The formation and implications of giant blocks and fluid escape structures in submarine lateral spreads

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Abstract

Lateral spread (or 'spreading') and submarine creep are processes that occur near the headwalls of both terrestrial landslides and submarine mass-transport complexes (MTCs). Both submarine creep and spread deposits may contain giant (km-scale) coherent blocks, but their transport processes remain poorly constrained. Here we use 2D and 3D seismic reflection data to determine the geometry, scale, and origin of an ancient (Late Miocene) mass-transport complex (MTC) located in the Kangaroo Syncline, offshore NW Australia. We show that this large remobilised mass of carbonate ooze is c. 170-300 m thick and covers an area of at least c. 1050 km^2. The deposit is defined internally by two distinct seismic facies: (i) large, upward-tapering blocks (up to 210-300 m thick, 170-210 m wide, and 800-1200 m long) with negligible internal deformation, which decrease in height and spacing along the transport direction (identical, but *in situ*, seismic facies forms undeformed slope material immediately updip of the deposit headwall); and (ii) troughs (160-260 m thick, 190-230 m wide and 800-1200 m long) comprising moderately deformed strata, which contain 'v'-shaped, pipe-like structures that extend upwards from the inferred basal shear surface to the top surface of the MTC. The lack of deformation within the blocks, and their correlation to adjacent in-situ deposits, suggests they underwent very limited transport (c. 50 m-70 m). The relatively high degree of deformation within the intervening troughs is attributed to the vertical expulsion of fluids and sediment during hydraulic failure of the sediment mass. We present a hydraulic failure model that accounts for the styles and patterns of intra-MTC

30 deformation process. This model invokes evacuation of the lower slope by a pre-cursor MTC

31 that formed the space to trigger the lateral spread event. Our study provides new insights

32 into the genesis and rheology of subaqueous lateral spreads, enabling improved assessments

33 of the threats posed to critical seafloor infrastructure. The genetic links identified between

34 mass wasting and spatially-focused fluid flow indicate that, as well as disturbing the deep

35 seafloor, submarine landslides may also create important deep-sea biodiversity hotspots.

36 Keywords: spread, slope failure, geohazard, mass-transport complex (MTC), submarine
37 landslide, Exmouth Plateau, NW Shelf, Australia

Introduction

39 Mass-transport complex (MTC) is a broad term typically used to describe slope failure

40 deposits resulting from creep, spread, slide, slump, and debris flow processes (Figure 1;

41 Nemec, 1990; Varnes, 1978). MTCs are responsible for transporting large volumes of

42 sediments from basin margins to the adjacent basin floor, often during single catastrophic

43 events (e.g. Posamentier and Martinsen, 2011). Because of their size, the generation and

44 emplacement of MTCs play a key role in shaping and controlling the stratigraphic evolution

45 of continental margins around the world (Posamentier and Martinsen, 2011). MTCs can

46 initiate and translate over very low-angle seafloors by hydroplaning, with sediments in the

47 overlying failure mass partly or fully disaggregated to form a genetically related debris flow

48 (De Blasio and Elverhoi, 2011). Partial disaggregation can result in the formation and

49 emplacement of relatively coherent, largely undeformed blocks (Alves, 2015; Jackson, 2011;

50 Li et al., 2016; Micallef et al., 2007) that may trigger tsunamis (Tappin, 2010), could damage

51 or destroy seabed infrastructure (Masson et al., 2006; Urlaub et al., 2013), be a pre-cursor for

52 subsequent slope failure events (i.e. Lee and Chough, 2001; Li et al., 2016), or increase the

53 slope stability by reducing gravitational potential (Shillington et al., 2012). The nature of any

54 impacts to seafloor structures, and also the potential for tsunamigenesis, strongly depend on

55 the degree of landslide disaggregation, the volume and strength of the failed mass, its

56 mobility, speed and direction of movement (e.g. Dutta and Hawlader, 2019; Randolph and

57 White, 2012; Watts et al., 2005; Zakeri, 2009; Zhu and Randolph, 2010). For instance, highly

58 mobile, yet relatively thin debris flows have toppled oil and gas platforms, and ruptured

59 pipelines in the Gulf of Mexico (e.g. Chaytor et al., 2020). Conversely, much larger, deep-

60 seated (i.e. relatively thick), and yet limited run-out MTCs triggered by the 2011 Tōhoku-Oki

61 earthquake (M_w 9.1) caused no discernable damage to seafloor telecommunication cables

62 (e.g. Pope et al., 2017; Strasser et al., 2013). Therefore, differentiating the nature of slope

63 failure processes is a key element in assessing their risk to coastal communities and critical

64 seafloor infrastructure.

