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Citation for final published version:

Li, Wei, Li, Yan, Omosanya, Kamaldeen O.L, Alves, Tiago M. ORCID: <https://orcid.org/0000-0002-2765-3760>, Jing, Song, Wang, Xiujuan, Wu, Nan and Zhan, Wenhuan 2022. Quantitative and geomorphologic parameterization of megaclasts within mass-transport complexes, offshore Taranaki Basin, New Zealand. GSA Bulletin 10.1130/B36446.1 file

Publishers page: <http://dx.doi.org/10.1130/B36446.1>
<<http://dx.doi.org/10.1130/B36446.1>>

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1 **Quantitative and geomorphologic parameterization of megaclasts**
2 **within mass-transport complexes, offshore Taranaki Basin, New**
3 **Zealand**

4
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21 **Highlights**

22 - Large-scale megaclasts are identified and analyzed in seismic data .

23 - A new classification of megaclasts is proposed based on their deformational styles.

24 - The identified megaclasts reflect two types of emplacement processes.

25 - Internal structures in megaclasts reflect their emplacement histories.

26 **Abstract**

27 Mass-transport complexes (MTCs) in sedimentary basins reflect the gravitational transport of
28 sediments from the shelf edge to the abyssal plain. As an integral part of MTCs, megaclasts (large
29 sedimentary blocks of 100s of meters long) can record kinematic and sedimentary information
30 deemed essential to understand source-to-sink systems. Yet, deformation structures in such
31 megaclasts remain poorly understood. This study uses high-quality three-dimensional (3D) seismic
32 reflection data from the deep-water Taranaki Basin offshore New Zealand to analyze the
33 morphological character of 123 megaclasts and propose a new classification scheme based on their
34 morphometric properties. The megaclasts are up to 400 m tall, 1900 m long and 1200 m wide. In the
35 study area, they are high- to moderate-amplitude features owing to their different lithology and
36 continuous to contorted seismic facies. The megaclasts can be classified as undeformed, rotated,
37 deformed, and highly deformed based on their internal deformational styles. Two different kinds of
38 morphological depressions observed on their basal shear zones further indicate that the megaclasts
39 are either transported or formed in-situ. Our study demonstrates that the quantitative parameterization
40 of the megaclasts provides important information on their deformational processes, helping a more
41 complete understanding of megaclast emplacement along continental margins.

42

43 **Keywords:** Mass-transport complexes, megaclasts, deformational styles, quantitative analysis,
44 classification, deep-water Taranaki Basin.

45

46 **1. Introduction**

47 Submarine mass-wasting is widely observed on continental margins as a primary process
48 transporting large volumes of sediment from continental shelves to deep-water sedimentary basins
49 (Hampton et al., 1996; Nisbet and Piper, 1998; Canals et al., 2004; Moscardelli and Wood, 2008).
50 Megaclasts are large blocks preserved within the sedimentary deposits resulting from submarine mass
51 wasting (Moore et al., 1995; Lee et al., 2006; Vanneste et al., 2006; Alves, 2015; Gamboa and Alves,
52 2015; Ogata et al., 2019). Megaclasts can be 100s of meters to kilometers long and/or wide (Alves,
53 2015; Hodgson et al., 2019; Nwoko et al., 2020b; Hunt et al., 2021) and have been documented in
54 multiple deep-water regions such as offshore Brazil (Alves and Cartwright, 2009; Jackson, 2011;
55 Omosanya and Alves, 2013; Gamboa and Alves, 2015), offshore New Zealand (Collot et al., 2001;
56 Joanne et al., 2013; Rusconi, 2017; Kumar et al., 2021), around the island of Anak Krakatau (Hunt et
57 al., 2021), in the Southwest Labrador Sea (Deptuck et al., 2007), in the Arctic Ocean (Vanneste et al.,
58 2006) and in the Central North Sea (Soutter et al., 2018) (Fig. 1).

59 Megaclasts can create uneven topographies at the top surface of mass-transport complexes
60 (MTCs), influencing the subsequent flows (e.g., turbidity currents) and their deposits (Ward et al.,
61 2018; Nwoko et al., 2020a). Relative to their surrounding host strata, megaclasts have much stiffer
62 geotechnical properties (higher density and lower porosity), promoting differential compaction under
63 variable overburden pressures (Soutter et al., 2018; Ward et al., 2018; Cox et al., 2020). This
64 differential compaction can lead to the formation of structural traps in younger strata above the
65 megaclasts and often influence the seafloor physiography 1000s of years later (Alves and Cartwright,
66 2009; Alves, 2010). Megaclasts also have a recognized erosional potential as they are capable of

67 generating grooves and striations on their basal shear zones Gee et al., 2005; Soutter et al., 2018;
68 Scarselli, 2020; Kumar et al., 2021). Importantly, the internal structures of megaclasts usually record
69 a continuum of deformational styles, which are important to estimate the flow directions of MTCs
70 (Jackson, 2011; Gamboa and Alves, 2015; Rusconi, 2017; Omeru and Cartwright, 2019; Nwoko et
71 al., 2020b).

72 The deep-water Taranaki Basin provides a natural laboratory to investigate the internal
73 architecture of megaclasts. Five MTCs (MTC 1 to 5 from bottom to top) have been recognized in the
74 deep-water Taranaki Basin offshore New Zealand (Kumar et al., 2021). One of them (MTC 2)
75 contains multiple megaclasts that are up to 1900 m long (Omeru and Cartwright, 2019; Bull et al.,
76 2020; Kumar et al., 2021). Previous studies in the Taranaki Basin have mainly focused on the
77 distribution, internal architecture and kinematic indicators of these MTCs and their roles on post-
78 MTC sedimentation (Omeru and Cartwright, 2019; Bull et al., 2019, 2020; Nwoko et al., 2020a).
79 However, few researchers have concentrated on the megaclasts within MTCs (e.g., Nwoko et al.,
80 2020b; Kumar et al., 2021). Despite the relevant information provided by megaclasts, little knowledge
81 exists on their dynamics vis-à-vis emplacement processes. Only a few studies have concentrated on
82 the internal structures of megaclasts, and these are purely limited to simple correlations between the
83 styles of deformation in megaclasts and their sliding directions and distances (e.g., Jackson, 2011;
84 Alves, 2015; Cardona et al., 2020; Ogata et al. 2020).

85 In this study, we use 3D seismic data to investigate the deformational styles, origin and
86 emplacement processes of megaclasts within MTC 2 (Figs. 2, 3 and 4). To achieve these aims we:
87 a) analyze their geometry, scale, distribution and internal seismic character; b) quantitatively classify

88 the megaclasts based on their different deformational styles, and c) propose a schematic model to
89 explain their emplacement process.

90

91 **2. Geological setting of the Taranaki Basin**

92 The Taranaki Basin is one of the largest Cretaceous-Cenozoic sedimentary basins offshore New
93 Zealand, covering an area of ~330 km² (Fig. 2). It is located ~190 km west of the North Island to the
94 west of the Australia-Pacific plate boundary zone (Fig. 2; Strogon et al., 2017). The study area is
95 located in the northeastern part of the Taranaki Basin, at water depths of 1000-1800 m, in the so-
96 called deep-water Taranaki Basin (Fig. 2). The basin is itself is related to the subduction of the oceanic
97 Pacific Plate under the continental Australian Plate (Fig. 2; Beavan et al., 2002; Giba et al., 2010;
98 Infante-Paez and Marfurt, 2017). As a back-arc rift depocenter, the Taranaki Basin has experienced
99 a complex tectonic evolution (King and Thrasher, 1992; Giba et al., 2010) that includes three major
100 stages of deformation: an extensional stage from the Cretaceous to the Paleocene (~84-55 Ma), a
101 shortening stage from the Eocene to Recent (~40-0 Ma), and a period of intense volcanism from the
102 Late Miocene to Recent (~12-0 Ma) (Giba et al., 2010; Infante-Paez and Marfurt, 2017). Two
103 extensional episodes occurred in the Taranaki Basin from the Cretaceous to the Paleocene: the
104 Zealandia rifting and the West Coast-Taranaki rifting (Infante-Paez and Marfurt, 2017). They caused
105 localized fault-controlled extensional subsidence, contributing to the development of graben and half-
106 graben sub-basins (King and Thrasher, 1992; Stagpoole and Nicol, 2008).

107 As for the depositional history of the Taranaki Basin, rapid sedimentation occurred from Late
108 Cretaceous to Early Miocene, with up to 8 km of sediments having been deposited during a

109 transgressive-regressive cycle (King and Thrasher, 1992). The transgressive phase reached its climax
110 in the Early Miocene with the deposition of calcareous mudstones in the Taimana Formation, and
111 siltstones in the Manganui Formation (King and Thrasher, 1992; Cooper et al., 2001). The regressive
112 phase started in the Mid-Miocene and continues to the present day (Higgs et al., 2012). Tectonic
113 compression affecting the northern part of the Taranaki Basin ceased in the Middle Miocene, resulting
114 in the formation of a submarine volcanic arc – the Mohakatino arc – and concomitant deposition of
115 sandstones (Moki Formation) and siltstones in the Manganui Formation (Fig. 3; Holt and Stern, 1994;
116 Hansen and Kamp, 2002; Kamp et al., 2004). A thick, mud-dominated progradational succession, the
117 Giant Foresets Formation, was deposited during the Plio-Pleistocene in the shallower parts of the
118 basin (Fig. 3; Hansen and Kamp, 2006).

119 Mass wasting is prevalent within the Taranaki Basin, and five large-scale MTCs (MTC 1 to 5)
120 have been documented in the late Miocene to Pleistocene succession based on the Romney-1 well
121 (Fig. 3; Rad, 2015). These MTCs can represent more than 50% of the near-surface stratigraphic
122 column. Based on the correlation between interpreted horizons and the regional geological
123 lithostratigraphy, megaclasts in MTC 2 are likely Late Miocene in age (Bull et al., 2020; Kumar et
124 al., 2021). They were sourced from the shallower outer shelf and upper slope of the North Island of
125 New Zealand and reveal a north-westerly transport direction (Bull et al., 2019). The triggers for the
126 MTCs are still unclear, but MTC 1-4 were likely affected by the high sedimentation rates recorded in
127 the basin, while the collapse of MTC 5 is related to overpressure build-up (Omeru, 2014).

