (ii) the local failures developed associated headwall scarps near
407 the continental shelf-edge have provided the initial sediment supply for canyon evolution, (iii) the
408 headwall scarps which developed in the slope setting may act as the preferential pathways for
409 sediment gravity flows, and facilitate canyon development, (iv) we thus indicate that retrogressive
410 failure mechanism can facilitate long-distance sediment transportation within canyon systems in
411 starved submarine settings.

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416 Figure Captions

417 Figure 1. (a) Model showing the time evolution of retrogressively failed MTCs, modified from
418 Sawyer et al. (2009). (b) Schematic sketch showing the different stages of a retrogressive failure,
419 modified from Locat et al. (2011).

420 Figure 2. (a) Regional map of the study area. (b) Zoom in map of the study area showing the location
421 of the city Portland and the Otway Basin. The white lines represent 2D seismic reflection data, and
422 the red polygon represents the location of the 3D seismic reflection dataset. Shaded relief
423 GEBCO_2014 bathymetry map downloaded from <https://www.ngdc.noaa.gov/maps/autogrid/>.

424 Abbreviations for the Otway Basin are as follows: SAC: South Australia Current, ZC: Zeehan Current.

425 Figure 3. (a) Stratigraphic and basin event chart for the Otway Basin (modified after Krassay et al.,
426 2004), including lithology interpretation and major tectonic events. The Horizon H1 has been
427 correlated to the intra-Maastrichtian unconformity surface from Holford et al. (2014). The Horizon
428 H2 is corelated to the base of the WBF. (b) Regional along slope seismic section showing the overall
429 tectonic of the study area. See location from Figure 2b. (c) Regional seismic section that
430 perpendicular to the slope, showing the four key seismic sections (H1 to seabed) and canyon
431 bearing intervals. See location from Figure 2b.

432 Figure 4. (a) Multi-beam bathymetry map of the study area illustrating the seafloor morphology.
433 The red polygon stands for the location of 3D seismic data. The location of this figure is marked by
434 the black dashed line in Figure 2b. (b) Bathymetric profile crossing the abyssal plain, showing the
435 cross-sectional morphology of two canyon systems. (c) Bathymetric profile revealing the
436 combination of the two canyon systems. See location in Figure 4a.

437 Figure 5. (a) Contoured seafloor map of the study area extracted from the 3D seismic reflection
438 data. (b) Schematic representation of seafloor geomorphologic interpreted from Figure 5a. See the
439 location of this figure from Figure 2.

440 Figure 6. (a) Zoomed in contoured seafloor map showing the region of MTC-1. (b) Interpreted map
441 of Figure 6a, showing the major headwall scarps in MTC-1 and the location of Canyon-1, Canyon-2,
442 and Canyon-3.

443 Figure 7. (a) The NW-S oriented seismic section of MTC-1 shows backstep shaped headwall scarps
444 and MTC-1's basal shear surface. (b) Seismic cross-section cutting through HS-5 and HS-4, showing
445 the cross-section of the upper part of the Canyon-1, Canyon-2, and Canyon-3. (c) Seismic cross-
446 section cutting through HS-3, showing the cross-section of the proximal part of the Canyon-1,
447 Canyon-2, and Canyon-3. (d) Seismic cross-section cutting through HS-2 and HS-1, showing the
448 cross-section of the post confluence part of the canyon system in MTC-1. See location in Figure 6b.
449 (e) Width profile of the canyon system in MTC-1. (f) Height profile of the canyon system in MTC-1.

450 Figure 8. (a) Zoomed in contoured seafloor map showing the location of MTC-2 and MTC-3. B)
451 Interpreted map of Figure 8a, showing the headwall scarps in MTC-2 and MTC-3, and the location
452 of Canyon-4, Canyon-5, Canyon-6, and Canyon-7.

453 Figure 9. (a) Seismic cross-section cutting through HS-5 and HS-4 of MTC-2, showing the upper part
454 of the Canyon-4 and Canyon-5. (b) Seismic cross-section cutting through HS-2 of MTC-2, showing
455 the proximal part of the Canyon-5. (c) Seismic cross-section cutting through MTC-2, showing the
456 distal part of Canyon-5. See location in Figure 8b. (d) Width and height profile of the Canyon-5 in
457 MTC-2.

458 Figure 10. (a) Seismic cross-section cutting through the headwall of MTC-3, showing the upper part
459 of the Canyon-7. (b) Seismic cross-section showing the proximal part of the Canyon-6 and Canyon-
460 7. (c) Seismic cross-section showing the distal part of Canyon-6 and Canyon-7. See location in Figure
461 8b. (d) Width and height profile of the Canyon-7 in MTC-3.

462 Figure 11. (a) 3D view of seafloor morphology showing the head of Canyon-5 and Canyon-7, and
463 the headwall scarps occurring on the shelf-edge. See location in Figure 5a. (b) 3D view of seafloor
464 morphology showing the head of Canyon-3, and the headwall scarps occurring on the shelf-edge.
465 See location in Figure 6a. (c) Sketch of 2D view of seafloor morphology showing the headwall
466 collapse and the initial stage of canyon evolution on shelf-edge. (d) Sketch of 2D view of seafloor
467 morphology showing the formation of the canyons.

468 Figure 12. Schematic figure showing the evolution model of the canyon system in the study area.
469 (a) Schematic figure showing that the occurrence of slope attached MTCs and associated headwall
470 scarps. (b) Schematic figure showing that canyons were captured, converged and re-directed by
471 the pre-existing headwall scarps.