65 Submarine creep (or 'spreading') and lateral spreading are gravity-driven processes that occur

66 near the headwall area of sediment failure in marine (syn.: 'submarine spread') and terrestrial

67 (landslides) settings, respectively (Figure 1). Submarine creep is defined as a slow, gravity-

68 driven, downslope motion or post- or syn-depositional deformation of a sediment mass

69 (Nemec, 1990; Silva and Booth, 1984). The deposits of submarine creep may contain giant

70 coherent blocks that are up to c. 300 m high and c. 4 km wide (e.g. Li et al., 2016).

71 Subaqueous spread (also known as gravitational spreading and lateral spreading; Savage and

72 Varnes, 1987; Varnes, 1978) is another type of gravity-induced failure. First defined in

73 terrestrial settings as 'lateral spreading', this type of failure is triggered by subsurface

74 liquefaction and the formation of an intra-stratal weak zone, above which the failed mass

75 translates (Varnes, 1978). Commonly, these masses are stretched and broken up into

76 internally coherent blocks (Figure 1). A key characteristics of spreads is that they can occur

77 above a very gently-dipping (*ca.* < 1°) failure surface (Cruden and Varnes, 1996; Micallef et al.,

78 2007). A subaqueous spread can have a lateral displacement of only a few tens of metres

79 (Micallef et al., 2007). Despite this, onshore analogues indicate that the emplacement of

80 spread-related blocks could be extremely hazardous. For example, a spread and its associated

81 debris occurred in Palu, Indonesia, following an earthquake in September 2018, leaving >2000

82 people dead and c. 1300 people missing (Bradley et al., 2019; Watkinson and Hall, 2019).

83 Subaqueous spread-related deposits have received less attention than their terrestrial

84 counterparts, despite 3D seismic reflection data being an excellent tool to resolve the external

85 and internal geometry, and origin of this particular type of submarine landslide (Micallef et

86 al., 2007). Although the deposits of submarine creep and spread have similar external

87 geometries and internal seismic facies, they are different failure process and are typically not

88 considered part of a continuum; i.e. creep would not transform into spread, or vice versa.

89 Many landslide hazard assessments are based solely on plan-view imaging using multibeam

90 bathymetric surveys (e.g. Geertsema et al., 2018). While incredibly valuable, such surveys the

91 lack subsurface information required to identify and diagnose the style and depth of landslide

92 failure, and the nature of internal deformation. Here we demonstrate the value of high
93 resolution 2D and 3D seismic reflection data to complement and advance modern seafloor
94 studies of MTCs. Our aim is to evaluate the morphology, internal structure, kinematics, origin
95 and geohazard risk of a large submarine MTC using a high-quality, 3D and 2D seismic
96 reflection dataset from the NW Shelf, offshore Australia. Using these data, we can quantify
97 the height and spacing of the contained blocks, whereas a detailed kinematic analysis of intra-
98 MTC structures allows the transport direction to be determined. The study also aims to offer
99 a better understanding of spread initiation, translation, and deposition, which will help to
100 build a more comprehensive model for submarine mass failures and to help understand, and
101 hence inform mitigation of the associated geohazard risk.