128

129 **3. Data and methods**

130

131 **3.1 Romney 3D survey and Romney-1 well**

132 The primary dataset used for this study is the Romney 3D survey acquired by the Ministry of
133 Business, Innovation and Employment of New Zealand in 2011. This survey covers an area of
134 approximately 1925 km² in the northeastern part of the Taranaki Basin, offshore New Zealand (Fig.
135 2). The 3D seismic data has a sampling interval of 4 ms and its bin size is 12.5 m × 25 m. As the
136 interval of interest has a velocity of 1850 m/s and a dominant frequency of 41 Hz (Rusconi, 2017),
137 the vertical resolution of strata in the studied MTCs is ~ 11.25 m. Exploration well Romney-1 is
138 located in the north of the study area and drilled through a 4594 m-thick clastic succession (Rusconi,
139 2017). In this work, interpreted seismic horizons were tied to the seismic data using well Romney-1
140 and information taken from the well-defined regional lithostratigraphic frameworks of Rusconi (2017)
141 and Nwoko et al. (2020a) (Fig. 3).

142

143 **3.2 Seismic interpretation**

144 The approach followed in this work includes a detailed seismic-stratigraphic interpretation
145 complemented by the compilation of time-structure and seismic-attribute maps (sensu Mitchum et al.,
146 1977). Based on seismic-well ties and published information (e.g., Bull et al., 2020), eight laterally
147 continuous seismic horizons are mapped in this work (Fig. 3b). Seismic interpretation is based on the
148 standard industry software Petrel[®] from Schlumberger.

149 We focus on the Upper Miocene to Holocene formations of the Taranaki Basin, in which five
150 MTCs (MTCs 1-5) are imaged (Figs. 3 and 4). The Upper Miocene to Holocene strata are delimited

151 by Horizon N60-4 and the seafloor (Fig. 3) and reflect the relatively fast deposition of fine-grained
152 sandstones (~30 cm/kyr; King and Thrasher, 1992; Scott et al., 2004; Strogon et al., 2019). Isochron
153 maps at the top MTC 2 were generated to highlight the location of megaclasts and assess their
154 influence on subsequent flows. The basal shear zone of MTC 2 was also mapped to reveal any
155 interactions amongst the megaclasts and their underlying strata.

156

157 **3.3 Calculations of deformation within megaclasts**

158 The deformation of discrete megaclasts refers to: (a) internal deformation and (b) angle of
159 external rotation, two parameters quantified based on morphological analysis of the megaclasts'
160 internal reflections (Fig. 5). Along their sliding direction, the length of curved line (LCL) and the
161 length of straight line (LSL) were measured in megaclasts to obtain their aspect ratio (LCL/LSL) (Fig.
162 5b). Here, the degree of internal deformation within megaclasts (DID) corresponds to LCL/LSL
163 minus 1 (LCL/LSL-1), i.e., a measure of whether the megaclasts comprise parallel, convex-up or
164 concave-up strata (Fig. 6). If the internal reflections within megaclasts are convex-up, the ratio of
165 DID is positive (DID >0). Conversely, DID is negative (DID <0) when the internal reflections in the
166 megaclasts are concave-up. If the internal reflections in the megaclasts are parallel, then DID is 0.

167 The angle of external rotation (θ) reflects the degree of rotation of the megaclasts and is derived
168 using the relationship between the straight line of the two endpoints of the same reflection axis and
169 the horizontal (Fig. 5b). Here, we define that point "B" is higher than point "A" and use point B as
170 the intersection point when calculating the external rotation of megaclasts. The angle is positive ($\theta > 0$)

171 when the inclination of the reflection axis is consistent with the sliding direction (e.g., Fig. 5b),
172 otherwise $\theta < 0$.

173

174 **4. Megaclasts within mass-transport complexes**

175 Five MTCs are interpreted in the study area and comprise low-amplitude, semi-transparent to
176 chaotic seismic reflections grouped into blocky and non-blocky MTCs (Fig. 4; Table 1). Blocky
177 MTCs show parallel to slightly deformed, high-moderate amplitude seismic reflections embedded
178 within a seismically chaotic matrix of the MTCs (Figs. 4 and 6).

179 On the structural map of MTC 2, blocks have principal axes that are 10s of meters to several
180 kms long (Figs. 4 and 6). They are interpreted as megaclasts based on their scales (e.g., Jackson, 2011;
181 Omosanya and Alves, 2013; Alves, 2015; Nwoko et al., 2020b). Many locally moderate- to low-
182 amplitude megaclasts are also identified in other MTCs (Fig. 4). However, megaclasts in MTC 2
183 display higher diversity of internal deformation when compared to other MTCs in the study area.
184 Well Romney-1 shows that MTC 2 occurs in Miocene strata and comprises rotated slumps in
185 claystone and mudstone intervals. At the top of the MTC lies a ~25 m-thick sandstone interval, while
186 its base contains several sandstone intervals grading into calcareous rocks (Fig. 3b).

187

188 **4.1 Geometry, scale and distribution of megaclasts in MTC 2**

189 In total, 123 megaclasts with clear boundaries and visible internal reflections are identified in
190 MTC 2 (Fig. 7a). Here, they are described based on their scale, internal stratigraphy and
191 morphological characters. The longest axis (L) of megaclasts is 400 m to 2000 m, whereas their

192 shortest axis (W) varies from 300 m to 1200 m (Figs. 5a and 7b). The average length and width of
193 megaclasts are ~1000 m and ~620 m, respectively (Figs. 5a and 7b). Their height (H) ranges from
194 150 to 400 m with an average value of ~250 m (Figs. 5a and 7b). Overall, the height of the megaclasts
195 increases from southeast to northeast (Fig. 4).

196

197 **4.2 Top surface and basal shear zone of MTC 2**

198 The top surface of MTC 2 is a high-amplitude positive reflection with a similar polarity to the
199 seafloor reflection (Figs. 4 and 6). Some of the largest megaclasts, greater than the thickness of MTC
200 2 at the considered point of observation, pierce the top of the MTC in the NE and SW to generate an
201 irregular top surface with local relief (Figs. 4, 6, 8 and 9a-b). The basal shear zone of MTC 2 is a low-
202 amplitude seismic reflection with a negative polarity (Figs. 4 and 6). Compared with the top surface,
203 the basal shear zone of MTC 2 is relatively flat, with gradients as low as $\sim 1^\circ$ (Figs. 4 and 8b). Several
204 linear grooves can be observed at the basal shear zone of MTC 2 and show an orientation of NWW-
205 SEE with a width of 300~330 m and a length of up to 18 km (Fig. 8b).

206 The basal shear zone of MTC 2 shows two types of depressions below the megaclasts (Figs. 8b
207 and 9c-d). Type I depressions are mostly found in the NE and SW of the study area (Fig. 8b). Type I
208 depressions are U-shaped in map view and open toward the SE, a character consistent with the sliding
209 direction of MTC 2 (Figs. 9c and 10a). Type I depressions have widths and lengths similar to the
210 overlying megaclasts. For example, one Type I depression in the northeast is ~1211 m wide, ~1500
211 m long, and up to 50 m deep (Figs. 9c, e and f). The megaclast overlying this Type I depression has
212 a length of 1000 m and a maximum height of 250 m, and its edge aligns with the boundary of the

213 underlying depression (Figs. 9a and c). This megaclast is deformed with overall concave-up and
214 forward-dipping internal reflections, with a DID of 0.05 and an external rotation of 15.17° (Fig. 10c).

215 Type II depressions are mainly found in the northwest part of MTC 2 (Figs. 8b and 9d). Type II
216 depressions are circular-, oval- or irregular-shaped (Figs. 9d, g, h and 10b). The shapes of Type II
217 depressions are entirely consistent with the boundaries of overlying megaclasts (Fig. 8). For instance,
218 one Type II depression found in the northwest part of the study area is 1244 m wide, 1311 m long
219 and ~45 m deep (Figs. 9d, e, f, and 10b). The overlying megaclast has exactly the same morphometric
220 values, despite being slightly deformed, with a DID of -0.009 and internal strata typically forward-
221 dipping at 11.99° (Fig. 10d).

222 223 **4.3 Classification of megaclasts based on morphometric parameters**

224 Based on their angle of rotation and degree of internal deformation, the megaclasts in the study
225 area are further divided into undeformed, rotated, deformed, and highly deformed types (Figs. 11 and
226 12). Their character is described as follows:

227 (1) Undeformed megaclasts ($DID = 0$, $\theta = 0$) comprise undeformed and non-rotated reflections
228 and quantitatively correspond to the planar-aclinic type (Fig. 11c). Undeformed megaclasts can also
229 be termed as remnant or in-situ megaclasts with no evidence for movement (i.e., Alves, 2015). Thus,
230 no basal and internal deformation features are observed.

231 (2) Rotated megaclasts ($DID = 0$, $\theta > 0$ or $\theta < 0$) show rotated internal reflections (Figs. 11a and
232 b). Based on the angle of rotation (θ) alone, the rotated megaclasts are further subdivided into planar-
233 forward dipping megaclasts (PF megaclasts, $\theta > 0$; Fig. 11a) and planar-backward dipping megaclasts

234 (PB megaclasts, $\theta < 0$; Fig. 12b). The PF megaclasts ($DID = 0$, $\theta > 0$) show rotated internal reflections,
235 and the direction of rotation is the same as their sliding direction (Fig. 11a). PB megaclasts ($\theta < 0$,
236 $DID = 0$) show rotated internal reflections whose direction of rotation is opposite to their sliding
237 direction (Fig. 11b).

238 (3) Deformed megaclasts ($\theta = 0$, $DID \neq 0$) are syncline-aclinic (SA) megaclasts and anticline-
239 aclinic (AA) megaclasts (Figs. 11f and i). SA megaclasts (Fig. 11f) show small-scale concave-up
240 reflections ($\theta = 0$ and $DID > 0$), while AA megaclasts (Fig. 11i) have convex-up reflections ($\theta = 0$
241 and $DID < 0$), reflecting syncline and anticline deformations, respectively.

242 (4) Highly deformed megaclasts ($DID > 0$ or $DID < 0$, $\theta > 0$ or $\theta < 0$) have deformed and rotated
243 reflections including syncline-forward (SF) dipping, syncline-backward (SB) dipping, anticline-
244 forward (AF) dipping, and anticline-backward (AB) dipping megaclasts (Figs. 11d, e, g and h). SF
245 megaclasts ($DID > 0$ and $\theta > 0$) show bent-down internal reflections and are rotated towards their
246 sliding direction (Fig. 11d). Internal reflections of SB megaclasts ($DID > 0$ and $\theta < 0$) are rotated
247 opposite to their sliding direction (Fig. 11e). AF megaclasts ($DID < 0$ and $\theta > 0$), showing anticline
248 and backward dipping reflections (Fig. 11g), are rotated in their sliding direction (Figs. 11g and h).
249 Highly deformed megaclasts are most common in MTC 2 and can reach up to 80% of the total amount
250 of mapped megaclasts (Fig. 12).

251

252 **5 Discussion**

253 Our observations and interpretations on the deformational styles and basal shear zones of the
254 megaclasts within MTC 2 enable us to better understand their origin and emplacement processes.