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664

Figures

Figure 1

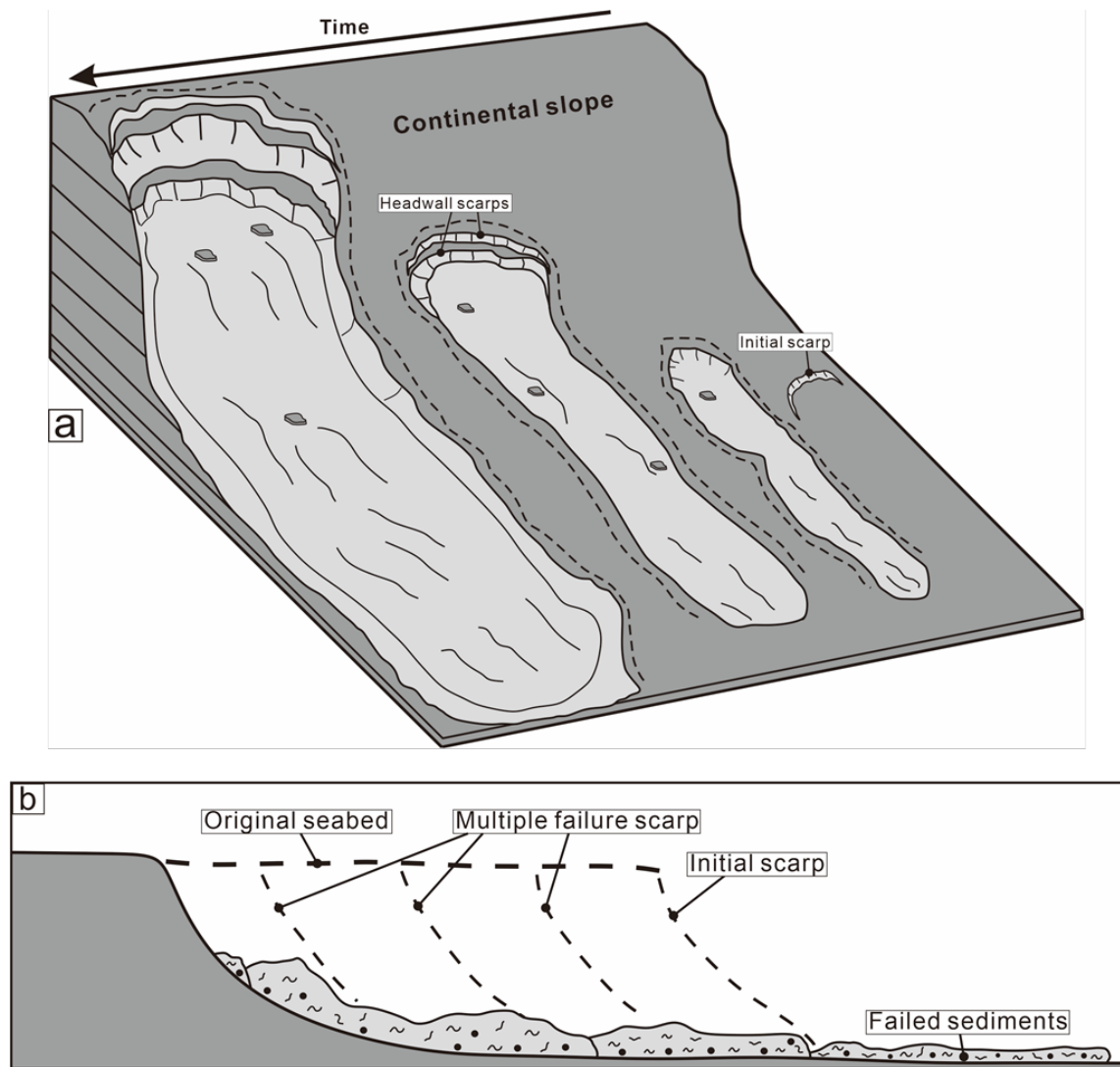


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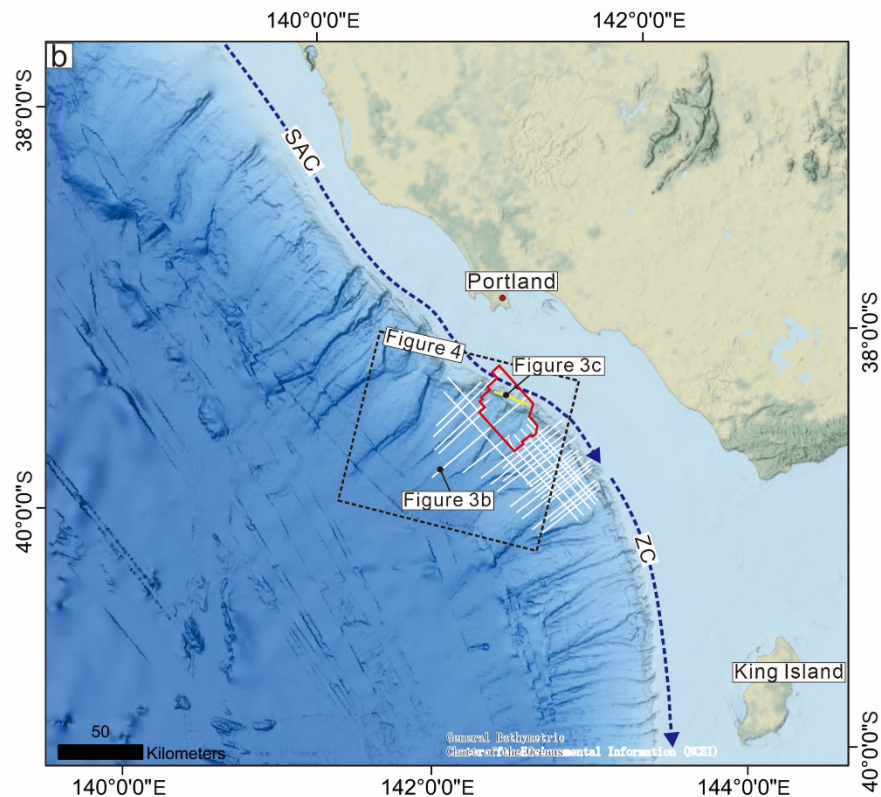
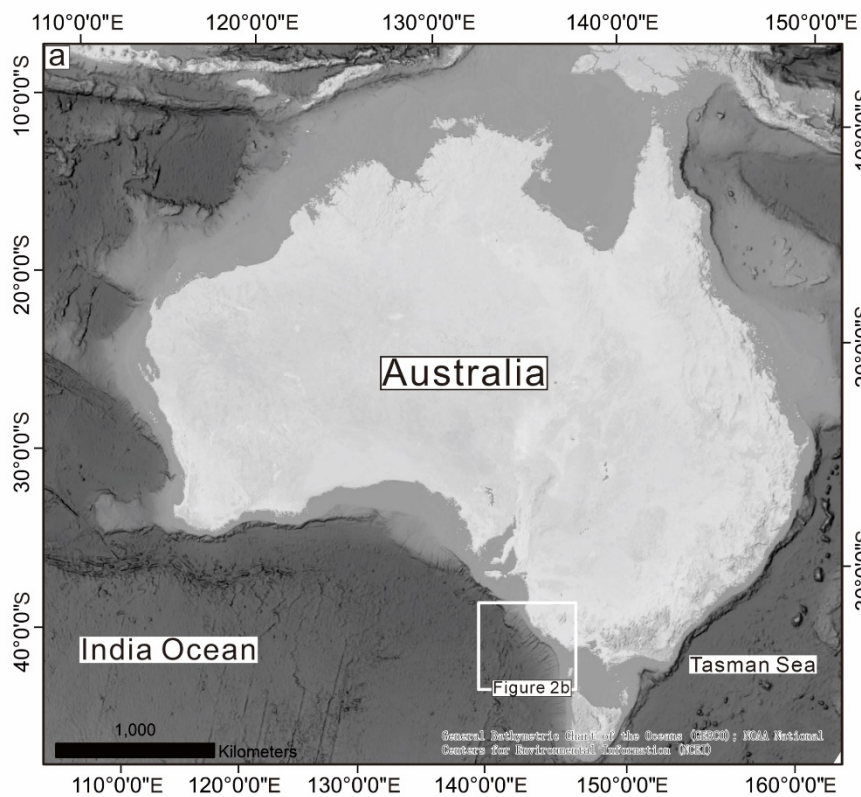