Geological setting

103 The Exmouth Plateau is located offshore NW Australia, c. 900 km south of the tectonically-
104 active boundary between the Australian and Eurasian tectonic plates (Fig. 2a, 2b) (Hengesh
105 et al., 2013; Hengesh et al., 2012). The Exmouth Plateau is c. 600 km long and c. 350 km wide,
106 and is presently located in water depths of 1100-5000 m (Exon et al., 1992; Falvey and Veevers,
107 1974; Hengesh et al., 2013) (Figure 2a). This study focuses on the Upper Miocene to Holocene
108 passive margin mega-sequence (Figure 2c). This interval records the relatively slow deposition
109 (c. 0.02 mm/yr) of very fine-grained carbonate in bathyal (200-2000 m) water depths (Exon
110 et al., 1992; Haq et al., 1992; Maher and Thompson, 1999). Cores from Ocean Drilling Program
111 (ODP) wells 762 and 763 have established that the dominant lithology in this interval is
112 nannofossil-rich carbonate ooze (Boyd et al., 1993; Exon et al., 1992; Haq et al., 1992). These
113 deposits are characterised by high porosities (c. 70%) and high water saturations (c. 40%), and
114 by an overall low strength profile (<20kPa) (see Figure 5 from Hengesh et al., 2012; von Rad,
115 1992). These physical properties increase the slope instability and related geohazard risk of
116 the Exmouth Plateau area. Prolonged slope instability is recorded in the presence of large
117 (e.g. c. 500km3 gorgon slide; Hengesh et al., 2012), stacked, slope-to-basin floor MTCs in the
118 upper part (i.e. post-Oligocene) of the passive margin mega-sequence (Hengesh et al., 2012;
119 Nugraha et al., 2019; Nugraha et al., 2018; Scarselli et al., 2013). The study area is located in
120 the axis of the Kangaroo Syncline, between the Exmouth Plateau to the west and the NW
121 Shelf to the east (Figure 2a, 2d). The stratigraphic interval under investigation extends
122 upwards from Horizon H1 (base) to the seabed (top) (Figure 2c, 3a-c). Horizon H1 (Figure 3b)

123 is a regionally mappable unconformity that defines the base of the Late Miocene, and which

124 records collision of the Australian and Eurasian plates (Boyd et al., 1993; Hull and Griffiths,

125 2002). The Late Miocene to Holocene succession thickens basinwards into the axis of the

126 Kangaroo Syncline, and thins to the east and west, towards the NW Shelf and the crest of

127 Exmouth Plateau, respectively (Nugraha et al., 2018).

Dataset and Methodology

129 In this study we use two types of seismic reflection data provided by Geoscience Australia

130 (http://www.ga.gov.au/nopims): (i) up to c. 500 km long, 2D seismic reflection surveys, which

131 were collected between 1993 and 2005; and (ii) a 3D seismic reflection survey (Willem 3D

132 seismic survey), which was acquired by Veritas DGC Australia in 2006. The Willem 3D seismic

133 survey covers a total area of c. 2628 km^2, extending along the Exmouth continental slope and

134 across the lower slope into the Kangaroo Syncline (Figure 2a-b). A downward decrease and

135 increase in acoustic impedance are expressed as blue (negative) and red (positive) reflection

136 events, respectively (Figure 3a). We estimate the spatial resolution of the Willem seismic

137 survey using the frequency content (c. 60 Hz decreasing to c. 40 Hz) and average seismic

138 velocity (1500 m/s decreasing to 2000 m/s) between the seabed and H1. Based on these data,

139 we calculate an approximate spatial resolution of 6.25 m at the seabed, decreasing to 11 m

140 near the base of the studied interval. This imaging quality is sufficient to map, at relatively

141 high-resolution, the geometry of structural features (e.g. scours, faults, etc) immediately

142 below and within the studied MTC.

143 We adopt the seismic-stratigraphic framework of Nugraha et al. (2018), which is based on

144 their analysis of the Exmouth Plateau, c. 50 km SW of the study area (Figure 2a). Our study

145 interval falls within SU3 of Nugraha et al. (2018), within which we map four horizons based

146 on the seismic continuity, amplitude, and frequency/spacing, as well as the seismic facies

147 characteristics of the packages they bound. The lithology and geotechnical properties (i.e.

148 water content, porosity, shear strength, etc.) of the studied stratigraphic interval are inferred

149 from ODP Wells 762 and 763, which are located c. 300 km SW of the study area where they

150 penetrate a similar seismic-stratigraphic succession. We extracted seismic attributes, such as

151 variance and amplitude contrast (see Supporting Information Appendix 1 for explanation),

152 from the 3D seismic reflection dataset to determine the external geometries and

153 geomorphology of the imaged deep-marine deposits (Brown, 2011; Chopra and Marfurt,

154 2007). The dimensions of the MTC-hosted blocks have been quantitatively analysed based on
155 their morphological characteristics: (i) *block height*, which is the height between the crest and
156 base of the blocks (i.e. the MTC basal shear surface); (ii) *block spacing*, which is the spacing
157 between the middle of the crests of two adjacent blocks; (iii) *block tip angle*, which is the
158 angle between the block tip and vertical; and (iv) *block friction angle*, which is the angle
159 between the side of the blocks relative to their base surface (see Figure 6b).