255 This section starts with a discussion on the source of these megaclasts. Secondly, a discussion follows
256 on how the different emplacement processes affect the deformational styles of megaclasts.

257

258 **5.1 Source of megaclasts: transported or in-situ?**

259 Megaclasts in mass-transport complexes have been widely studied and proposed to be derived
260 from: a) fragmented strata derived from the headwall region of landslides (Moore et al., 1995;
261 Huvenne et al., 2002; Alves and Cartwright, 2009; Ortiz-Karpf et al., 2017; Wu et al., 2021); b)
262 collapsed strata along the lateral margins of MTCs (Alves, 2010; Joanne et al., 2013; Hodgson et al.,
263 2019); or (c) basal shear zones (Ortiz-Karpf et al., 2015; Hodgson et al., 2019). Regardless of their
264 provenance or size, blocks within MTCs can generally include transported and remnant types
265 (Gamboa et al., 2012; Alves, 2015; Omosanya, 2018).

266 Two types of megaclasts can be determined based on the different depressions they left on the
267 basal shear zone (Figs. 8b, 10a and b, Table. 2). It is worth noting that Type I megaclasts are
268 characterized by the presence of U-shaped depressions at their basal shear zones and these
269 depressions are aligned with the sliding direction and the boundaries of their overlying megaclasts
270 (Figs. 8b, 9c, 9e and 9f). These U-shaped depressions are much wider than the classical grooves
271 and/or striations observed at the base of MTCs, which are key kinematic indicators on the orientation
272 of MTCs (e.g., Gee et al., 2005). Seismic profiles crossing Type I megaclasts show obvious
273 truncations along their basal shear zone (Fig. 10c). This suggests that these megaclasts have severely
274 eroded the underlying strata (e.g., Gee et al., 2005; Draganits et al., 2008; Joanne et al., 2013; Nwoko

275 et al., 2020b), leading to the formation of U-shaped depressions. Therefore, Type I megaclasts with
276 U-shaped depressions at their basal shear zones are considered to be transported megaclasts.

277 Compared to the Type I megaclasts with U-shaped depressions, several Type II megaclasts in
278 the west of our study area are characterized by circular-, oval- or irregular-shaped depressions (Fig.
279 8b). These depressions have similar dimensions to the boundaries of overlying megaclasts (Fig. 8b,
280 9d, g and h). The seismic reflections below the base of the megaclasts are continuous (Fig. 10d),
281 suggesting the absence of erosion along their basal shear zone. As for the origin of this kind of
282 megaclasts, one interpretation is that they were buoyant due to the presence of sufficient debris-flow
283 matrix and they would not leave grooves and striations on the basal shear zone of MTCs (e.g., Gee et
284 al., 2005; Joanne et al., 2013). According to Johnson (1970), whether the megaclasts can be buoyant
285 or not depends on the yield strength (a critical rheological parameter) of the debris flow, which affects
286 the flow transporting competence. The dimension of Type II megaclasts is larger than the nearby
287 Type I megaclasts (Figs. 4 and 8b, Table 2). If the Type II megaclasts can be buoyant, then the
288 adjacent ones with smaller sizes should also have been buoyant and transported by the debris flows.
289 However, the smaller-scale Type I megaclasts have obvious U-shaped depressions at their bases,
290 suggesting that the larger Type II megaclasts were not buoyant within moving debris flows.

291 The second hypothesis for the source of Type II megaclasts is that they might be derived from
292 in-situ strata (e.g., Ortiz-Karpf et al., 2015). Compared to the transported megaclasts, strata at the
293 bottom of the Type II megaclasts are continuous and their internal reflections are slightly deformed
294 (Fig. 10d). This observation also suggests that these megaclasts would have not undergone obvious
295 transportation (e.g., Masson et al., 1993; Hodgson et al., 2019). Following this hypothesis, the

296 megaclasts with Type II depressions are, therefore, considered as remnant megaclasts, or reflecting
297 limited transport distance.

298
299 **5.2 Deformational styles and emplacement processes of megaclasts**

300 Megaclasts within MTC-related debris flows can be deformed, and this is related to local
301 differential shear within the debris flows and subsequent interaction with the basal shear zone (Bull
302 et al., 2009; Alves, 2015). The investigated megaclasts in MTC 2 show various deformational styles,
303 including undeformed, rotated, deformed and highly deformed megaclasts (Fig. 12). These different
304 deformational styles may provide kinematic indicators related to the initiation, motion and arrest of
305 the debris flows (e.g., Lucente and Pini, 2003; Bull et al., 2009) and can also be used to infer the
306 emplacement processes of megaclasts (Fig. 13; e.g., Jackson, 2011).

307 Two different types of megaclasts have been determined in the previous section, i.e., transported
308 (Type I) and remnant (Type II) megaclasts. In general, the dimension (height, length and width) of
309 transported megaclasts is observed to decrease along the sliding direction (Fig. 4), and their average
310 height is 7.6% smaller than the remnant megaclasts (Table 2). During sliding, megaclasts are likely
311 affected by friction and their bottom surfaces can be abraded along the basal shear zone (Fig. 13b;
312 Moore et al., 1995; Tinti et al., 1997; Alves and Cartwright, 2009; Alves, 2010; Ogata et al., 2014;
313 Soutter et al., 2018; Hodgson et al., 2019). This would make the heights of transported megaclasts
314 decrease, leading to the formation of faults within them (Fig. 4). As the sliding distance increases,
315 faults within the megaclasts may gradually develop until they penetrate and deform the entire
316 megaclasts, resulting in their disintegration into smaller pieces with a decrease in their dimensions

317 downslope (Fig. 4; e.g., Alves and Cartwright, 2009; Ogata et al., 2014; Ortiz-Karpf et al., 2017;
318 Hodgson et al., 2019).

319 Our observations show that almost all the transported megaclasts have been tilted, regardless of
320 their forward- or backward-dipping geometry (Table 3). One explanation for this marked tilting of
321 megaclasts is that they might be influenced by the surrounding debris flows. Megaclasts are
322 transported downslope together with debris flows and they can be partially pushed and dragged by
323 the latter (e.g., Lastras et al., 2005). This would lead to the formation of forward-dipping megaclasts
324 and abrasion would occur in their frontal parts. Our results also show that the forward-dipping
325 transported megaclasts are larger than the backward-dipping ones (Table 4). If the larger megaclasts
326 can be forward-dipping under the influence of debris flows, then the smaller megaclasts should have
327 also been tilted forward. However, this interpretation contradicts our previous observations (Table 4).
328 Thus, we do not think that the debris flows have played a vital role in the tilting of megaclasts. The
329 most likely reason to explain the tilting of megaclasts is that the paleo-seafloor is not smooth and
330 megaclasts interacted with the rugged paleo-seafloor when moving downslope. This interaction was
331 capable of enhance erosion in the front or back of the megaclasts, generating forward- or backward-
332 dipping strata in their interior (Figs. 7a, 13a-b and Table 5). In addition, most of the megaclasts
333 contain folds and normal faults, indicating that they have undergone severe internal deformation
334 during their downslope movement (Fig. 7a).

335 Remnant blocks show little internal deformation and vertical stratigraphic continuity with
336 underlying strata (Alves and Cartwright, 2009; Gamboa et al., 2011). They are considered to be in-
337 situ portions of strata that were not remobilized during slope failure, which might be related to their

338 harder lithologies, e.g., limestones, and cemented siliciclastic sediment (Mohriak et al., 2008).
339 Remnant blocks are laterally bounded by faults propagating from underlying strata and their bases do
340 not show any significant disruption (e.g., Gamboa et al., 2011). However, most (76.7%) of the
341 remnant megaclasts (Type II) identified in this study are observed to be tilted and/or internally
342 deformed (Fig. 7b, Table 5). In addition, some of the remnant megaclasts show some degree of
343 erosion at their bases, especially in their frontal parts (Figs. 7b, 10d). This suggests that these remnant
344 megaclasts might have been moved for a quite limited distance, pushed by the surrounding mass
345 wasting strata or by other moving megaclasts (Fig. 13d-e; Vanneste et al., 2006). Therefore, the
346 significant differences between the remnant and transported megaclasts in terms of their scales,
347 degree of internal deformation and external rotation can be attributed to their different emplacement
348 processes. Finally, the strata below the megaclasts would have been deformed due to compaction
349 after their emplacement, leading to the formation of Type II depressions (Fig. 13f).

350 We recognize some limitations in the approach we used to quantify the morphological parameters
351 of megaclasts within MTCs. The vertical exaggeration (V.E.) and vertical scale of seismic profiles
352 may influence the actual observed shapes and internal architectures of megaclasts. However, it is not
353 possible to conduct a time/depth conversion to show the real vertical scale on the seismic profiles due
354 to the lack of velocity values for the interval of interest, especially for the megaclasts. As for the
355 vertical exaggeration, we use a constant value of 5:1 for all the seismic profiles we used in this study.
356 All these caveats should be taken in consideration by interpreters and structural geologists when
357 analyzing megaclasts in seismic data.

358

359 **6 Conclusions**

360 We use high-resolution 3D seismic reflection data to investigate the morphological and seismic
361 characteristics of 123 megaclasts within a mass-transport complex in the deep-water Taranaki Basin,
362 offshore New Zealand. The main conclusions of this work are:

363 (1) Megaclasts are characterized by moderate-to-high amplitude seismic reflections and can
364 reach up to 1900 m in length, ca. 1200 m in width and ca. 400 m in height.

365 (2) In seismic data, the internal reflections or strata in megaclasts appear rotated and deformed.

366 (3) A new morphometric classification of megaclasts is based on the deformational styles in
367 terms of internal deformation and external rotation. Hence, megaclasts in the study area are
368 quantitatively divided into four types: undeformed, rotated, deformed, and highly deformed.

369 (4) The two different kinds of depressions formed at the basal shear zones indicate if the
370 megaclasts in MTC 2 are either transported or remnant.

371 (5) Downslope movement of large slide blocks or megaclasts during mass wasting can promote
372 erosion of their underlying strata and internal deformation.

373

374 This work quantitatively clarifies the relationships between the deformational styles of
375 megaclasts and the basal shear zone, which is better for understanding the emplacement processes of
376 megaclasts along many continental margins. Our approach is able to reflect the relatively different
377 types of megaclasts in terms of their internal deformation and angle of rotation.