Figure 3

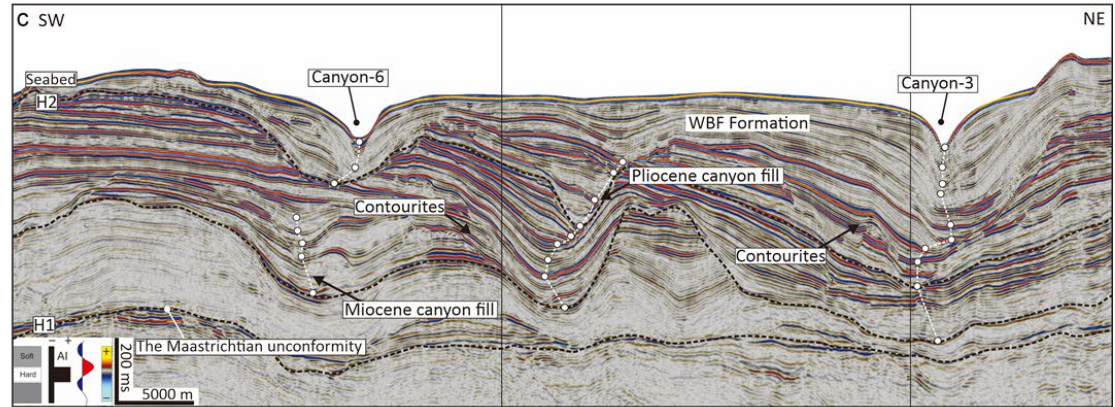
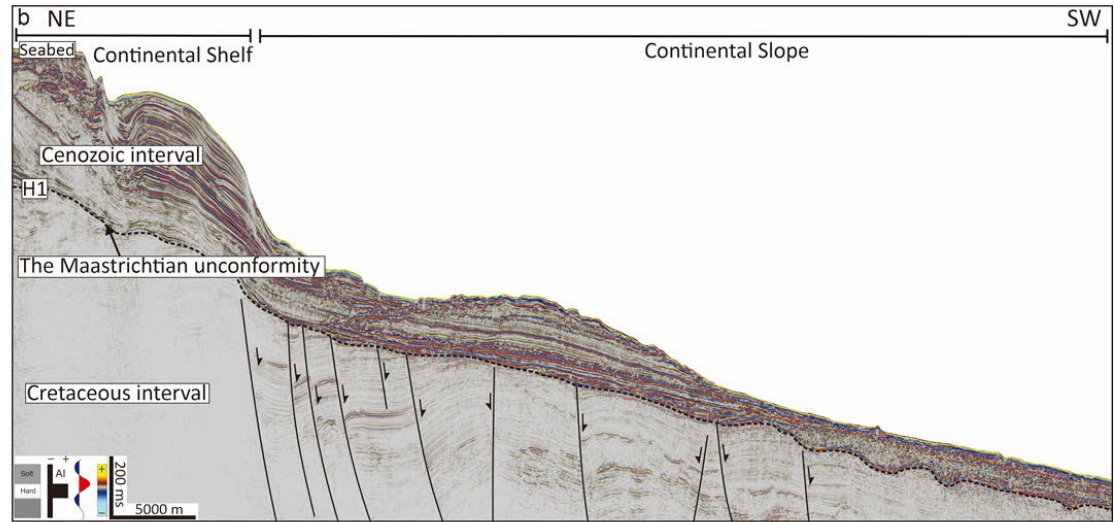
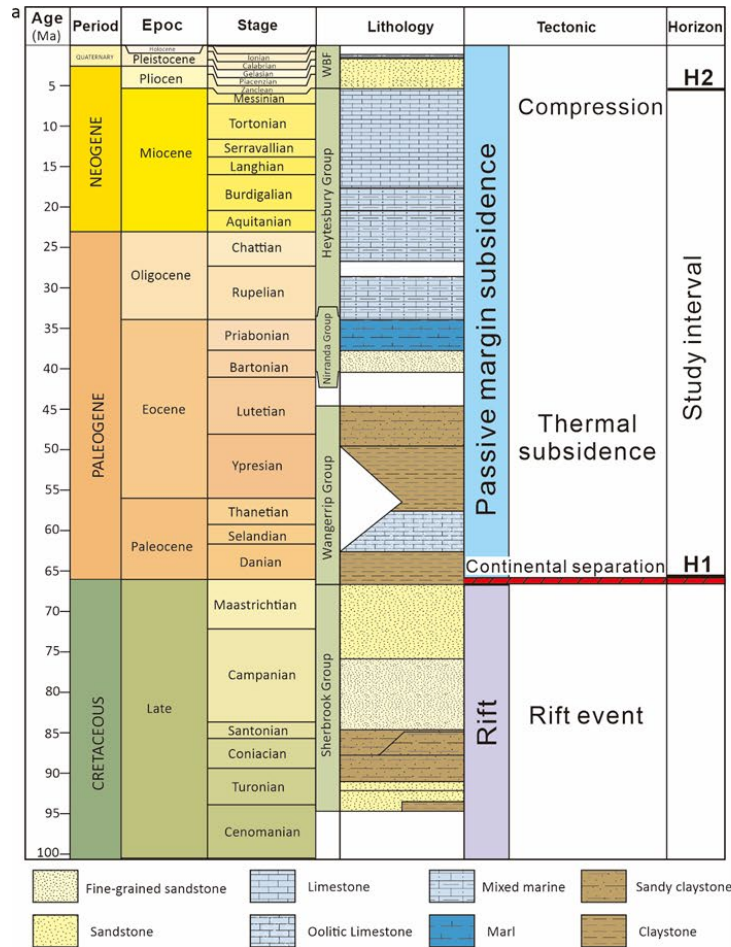


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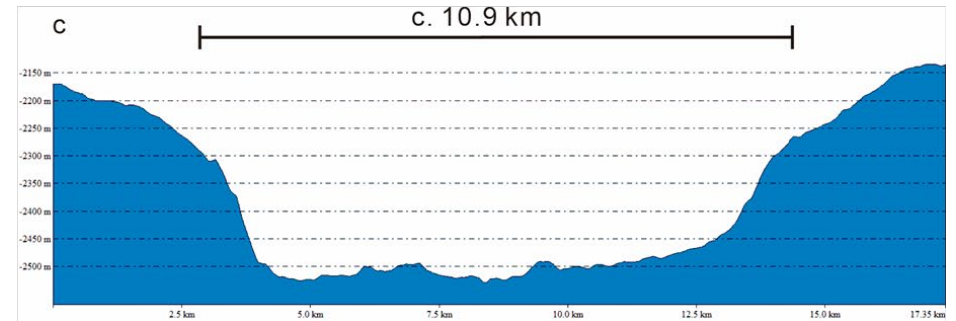
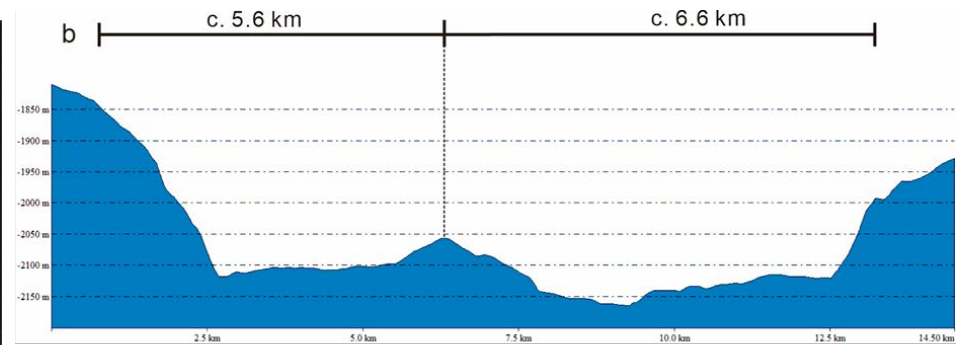
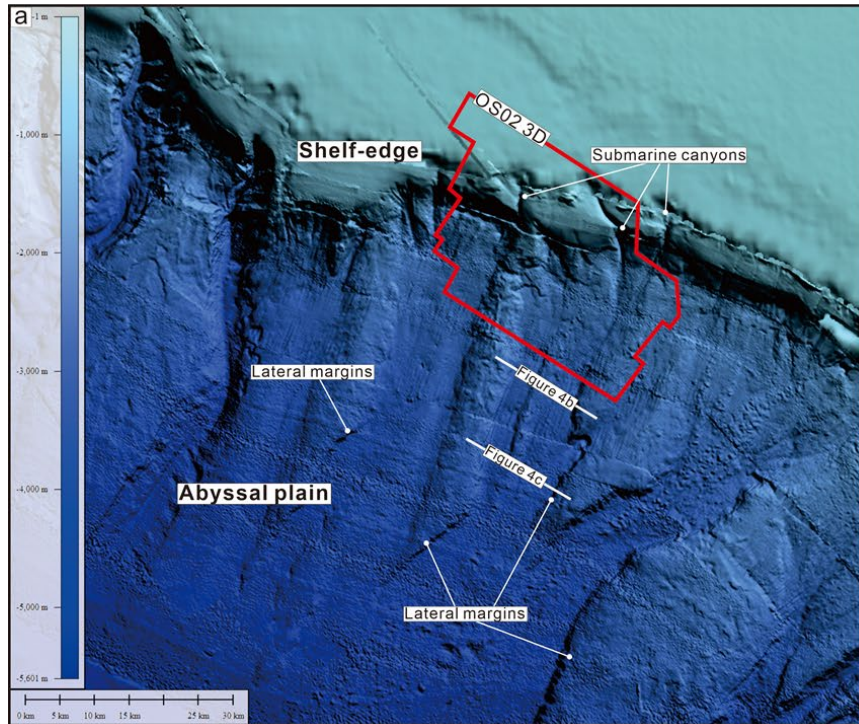