Seismic-stratigraphic analysis

161 We identified and mapped four key horizons (H1-H4) in this study based on their strong
162 amplitude, continuity (i.e. they are regionally mappable and extend across the study area),
163 and stratigraphic distribution (i.e. they are relatively evenly distributed throughout the
164 stratigraphic succession of interest). Horizon H1 (Figure 2b) is a regionally mappable
165 unconformity that defines the base of the Late Miocene, and which formed as the result of
166 the collision of the Australian and Eurasian plates (Boyd et al., 1993; Hull and Griffiths, 2002).

SU-1 and SU-2

168 We divide the studied stratigraphic interval into three seismic units (SU-1-3). SU-1 is c. 500 m
169 thick near the axis of the Kangaroo syncline, thinning westward and eastward to c. 200 m. SU-
170 1 contains packages of chaotic, medium- to high-amplitude seismic reflections interpreted as
171 stacked MTCs (Figure 3b-c) (Hengesh et al., 2012; Nugraha et al., 2018). SU-2 is thinner than
172 SU-1, but also varies in thickness, being slightly thicker near the centre of the Kangaroo
173 Syncline (c. 60 m) and thinning gradually westward and eastward to c. 30 m (Figure 3b). SU-2
174 contains two distinct seismic facies: (i) continuous, low- to medium-amplitude, sub-parallel
175 seismic reflections in the east; and (ii) discontinuous to chaotic seismic facies in the centre
176 and west (Figure 3b-c). The continuous seismic facies is interpreted as slope-to-basinfloor,
177 carbonate ooze deposits, whereas the more discontinuous seismic facies is interpreted as
178 deformed carbonate ooze drape deposits (Nugraha et al., 2018). Variance attribute-based
179 analysis of the base of SU-2 (Horizon H2) in the central part of the study area reveals a
180 concentrated high variance response with circular shape in an NW-SE linear trend (Figure 5a).
181 These high variance circles form bulges in seismic section that are c. 30-70 m in diameter,
182 disaggregating the overlying strata (see the seismic section in Figure 5a). Based on their size,
183 geometry, and distribution, these circular bulges are interpreted as fluid expulsion-related

184   pockmarks (e.g. Plaza-Faverola et al., 2011). Fluid escape features such as these are common

185   on the Exmouth Plateau (i.e. Velayatham et al., 2019; Velayatham et al., 2018).

SU-3

187   SU-3 is c. 500 m thick in the axis of the Kangaroo Syncline, gradually thinning westward due

188   to truncation below MTC 3 (Figure 4a, 4b). We identify three distinct seismic facies in SU-3,

189   which we describe below (pre-MTC 3, MTC 3, and MTC 2; Figure 3b).

Pre-MTC 3

191   The pre-existing interval defines the eastern part of SU-3 and is characterised by a thin (70 ms

192   TWT; 25% of the total thickness of SU-3) package of chaotic to discontinuous, low- to medium-

193   amplitude seismic reflections at its base, which is overlain by a thick (170 ms TWT; 75% of the

194   total thickness of SU-3) package of continuous-to-locally slightly wavy, low- to medium-

195   amplitude seismic reflections (Figure 3c). The chaotic seismic facies is interpreted as an MTC

196   (MTC 1), whereas the continuous seismic facies likely represents carbonate ooze (Figure 3b,

197   3c) (Nugraha et al., 2018).

MTC 3

Description

200   MTC 3 defines the central part of SU-3, near the axis of the Kangaroo Syncline, where the

201   seafloor presently dips very gently (c. 0.4°) (Figure 4b). Approximately 1050 km^2 of MTC 3 is

202   imaged in the 3D seismic data, although 2D seismic data show the deposit covers c. 3600 km^2

203   (Figure 4a, 4b; Figure 5b, 5c, 5d). We describe MTC 3 with respect to the following features:

204   (i) the geometry of its basal shear surface and seismic facies of its substrate, (ii) the seismic

205   facies and geometrical characteristics of its contained blocks and troughs, and (iii) its overall

206   geometry and the geometry of its top surface.