378

379 **Acknowledgments**

380 We thank New Zealand Crown Research Institute (GNS Science) for providing the Romney 3D
381 survey, well data and report for this work (<https://data.nzpam.govt.nz/>). This work was financially

382 supported by the Key Special Project for Introduced Talents Team of Southern Marine Science and
383 Engineering Guangdong Laboratory (Guangzhou) (GML2019ZD0104), Guangdong Basic and
384 Applied Basic Research Foundation (2020B1515020016) and National Natural Science Foundation
385 of China (41876054 and 41976077). Dr. Wei Li is funded by CAS Pioneer Hundred Talents Program
386 (Y8SL011001). Two reviewers, Kei Ogata and Julien Bailleul, Associate Editor Stefano Mazzoli and
387 Science Editor Mihai Ducea are acknowledged for their constructive comments, which greatly
388 improved the manuscript.

389

390 **Data Availability**

391 The seismic and well data that support the findings of this study are available upon request from
392 <https://data.nzpam.govt.nz/GOLD/system/mainframe.asp>.

393

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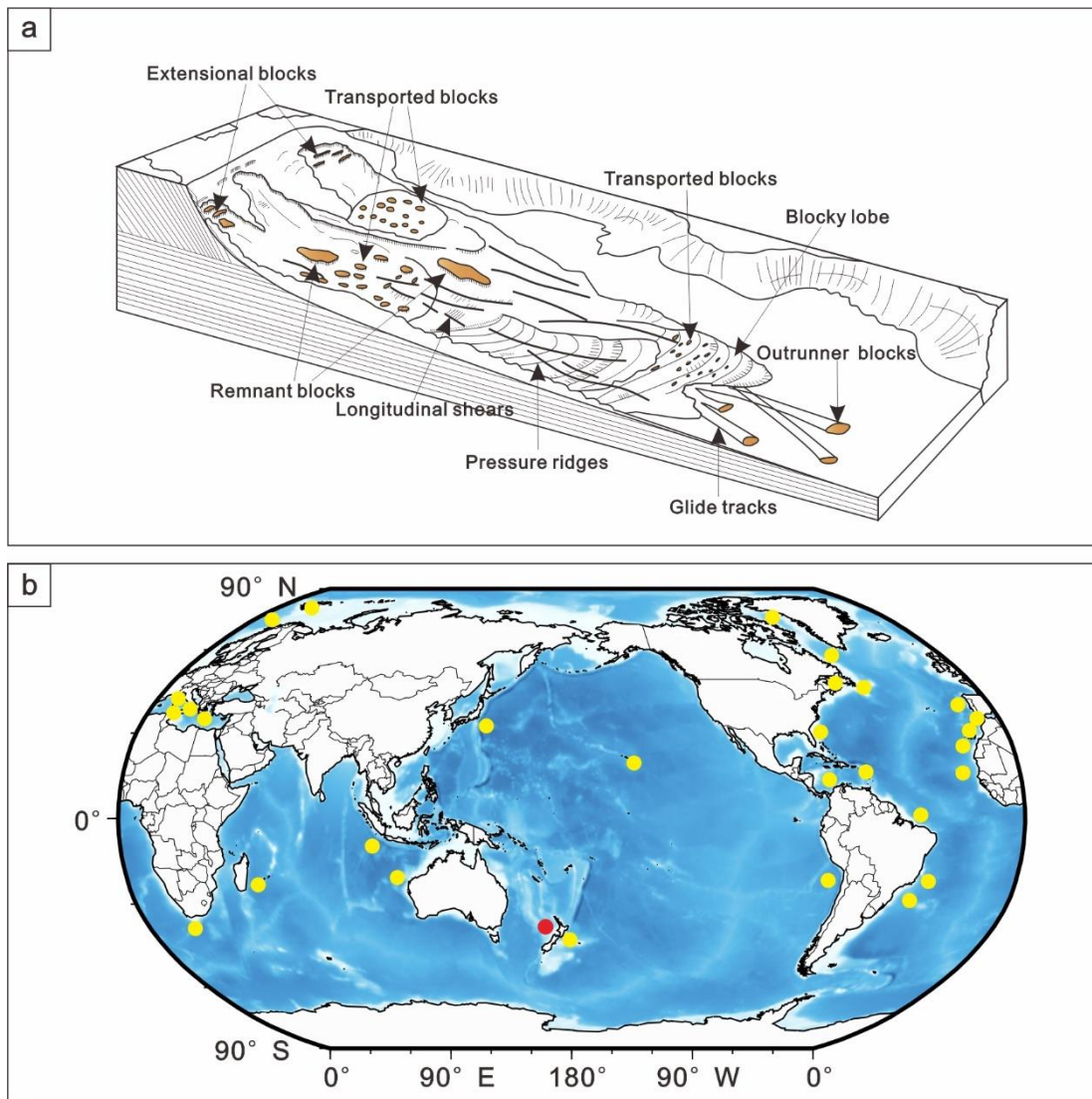
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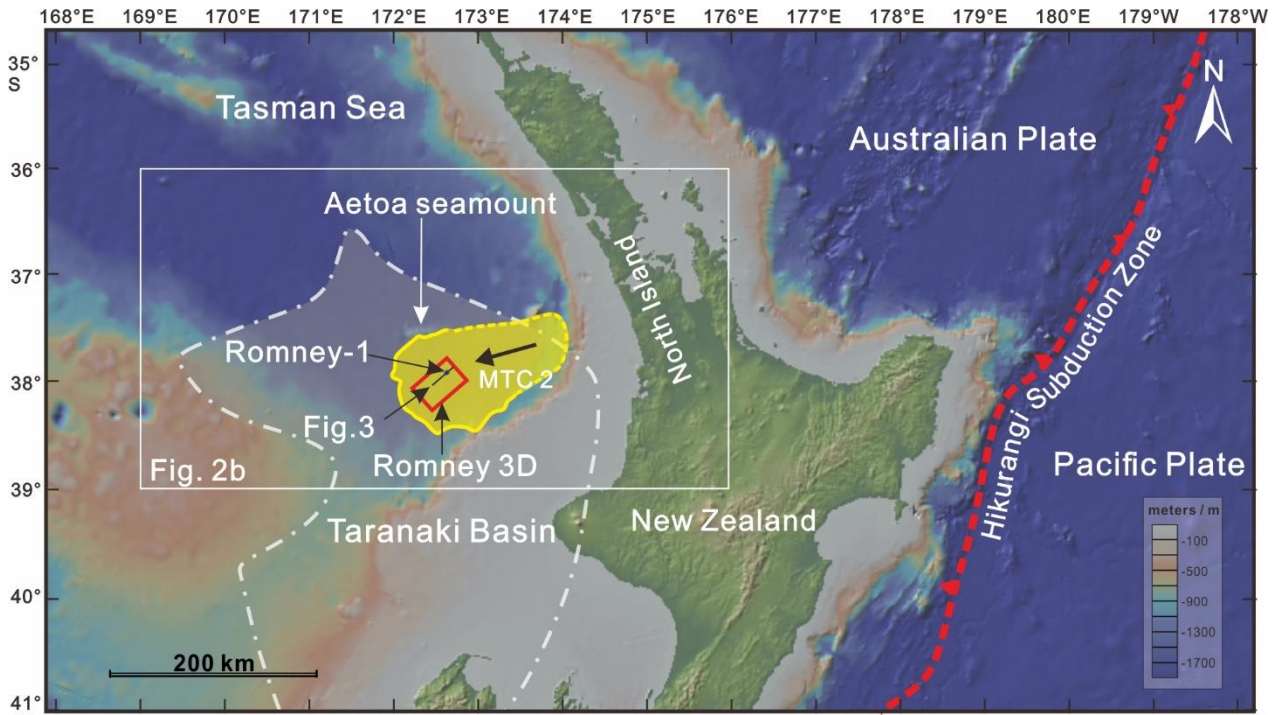
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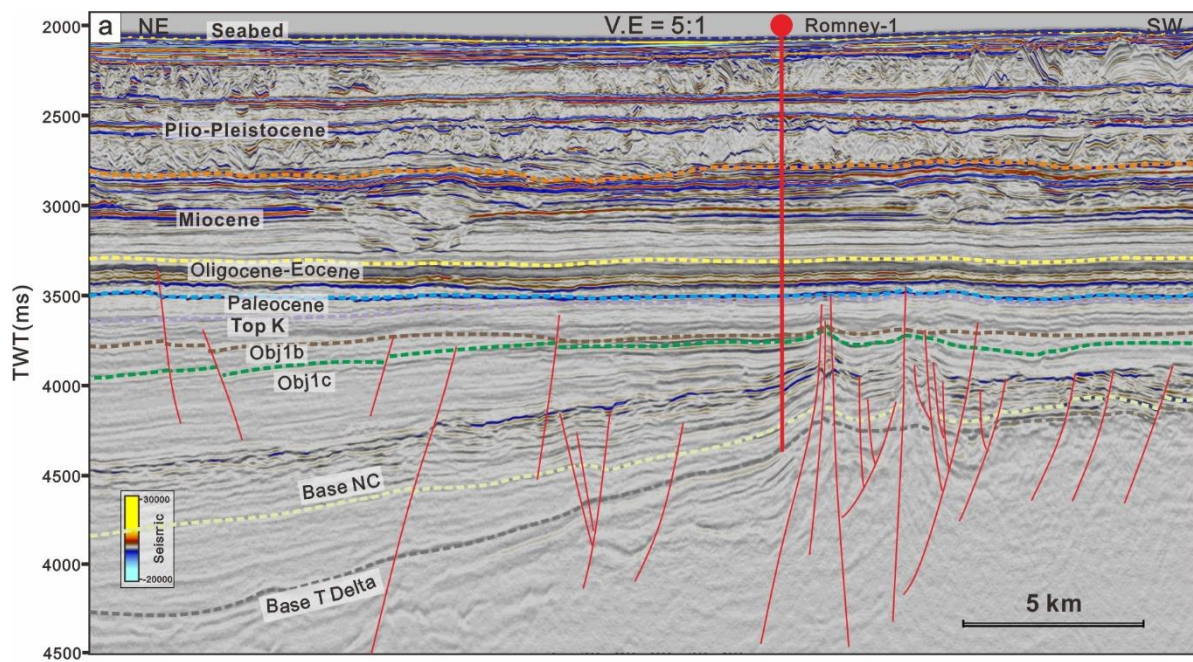
566 Fig. 1 (a) Model for mass-transport complexes (MTCs) showing four types of blocks: extensional
 567 blocks, remnant blocks, transport blocks and outrunner blocks (figure adapted from Nissen et al.,
 568 1999). (b) Global distribution of blocky MTCs (yellow dots, modified from Alves, 2015) and the
 569 location of the study area (red circle).