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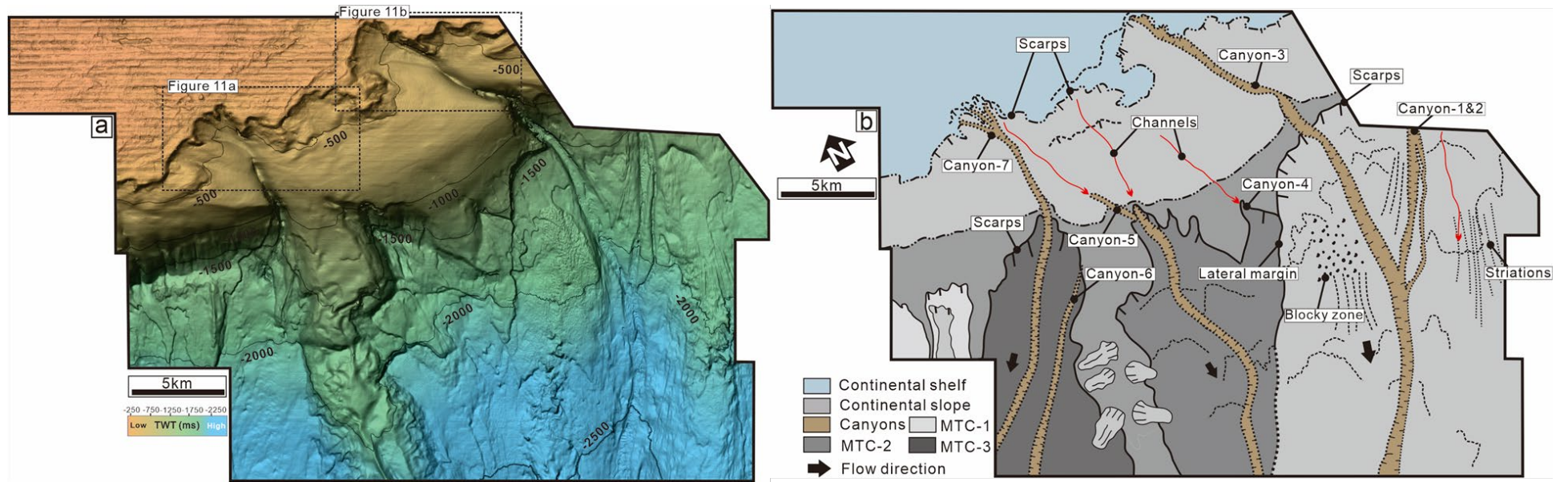