(i) The basal shear surface and substrate

208   The basal surface of MTC 3 is characterised by a continuous, high-amplitude, positive seismic

209   reflection (Figure 6a). In the east, this surface merges with the basal shear surface of MTC 1

210   (Figure 6a). The basal surface of MTC 3 does not contain any seismic-scale erosional features

211   such as scours, striations, or grooves (Figure 5c, 5d) (e.g. Bull et al., 2009a; Sobiesiak et al.,

212   2018). As such, it is not easy to determine the MTC transport direction. However, the surface

213   defines a sharp boundary between different facies (i.e. weakly deformed below and very

214   chaotic above), and the high-amplitude character supports an interpretation of a basal shear

215   surface (e.g. Wu et al., 2019). The 60 ms TWT thick (c. 60 m) unit immediately underlying and

216   representing the substrate of MTC 3 ranges from discontinuous and moderately deformed

217   near the eastern-margin of MTC 3, to chaotic and highly deformed near the proximal part of

218   the deposit (Figure 6a, 6b).

219   (ii) Blocks and troughs

220   Map-view images show that MTC 3 contains parallel to sub-parallel, block-shaped packages

221   (Figure 5c, 5d). In seismic cross sections, these form ridge-shaped blocks flanked by troughs

222   (Figure 6b). The blocks are 210-300 m high, 170-210 m wide, and 800-1200 m long are

223   relatively undeformed (Figure 6b). The intervening troughs are 160-260 m high, 190-230 m

224   wide, 800-1200 m long, and are defined by a very chaotic, variable-amplitude seismic facies.

225   All the blocks contain two distinct seismic facies that are similar to those defining undeformed

226   slope strata outside of the MTC (Figure 6a, 6b). Seismic reflection within the blocks are sub-

227   horizontal and are approximately parallel to the basal shear surface and underlying substrate

228   strata. Three seismic reflections, intra-block reflections a-c, are identified within the blocks,

229   which can be correlated with confidence from block-to-block over a large area (seismic

230   reflection a-c; Figure 6b). However, the blocks become more disaggregated, and their external

231   form become less pronounced, adjacent to the headwall in the E and adjacent to its toe in the

232   SW. Downslope, intra-block reflections a-c become harder to identify and trace (Figure 6c).

233   The blocks ultimately become extremely chaotic in the distal part of MTC 3, showing similar

234   facies to MTC 1 (Figure 6c). Upslope, the relationship between the blocks and the undeformed

235   strata show a clear increasing deformation systematically eastward (Figure 6a).

236   The average tip angle of the blocks is c. 38°, with little variability about this value (Figure 6d).

237   The angle of the tip to the basal shear surface ranges from 55-80° (average 71°) (Figure 6d).

238   The height of the blocks gradually decreases downslope to the SW towards the distal end of

239   MTC 3, from c. 290 m to c. 190 m (Figure 6e). Block spacing increases towards the SW, from

240   c. 610 m near the centre to c. 760 m near the distal region of MTC 3 (Figure 6e).

241   The intra-block troughs are characterised by moderately discontinuous to chaotic seismic

242   facies (Figure 6b). By blending variance and amplitude data we see that the troughs contain

243   numerous 'v'-shaped, vertical to sub-vertical, pipe-liked structures that extend from the basal

244   shear surface of MTC 3 to its top. We refer to these c. 280 m tall, up to 100 m diameter

245   features as 'subvertical deformation zones' (SDZs) (Figure 7a). Within troughs, seismic

246   reflections are mostly sub-horizontal and discontinuous, the edge of the reflections can be as

247   steep as 50° near the trough margin (Figure 7a). Locally, where the magnitude of intra-trough

248   deformation is low, we can trace seismic reflections from within the troughs into adjacent

249   blocks (see the coloured dots in Figure 7a). The width of the VDZs increase upward, from c.

250   40 m at their narrowest basal point to up a few hundreds of metres at their tops (Figure 7b

251   and c).

252   (iii) Top surface

253   The top of MTC 3 is characterised as a rugose low-amplitude, positive seismic reflection. The

254   crests of intra-MTC blocks define locally positive relief that are onlapped by overlying

255   reflections, whereas intervening troughs define concave-up structural lows (Figure 6a, 6b).

256   The VDZs extends throughout the vertical extent of the trough, and reflections onlap the

257   blocks (Figure 7a).