570



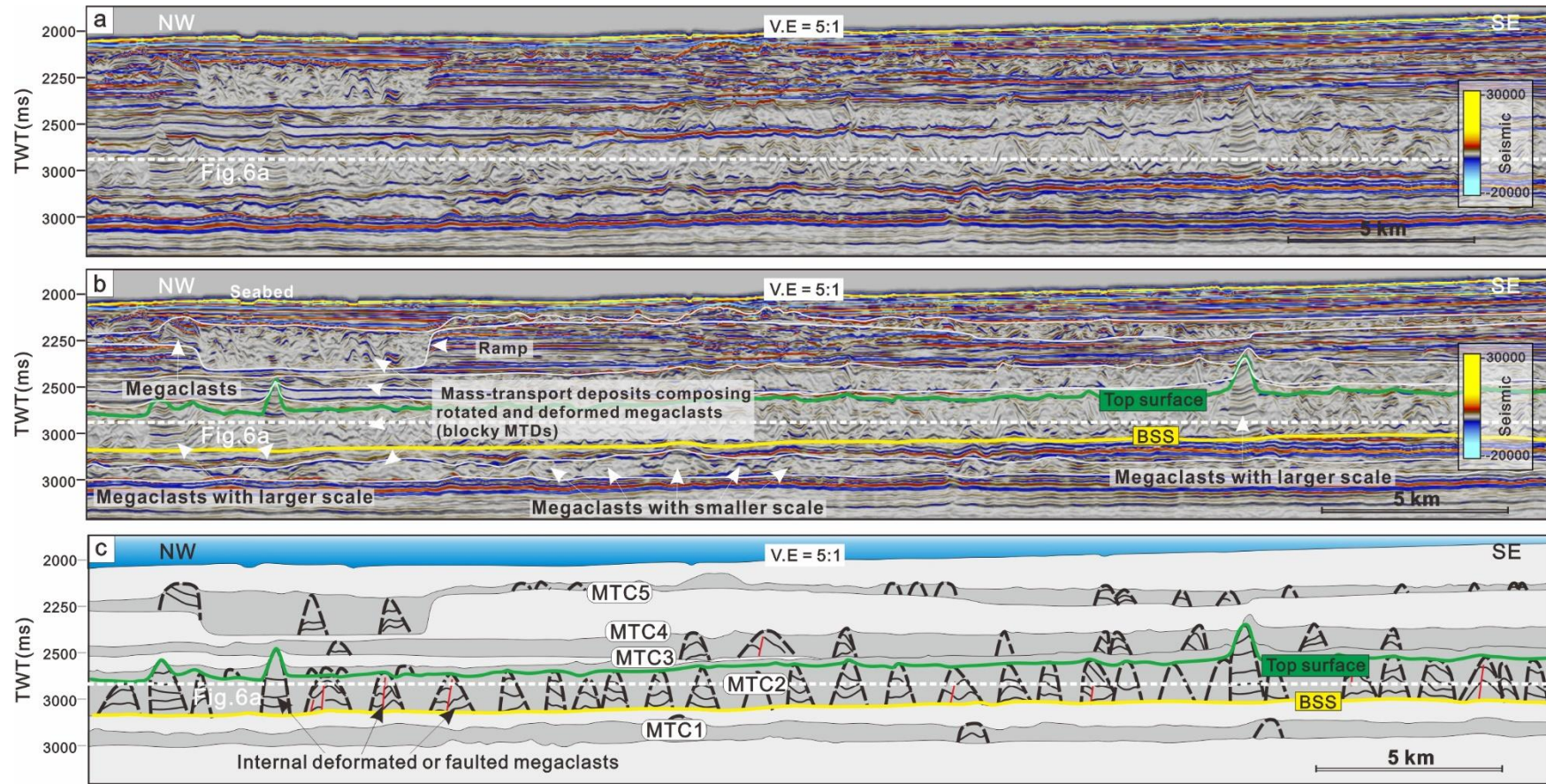
571

572 Fig. 2 Topographic map showing main structural elements (Australian Plate, Pacific Plate and
 573 Hikurangi Subduction Zone), location of the Taranaki Basin (figure adapted from Stroger et al., 2017),
 574 the distribution of MTC 2 (marked in yellow; figure modified from Omeru et al., 2014), and the study
 575 area (red box), located in the translational domain of MTC 2.



Age	Formation	Lithology	Seismic Markers	Seismic	Lithological Description
Plio-Pleistocene	Volcanics	Whenuakura	Seabed 1575 m	Romney-1	Siltstone, shale w/ intbddd ss
	Giant Foresets		MTCs		
	Tangahoe Matemateaonga		H50 2280 m		
Miocene	Urenui	Ariki			Shale & siltstone w/ SS & Lst stringers, becoming more cal- careous towards base
	Mt Messenger				
	Moki	Miocene Volcanics			
	PI Fan	Manganui			
	Taimana				
			2975 m		

576
 577 Fig. 3 (a) Interpreted seismic profile crossing well Romney-1 showing regional seismic-stratigraphy
 578 units and the eight (8) seismic horizons that bound them (figure modified from Bull et al., 2020). The
 579 location of seismic profile is shown in Fig. 2b. (b) Lithological column highlighting the stratigraphic
 580 succession intersected by well Romney-1.

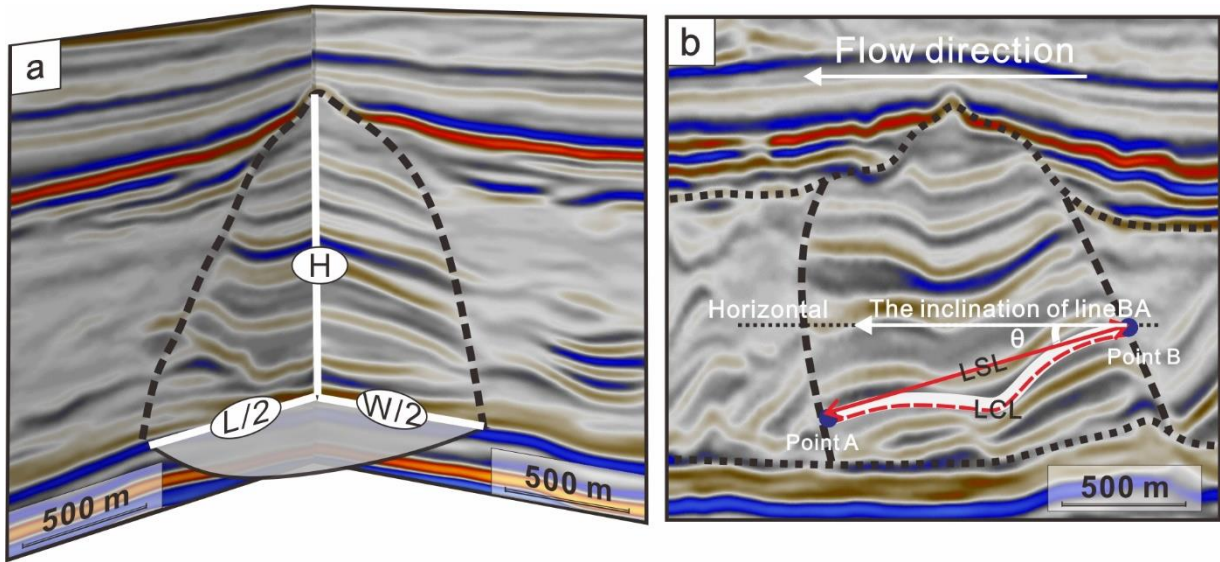


581

582 Fig. 4 (a) Uninterpreted regional seismic profile. (b) Interpretation of the regional seismic profiles showing megaclasts of different sizes within MTCs.

583 VE: Vertical Exaggeration. BSS: basal shear surface. (c) interpretation on the seismic profiles shown above.

584



585

586 Fig. 5 (a) Geometric parameters measured for the megaclasts include length (L), width (W) and height

587 (H). (b) The 2D model of the megaclasts highlights their internal deformation. Note that the “LCL”

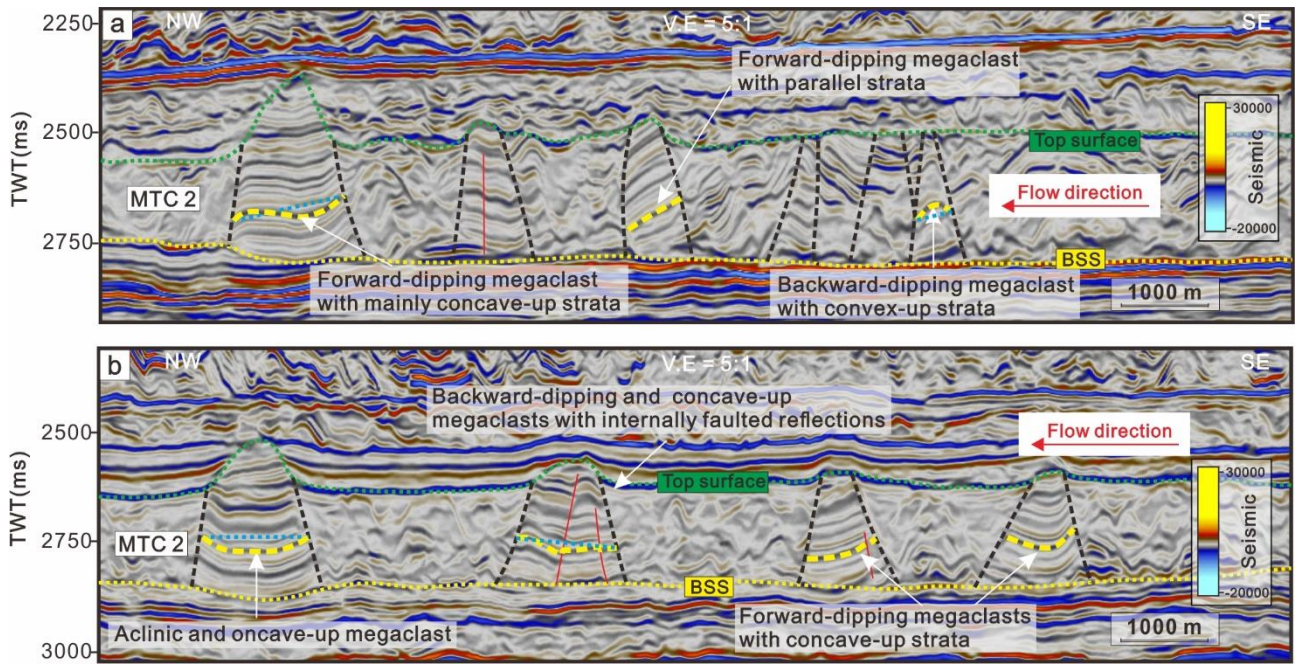
588 represents the length of the curve line, corresponding to the true trace of reflection axis within

589 megaclasts, the “LSL” represents the length of the straight line between the two points of the

590 reflection axis, and “ θ ” represents the angle between the horizontal and the straight line between the