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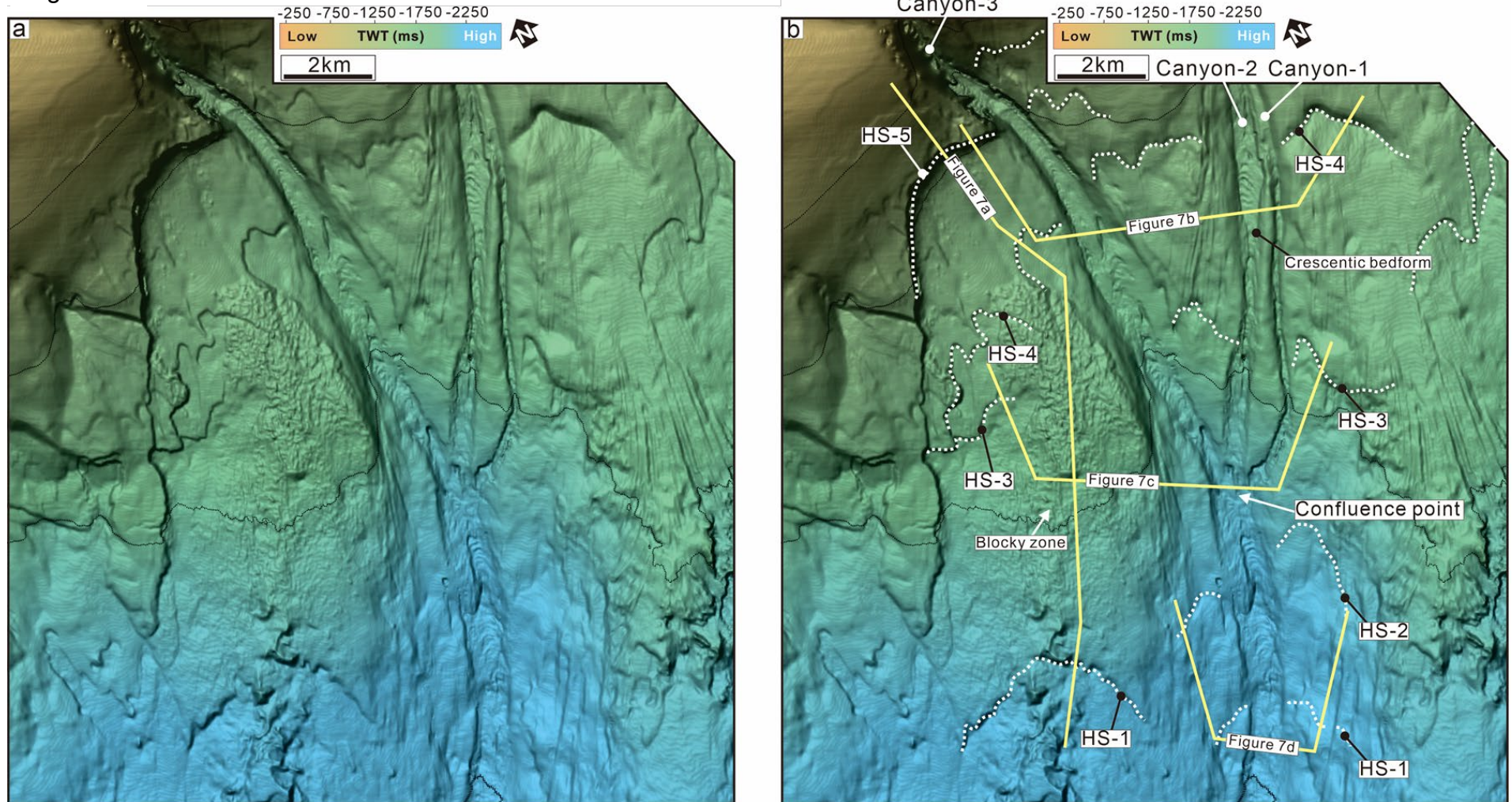
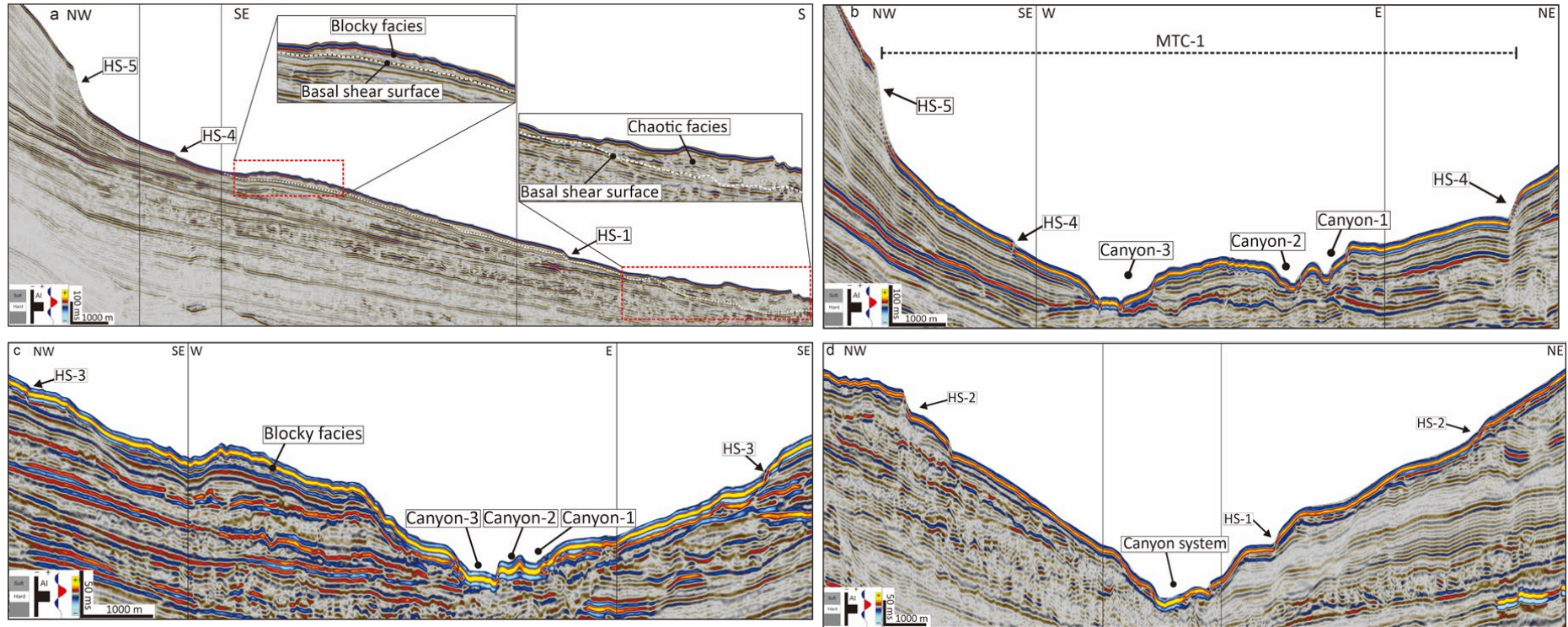