258   Interpretation

259   The similarity in the seismic facies succession characterising the intra-MTC blocks and the

260   undeformed strata (i.e. a thin MTC overlain by largely undeformed, slope-to-basinfloor strata)

261   suggest the former are derived from the latter. This is supported by the blocks in the eastern

262   part of MTC 3 being the same thickness as the laterally adjacent, largely undeformed interval.

263   We therefore interpret the boundary between MTC 3 and the undeformed strata is the MTC

264   headwall. The fact we can correlate the intra-MTC seismic horizons (reflection a-c; Figure 6a,

265   b) within the blocks and flanking, more highly deformed troughs, suggest that the blocks were

266   initially transported as a coherent mass. The continuity of the intra-block reflections also

267   indicate that the blocks were only weakly deformed during the transport.

268   We interpret that the westward decrease in block height and spacing, normal to the broadly

269   NE-trending headwall, suggest MTC 3 was translated westwards, approximately

270   perpendicular to the depth contour of the interpreted base of the MTC 3 (Figure 5b, 5d). We

271   also note that the amount of deformation below MTC 3, inferred from the thickness of the

272   highly deformed package, increases westwards at the transition from beneath the relatively

273   thin MTC 1, which forms part of the pre-existing, broadly undeformed slope strata, to below

274 the relatively thick MTC 3. The low degree of internal deformation, limited distance from the

275 headwall, and lack of kinematic indicators, supports an interpretation that the blocks moved

276 a limited horizontal distance. Therefore, we suspect that the relatively highly deformed

277 nature of the substrate near the proximal part of MTC 3 may not have been directly caused

278 by shearing of the substrate by the overlying mass. We instead interpret that this deformation

279 occurred due to the presence and catastrophic failure of an overpressured substrate by

280 liquefaction or strain softening, which both would have caused intense stratal disruption.

281 Similar liquefaction-driven seismic facies (i.e. medium- to high-amplitude, chaotic seismic

282 reflections) are described in the literature (e.g. Ogata et al., 2014).

283 The moderately-deformed reflections defining the VDZs indicate modest internal

284 deformation within these areas. We infer that the VDZs represent vertical fluid migration

285 conduits, which drove fluid expulsion from the underlying, over-pressured substrate (e.g.

286 Cartwright and Santamarina, 2015; Løseth et al., 2011; Moss and Cartwright, 2010). The

287 overlying elliptical depressions, which define structural lows along the top of MTC 3, reflect

288 overburden collapse due to the expulsion, upward migration, and expulsion of deeper

289 material. Seismic reflections onlapping blocks protruding from the top surface of MTC 3 may

290 represent the extruded sediments or subsequently deposited deep-water sediment (e.g. Clari

291 et al., 2004; Roberts et al., 2010; Watkinson and Hall, 2019).

292 MTC 2

293 MTC 2 occurs in the western part of SU-3 (Figure 4b, 5c-d). This deposit is deeply eroded on

294 its NW margin by a subsequent mass failure event (MTC 4), and is hard to differentiate from

295 MTC 3 in the NE (Figure 4b, 5d). However, the boundary between MTC 2 and 3 can be inferred

296 from their slightly differing seismic facies; MTC 3 is defined by an overally higher-amplitude,

297 blockier seismic facies, whereas MTC 2 is defined by overall lower-amplitude, chaotic seismic

298 facies (Figure 3a-c). MTC 2 has an NW-trending headwall (Figure 8a) and NE-SW trending

299 lateral margins (Figure 8b), and comprises low- to very low-amplitude, chaotic reflections. In

300 the northern part of the Kangaroo syncline, MTC 2 increases in thickness away from its

301 headwall, from c. 70 ms near its headwall (Figure 8a) to c. 200 ms further NE (Figure 8c). The

302 orientation of the headwall scarp and lateral margins suggest that MTC 3 was transported

303 towards the NNE, following the overall dip of the Kangaroo Syncline (Figure 4b).