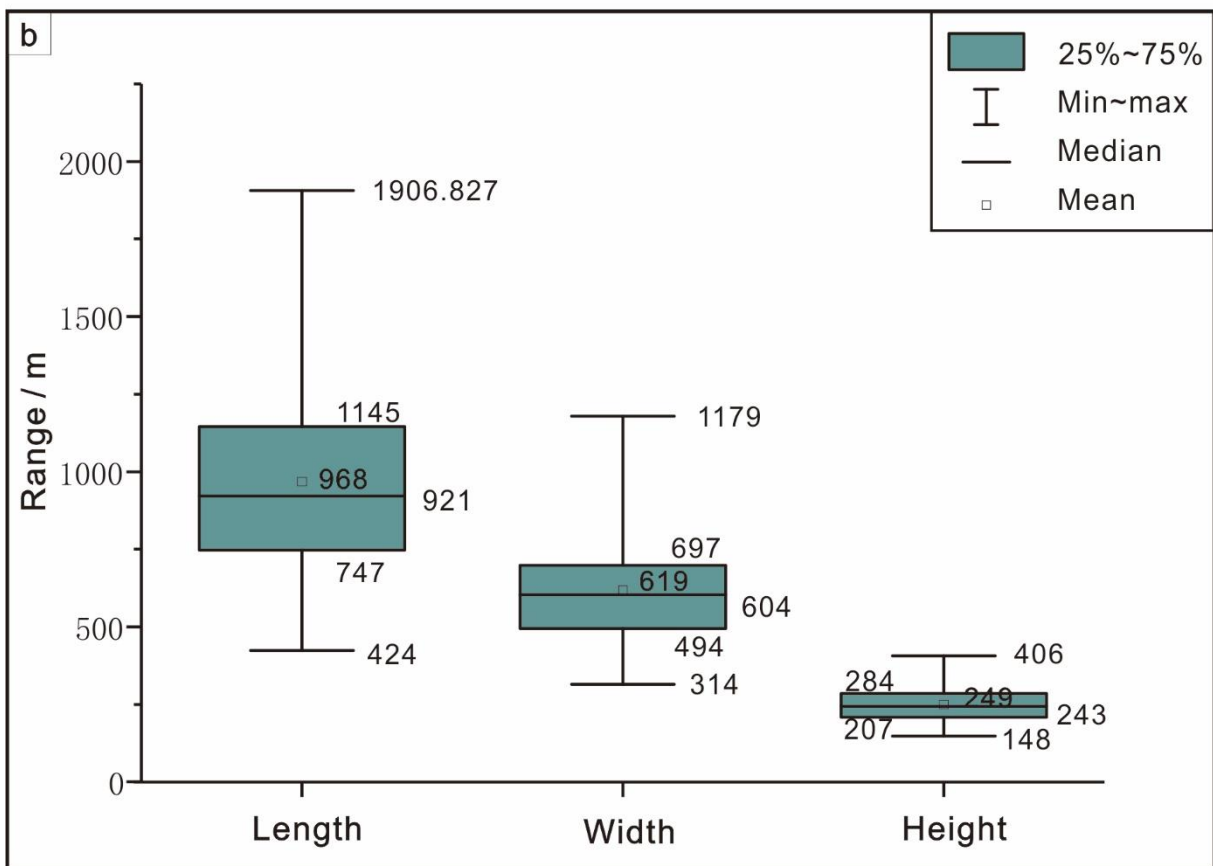
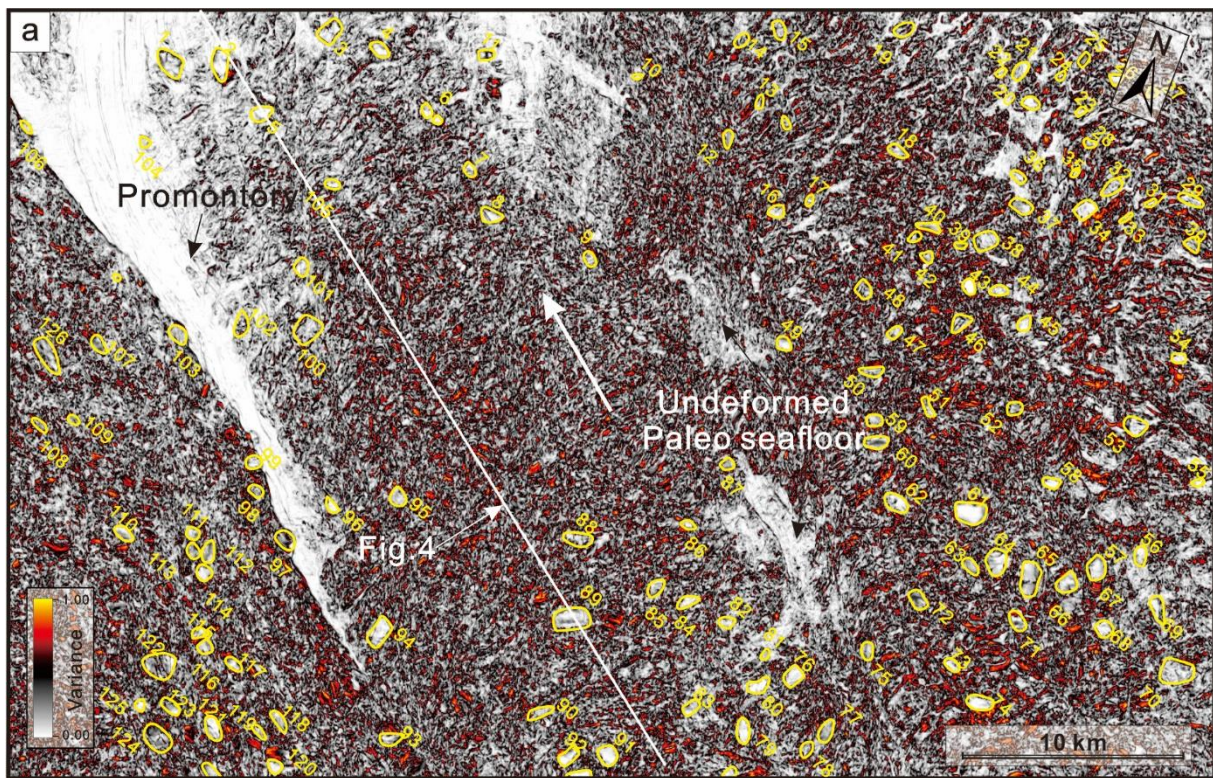
591 two points of the reflection axis.

592



593

594 Fig. 6 Seismic profiles showing seismic characteristics of megaclasts within MTC 2 in the (a) eastern
 595 part and (b) western part of the study area. BSS: basal shear surface. Note that the yellow thick dotted
 596 lines within megaclasts indicate their deformation, while the blue thin dotted lines connect the two
 597 ends of the thick yellow dotted line and are used as a reference line to judge the external rotation and
 598 internal deformation of the megaclasts. BSS is basal shear surface.