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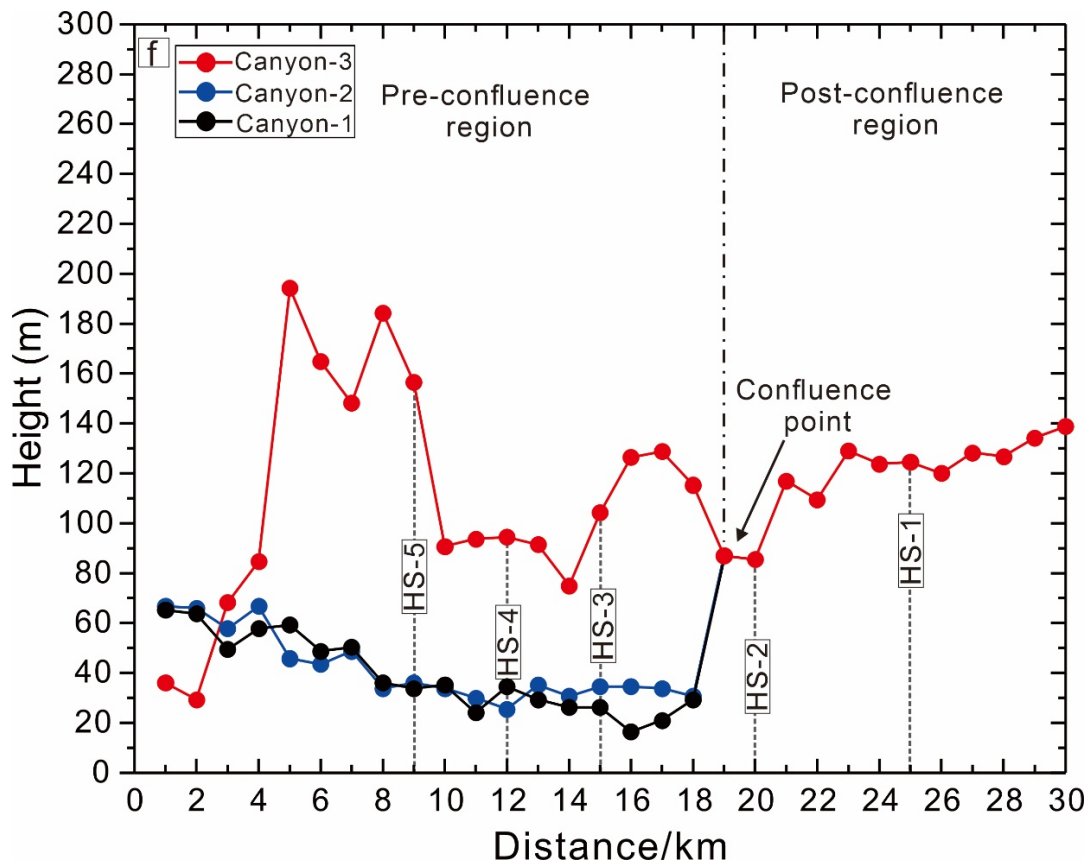
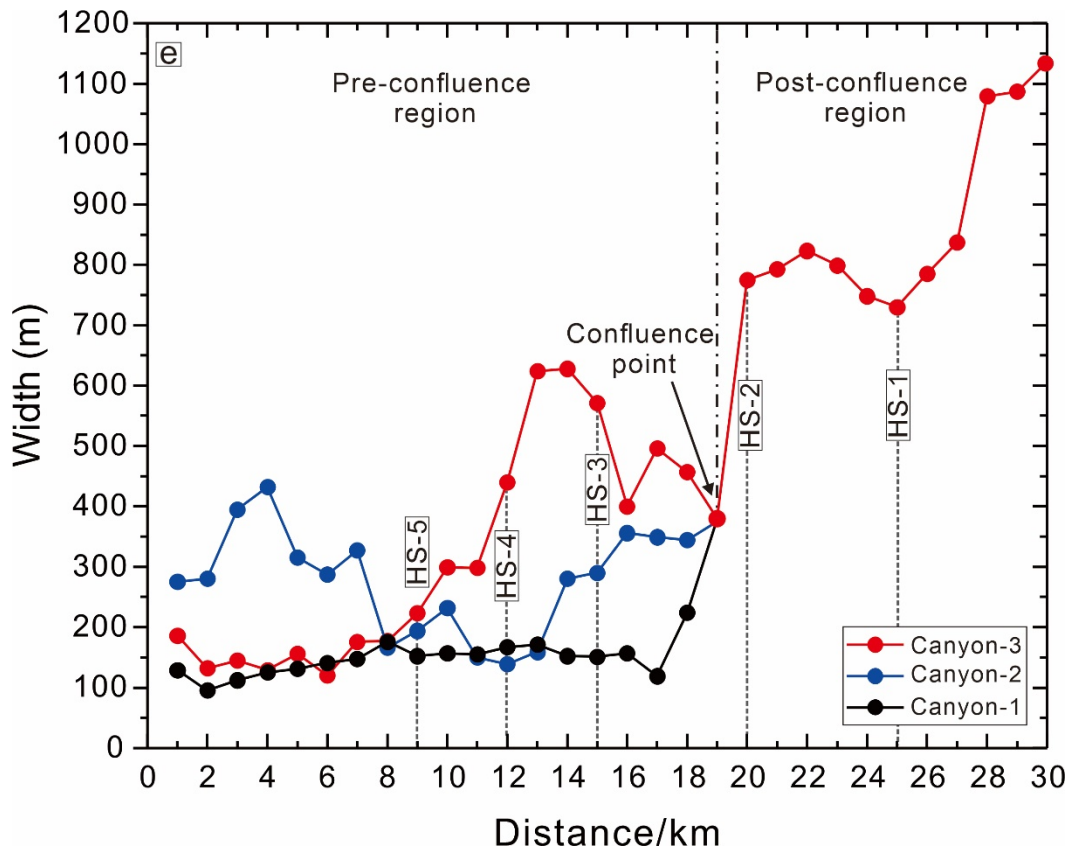


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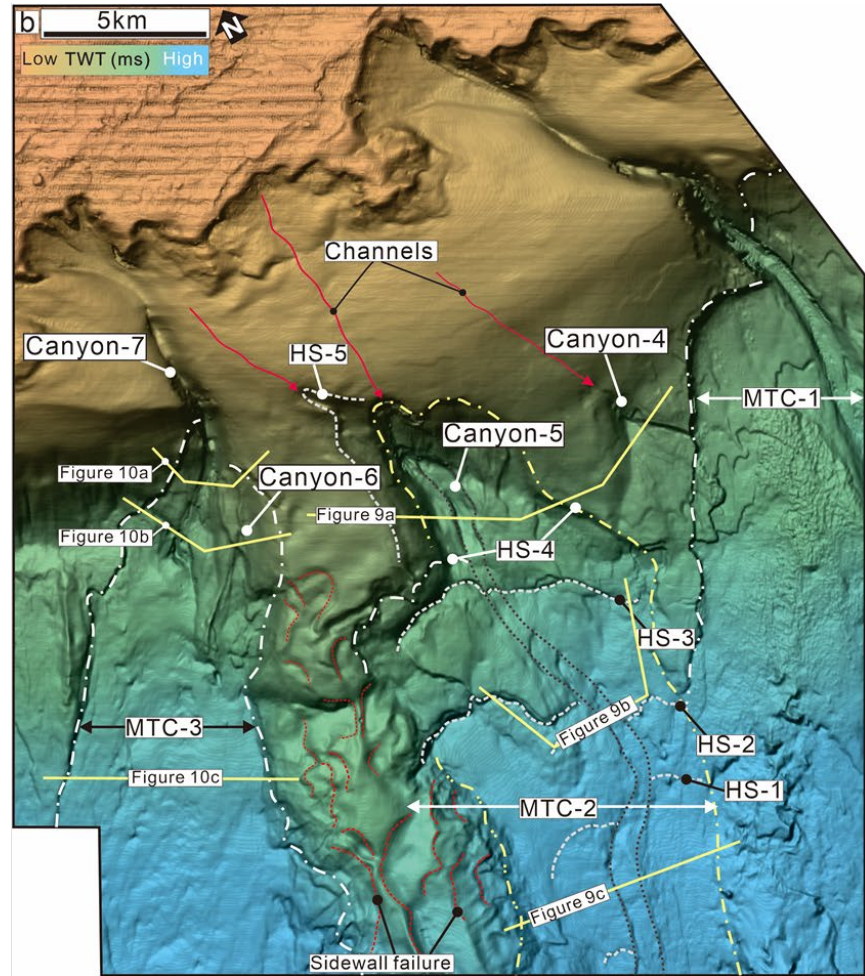
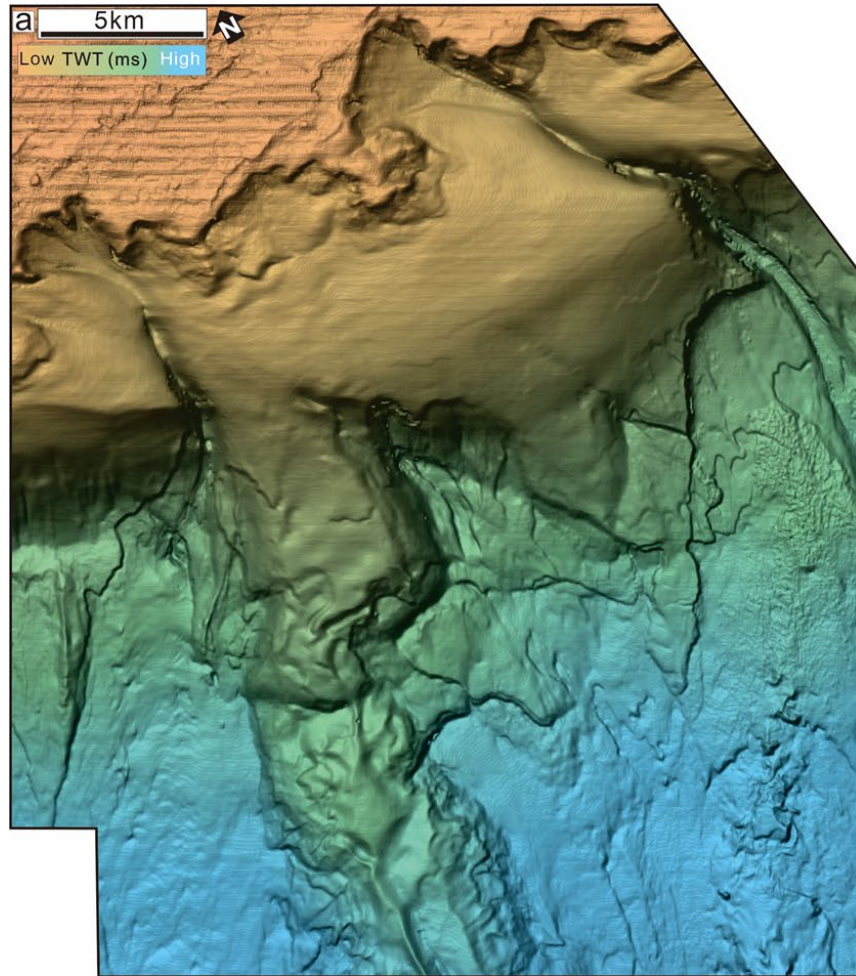


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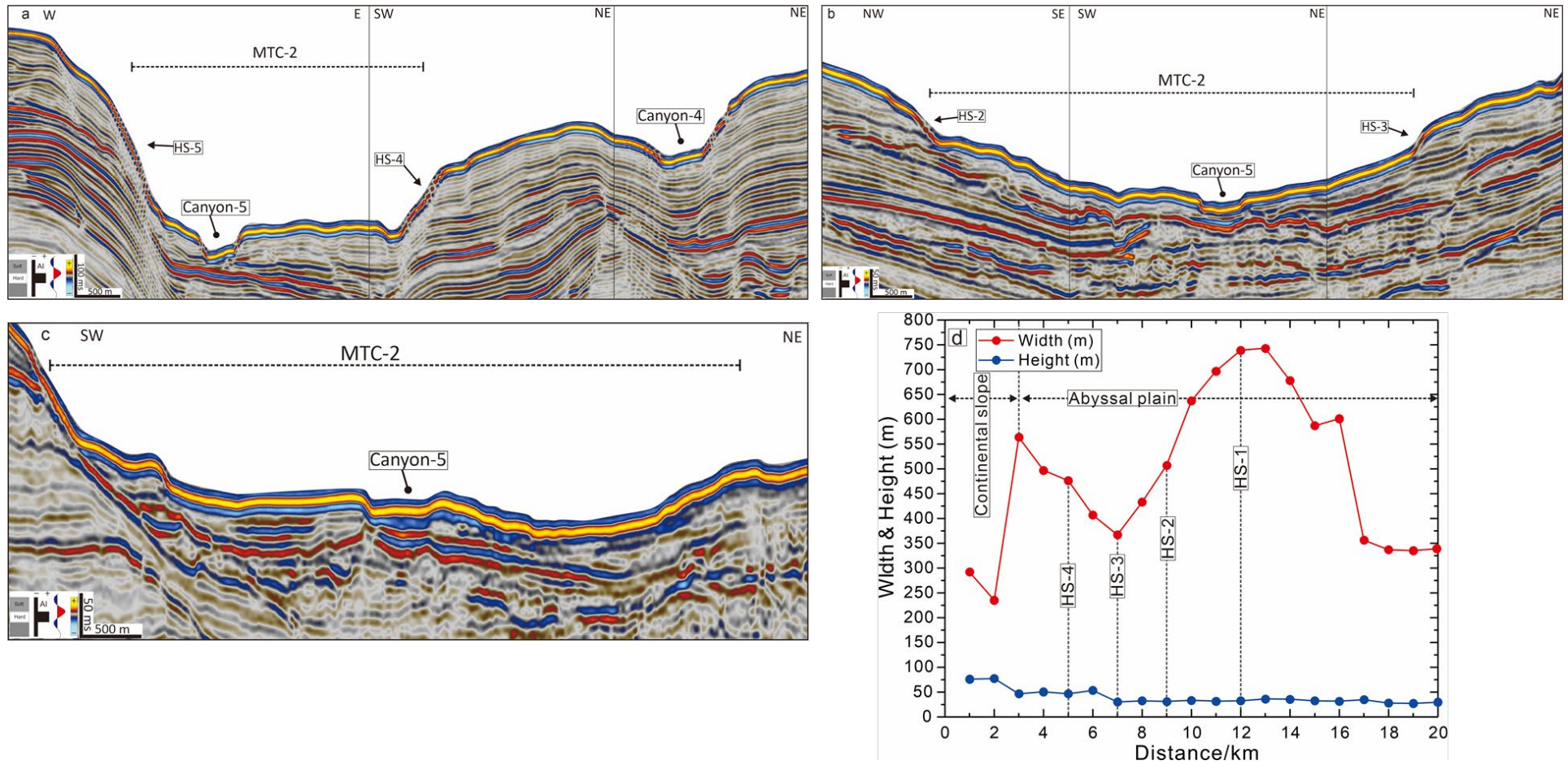


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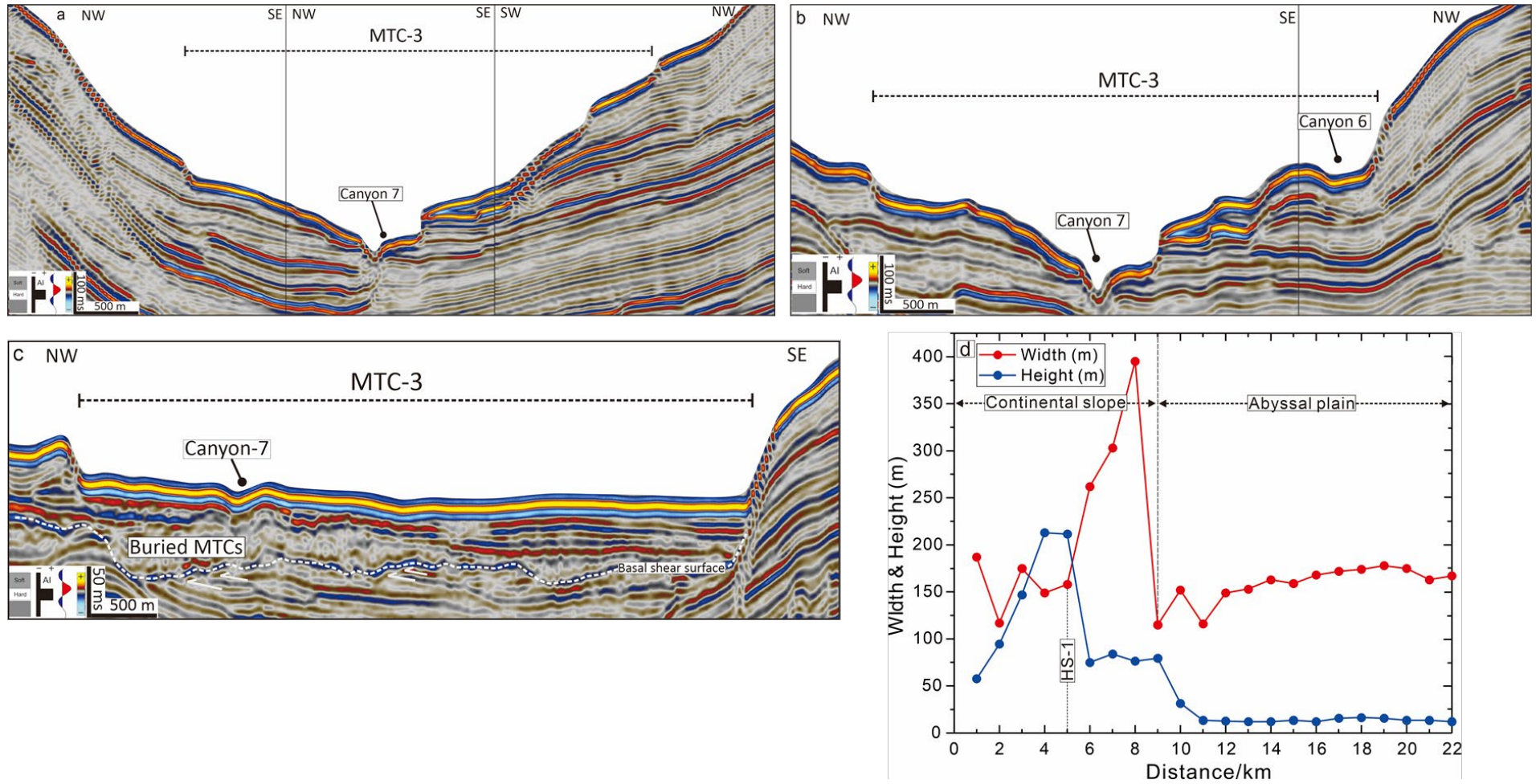