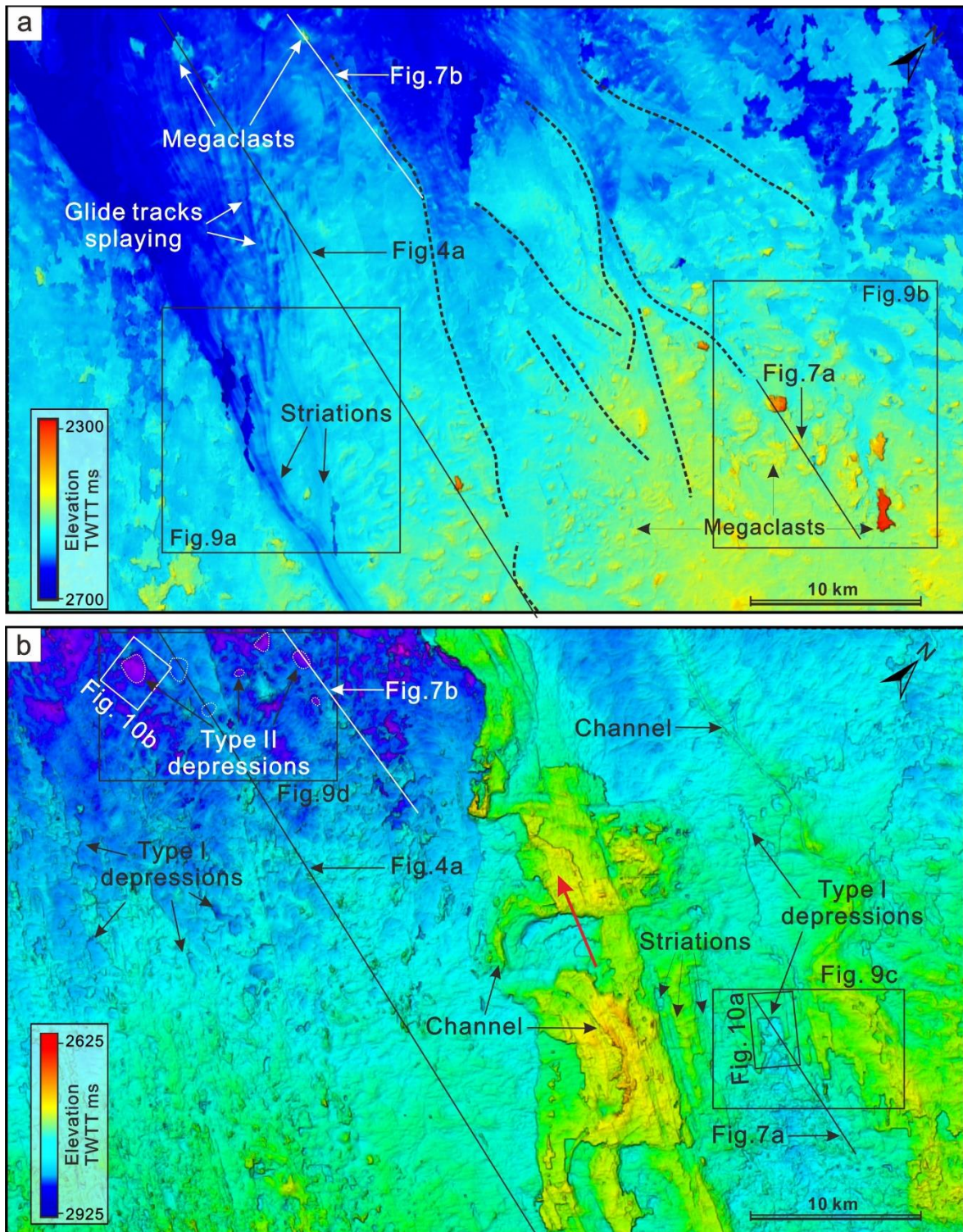


599

600 Fig. 7 (a) Time slice at T=2672 ms showing the distribution of megaclasts in MTC 2. The white arrow

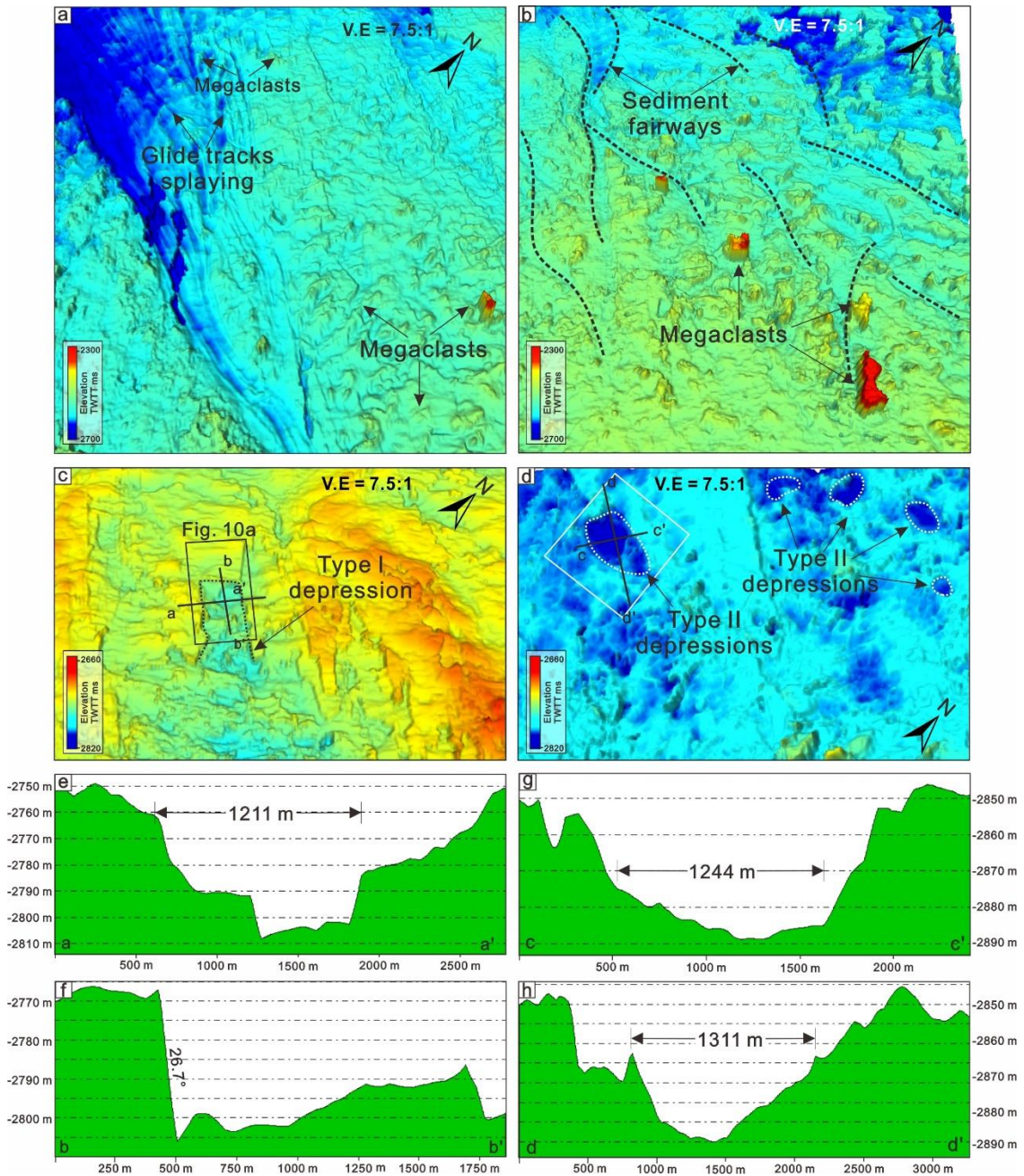
601 represents the sliding direction of MTC 2. The yellow lines indicate the boundaries of identified

602 megaclasts in the study area. (b) Basic parameters of megaclasts in MTD 2 highlighting their length
603 (L), width (W), and height (H).



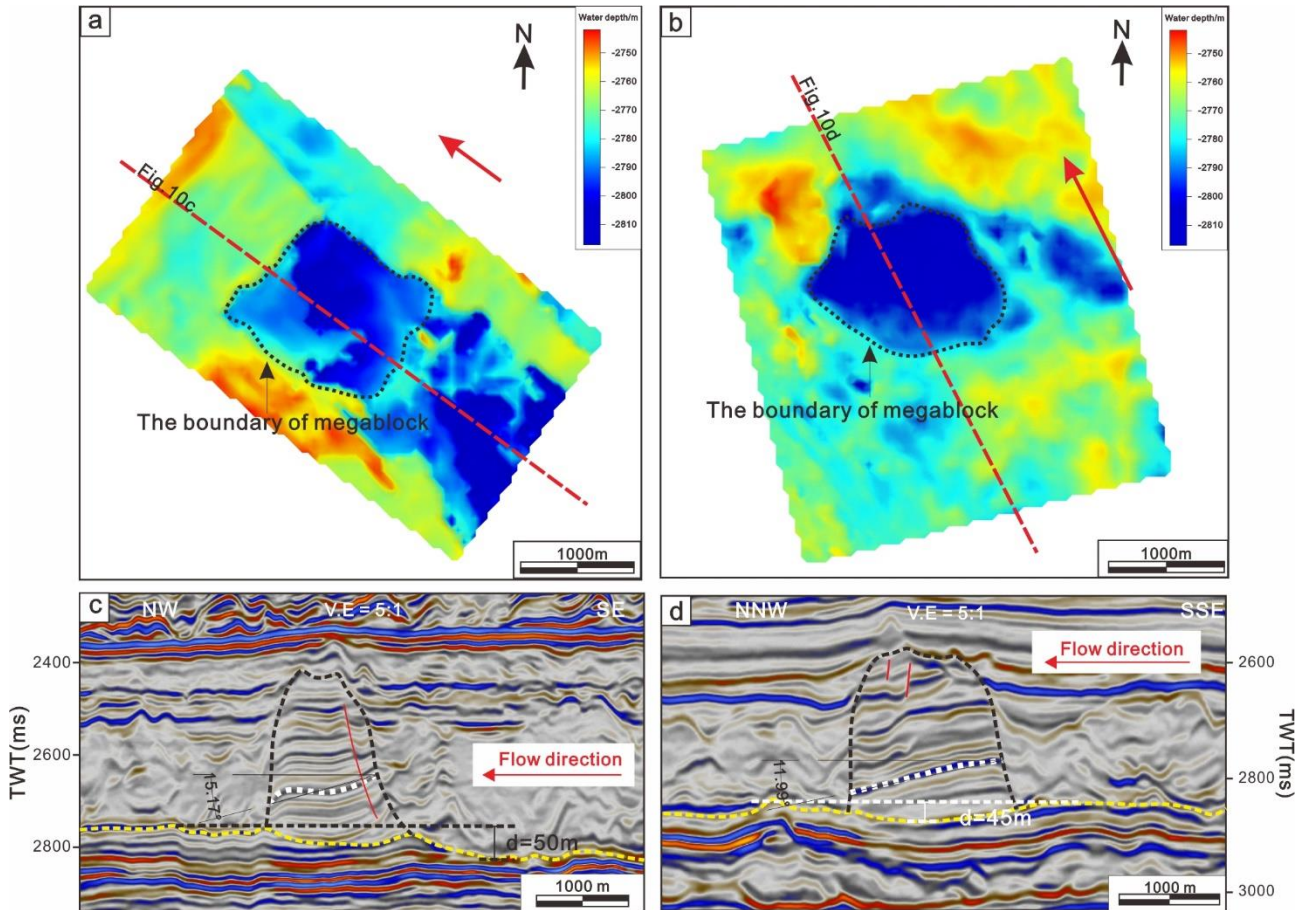
604
605 Fig. 8 (a) Structural map of the top MTC 2, showing the spatial distribution of megaclasts in the
606 study area. At the NE part of the MTC 2, the rugged topographies at the top of the megaclasts created

607 fairways associated with the deposition of the overlying MTC (i.e. MTC 3). While the NW part of
 608 the MTC 2 is characterized by glide tracks and striations associated with the translation of overlying
 609 MTC (i.e., MTC 3). (b) Structural map of the basal shear zone of MTC 2, showing the depressions
 610 and other geomorphological structures. Negative relief at the base of the MTC 2 is caused by channels.
 611 The red arrow represents the slip direction of MTC 2.