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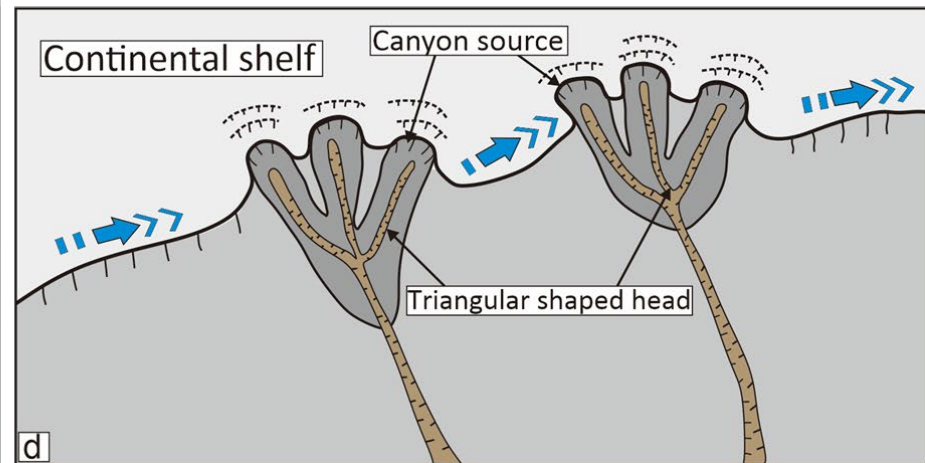
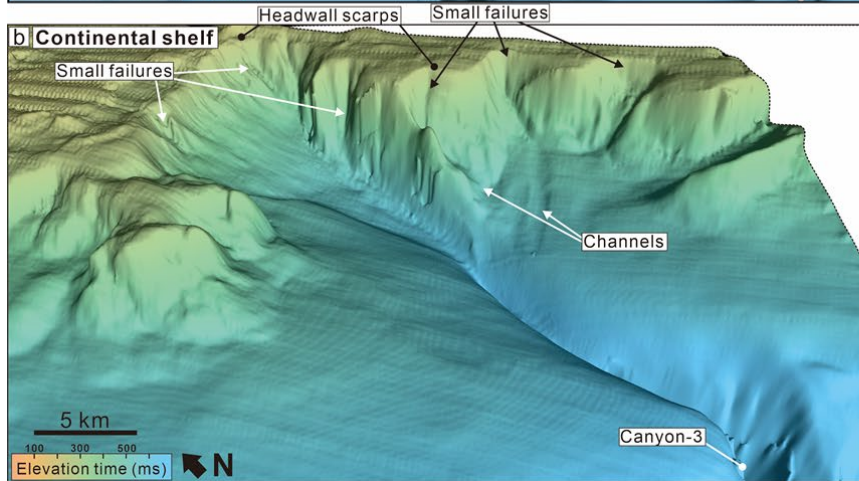
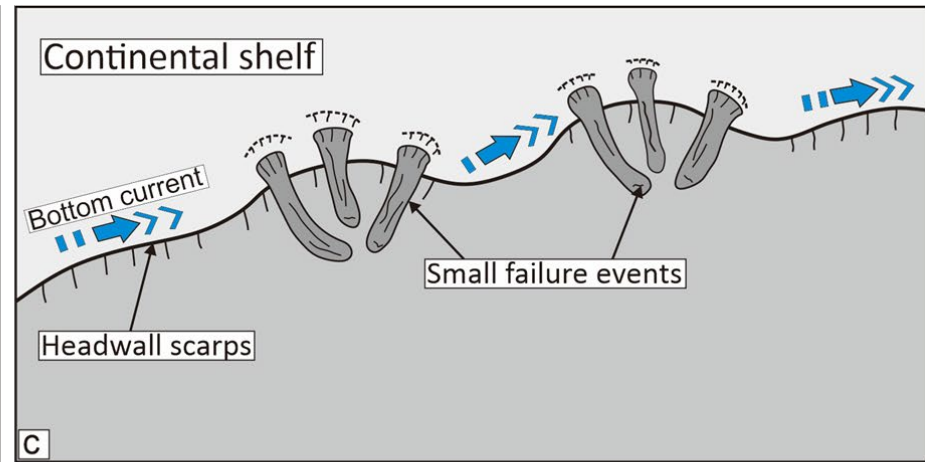
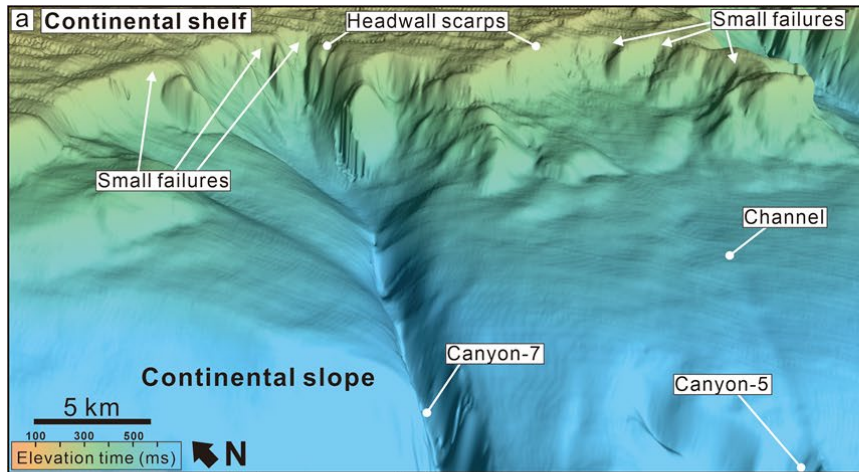


Figure 12