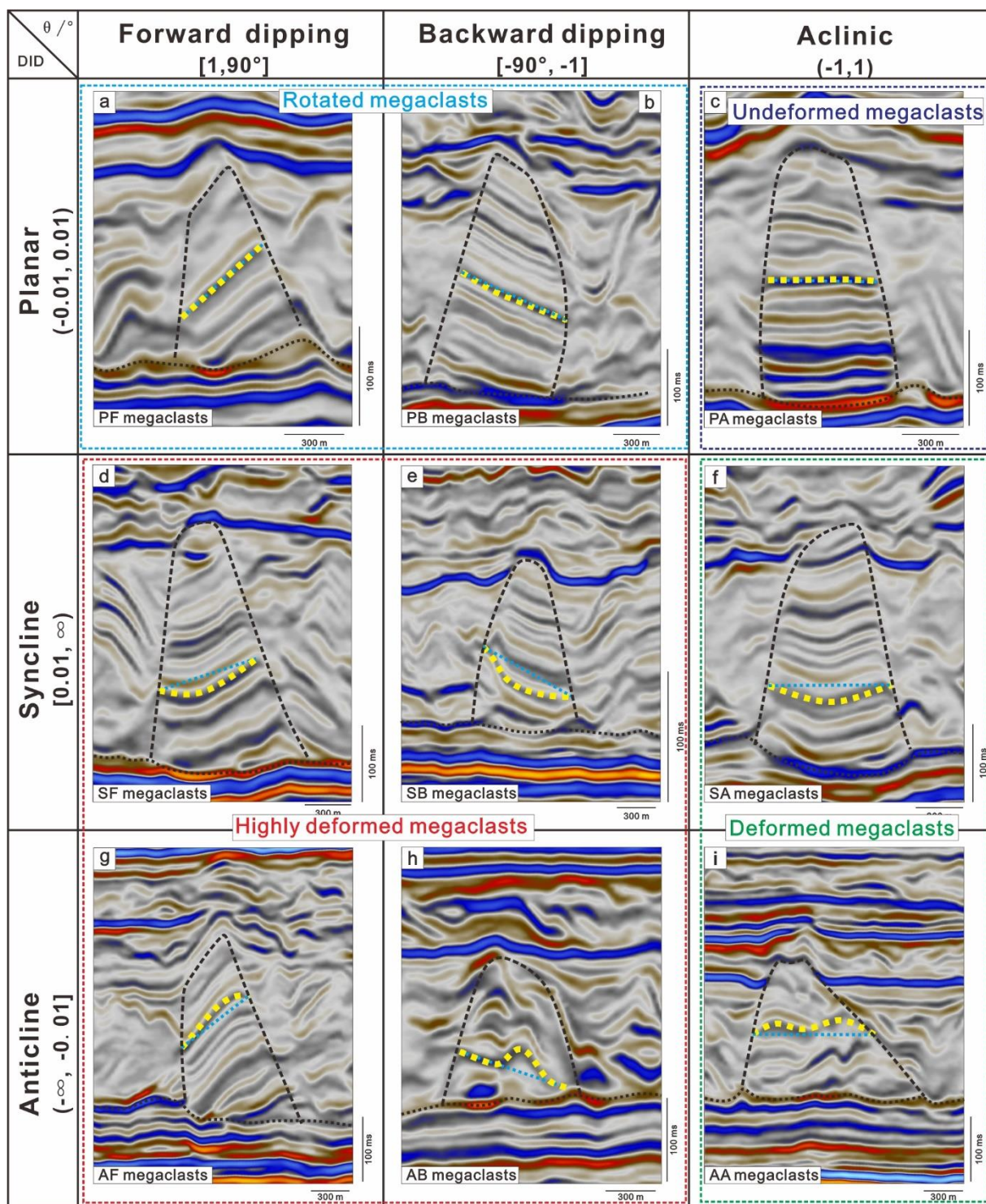


612

613 Fig. 9 3D view (a) Megaclasts and glide tracks at the top MTC 2 level and (b) sediment fairways
 614 created by the rugged topographies associated with the tops of the megaclasts. V.E refers to the high
 615 ratio of figure height and real high. Examples of (c) Type I and (d) Type II depressions associated
 616 with the base of the megaclasts. (e) and (f) Bathymetric profile of the type1 depressions shown in (c).
 617 (g) and (h) Bathymetric profile of the type 2 depressions shown in (d).



618
 619 Fig. 10 (a) and (b) Time structural maps illustrate two different types of depressions on the basal
 620 shear zone of MTC 2. The boundaries of megaclasts are marked by black dotted circles. (c) and (d)
 621 Two-dimensional seismic profiles from three-dimensional seismic volume illustrating geometry and
 622 key internal deformation of megaclasts of figures 10a and b, respectively.

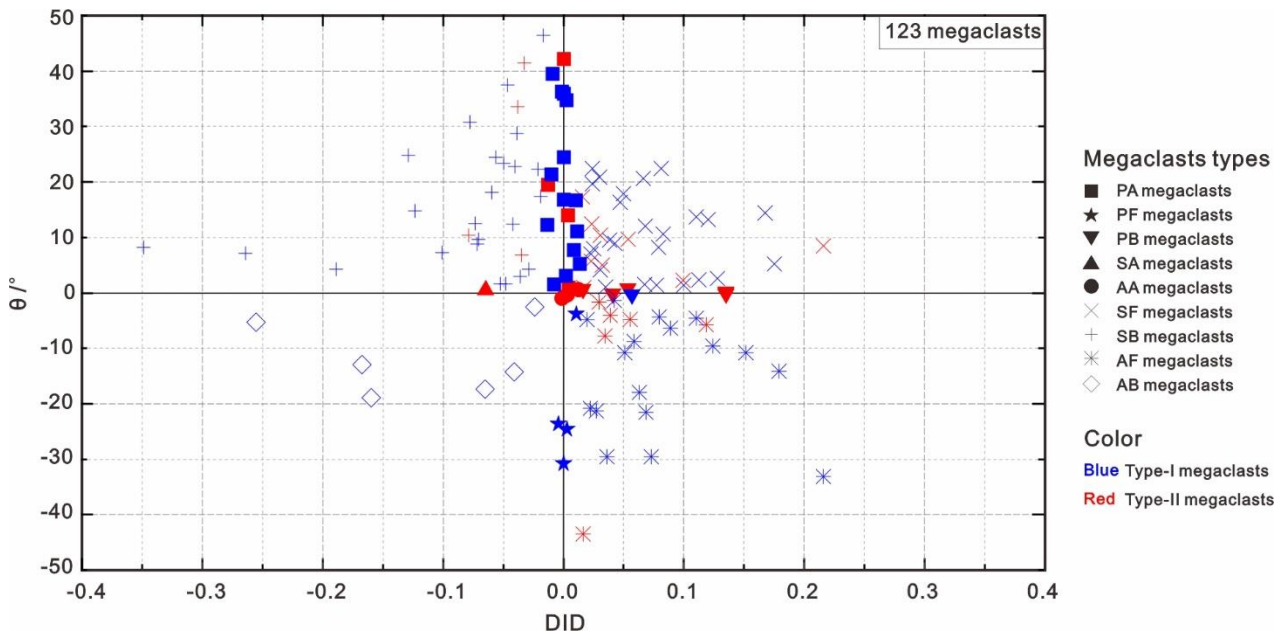


← Sliding direction

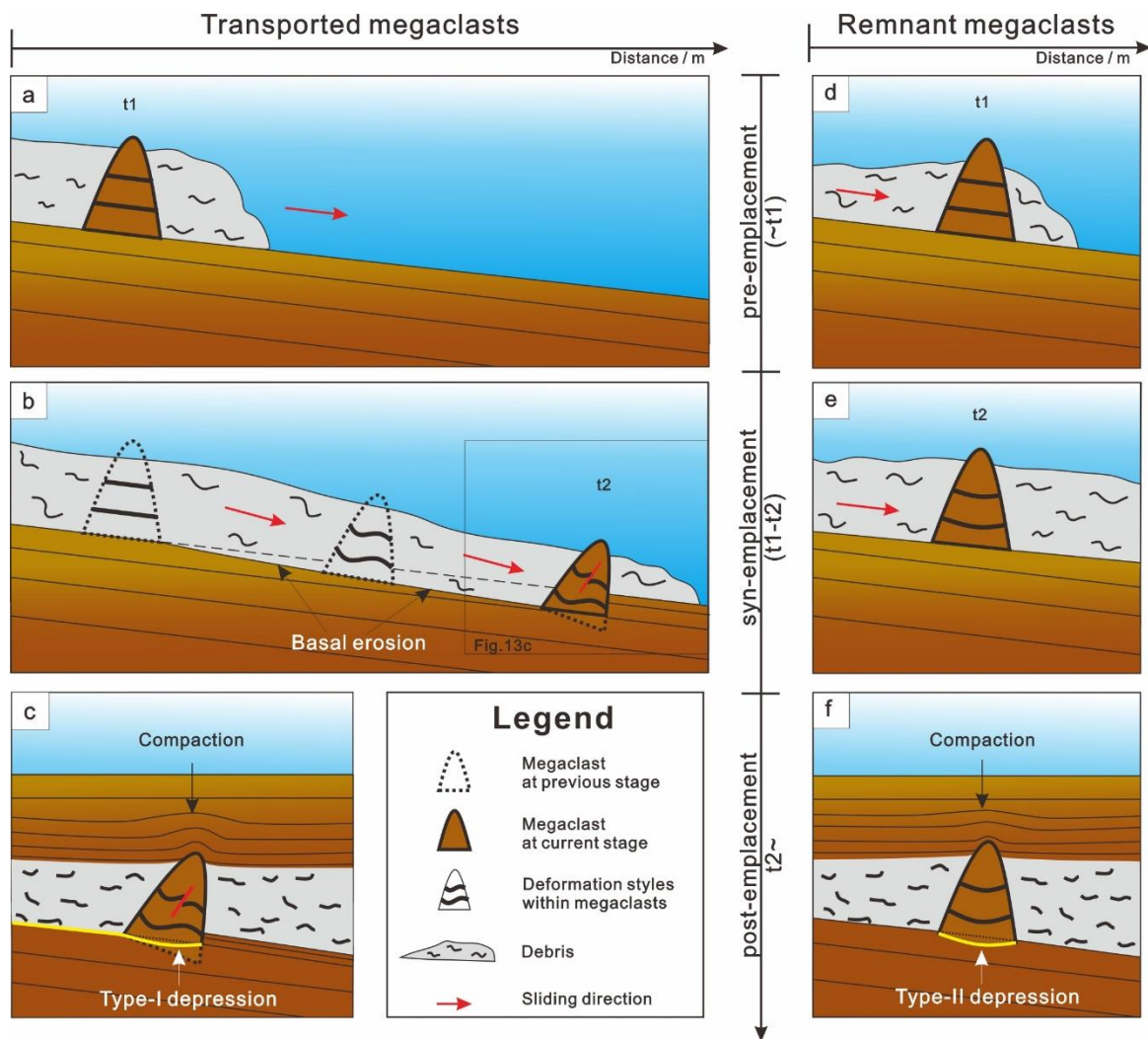
623

624 Fig. 11 New classification of megaclasts based on their angle of rotation (θ) and degree of
 625 deformation (DID) along the sliding direction. Note that the megaclasts can be quantitatively

626 classified into four main types: undeformed megaclasts, rotated megaclasts, deformed megaclasts and
627 highly deformed megaclasts.



628
629 Fig. 12 Quantitative analysis of the deformational styles of megaclasts showing the internal
630 deformation (DID) and rotation (θ) of 9 types of megaclasts with different symbols. Note that the
631 blue symbols indicate the transported megaclasts and the red symbols represent the remnant
632 megaclasts.



633

634 Fig. 13 Conceptual model shows the two different types of emplacement processes of megaclasts. (a)

635 to (c) The transported megaclasts have eroded the underlying strata and produced the Type I (U-

636 shaped) depressions during their emplacement. (d) to (f) Remnant megaclasts do not show obvious

637 erosion at their bases and only leave Type II (circular-, oval- or irregular-shaped) depressions on the

638 basal shear zone. Note that the emplacement processes of megaclasts can be divided into three stages

639 (pre-, syn- and post-emplacment). Pre-emplacment (~t1): the internal structures within megaclasts

640 are deformed (a) with the increasing sliding distance or (d) pushed by the surrounding mass-wasted

641 chaotic strata and/or transported megaclasts. Syn-emplacment (t1-t2): (b) the transported megaclasts

642 erode the basal shear zone and cease sliding; (e) the remnant megaclasts do not move or transport for

643 a quite limited distance. Post-emplacment (t2~): (c) and (f) Both types of the megaclasts are buried
644 after their emplacement and circular depressions are generated on the basal shear zone due to
645 compaction.