304 Stratigraphic evolution

305 Based on the observations made above, we propose that the study area has experienced
306 several episodes of slope failure-driven erosion and deposition (Figure 9). First, multiple,
307 stacked MTCs were deposited (SU1; Figure 9a) that were subsequently draped by carbonate
308 ooze (SU-2; Fig. 9b). Gas or fluids, sourced from deeper stratigraphic levels, migrated upward
309 into SU-2 (Figure 9b). During the initial stage of SU-3 deposition, an MTC was emplaced (MTC
310 1), which was overlain by a thick, carbonate ooze-bearing sequence (Figure 9c). MTC 2 was
311 subsequently emplaced in the west of the study area (Figure 9d). The removal of sediment
312 during the evacuation of MTC 2 likely had a debuttressing effect, promoting subsequent slope
313 failure and the triggering of MTC 3 through removal of lateral and down-slope confining
314 support (Figure 9d). As a result of overpressure released by slope failure, sediments extruded
315 from below MTC 3 were transported upward through, and deposited on top of, the overlying
316 mass. MTC 4 was subsequently emplaced in the west of the study area on top of MTC 3,
317 followed by draping of the entire succession by carbonate ooze (Figure 9e).

318 ## Discussion

319 Was MTC 3 emplaced by a creep or spread?

320 Creep is a gravity-driven process, with the updip margins defined by retrogressively formed
321 faults and folds (Lee and Chough, 2001; Li et al., 2016). In contrast, spreading occurs above a
322 pre-cursor failure surface, with the failed mass translating laterally and being broken into
323 blocks and troughs that are bounded by internally generated faults (Micallef et al., 2007).
324 Subaqueous creep has been reported from relatively steep slopes (>3°) (i.e. Shillington et al.,
325 2012; Silva and Booth, 1984), whereas subaqueous spread is reported from gentler slopes
326 occur (<1°) (i.e. Micallef et al., 2007). Although we have not undertaken a balanced structural
327 restoration to investigate the slope dip at the time of MTC 3 emplacement, it is likely that,
328 given its current position beneath the present basin floor, some c. 300 km from the Late
329 Miocene shelf margin, it was deposited on a gently dipping slope (<1°). The coherent blocks
330 within MTC 3 occur above a low-angle failure surface, suggesting gravity played only a minor
331 role in their formation, as well as that of the MTC in which they are contained. The blocks are
332 also bound by numerous sub-parallel faults that are of very similar dip; such features are
333 strongly characteristic of the deposits of spreads, rather than creep (Micallef et al., 2007).

334   MTC 3 emplacement model

335   Stage 1: Priming

336   Before the emplacement of MTC 3, the basal shear surface of MTC 1 may have represented a

337   hydraulic boundary between the overlying c. 300 m thick sediment pile, and the underlying

338   substrate, defined by sharp decrease in permeability and density (i.e. Madhusudhan et al.,

339   2017; Wu et al., 2019) (Figure 10a, 10b). Excess pore pressure could have built up at this

340   boundary, driven by the ascent of fluids from the lower SU-2 and SU-1 (Figure 10a and b). The

341   properties of the biogenic carbonate ooze sediments (i.e. low permeability, high water

342   content, fine-grained) defining the substrate of the eventual spread may have a direct

343   contribution to the build-up of pore pressure (Bryn et al., 2005; Bull et al., 2009b; Kvalstad et

344   al., 2005; Urlaub et al., 2015). There is also ample evidence that during the early Miocene to

345   Pliocene, the Exmouth Platform was seismically active, with the Kangaroo Syncline

346   representing an inversion-related structure linked to the collision of the Indo-Australian and

347   Eurasian plates (Keep et al., 2007). Related seismicity may have reduced the shear strength

348   of sediments, and built up the pore fluid pressure within the substrate of MTC 3. The

349   increased pore pressure was transferred laterally westwards away from, and sealed by, the

350   overlying basal shear surface of MTC 1 (Figure 10a) (see also examples of pore pressure lateral

351   propagation from Aylsworth and Lawrence, 2003; Legget and LaSalle, 1978).

352   Stage 2: Distal evacuation

353   We suggest that MTC 3 was triggered due to the removal of material from its distal margin by

354   the emplacement of MTC 2. The absence of a buttress after northward transport would have

355   removed the lateral confining pressure within the western part of the pre-spread strata to

356   drive the spreading (Figure 10c). The sediments immediately around the debutressing

357   became a flow (i.e. slump), due to the biogenic structure of carbonate ooze that is rapidly

358   destroyed under loading, transitioning from a coherent to fully disaggregated chaotic mass in

359   a relatively short distance (i.e. 10-20 km; Principaud et al., 2015; Watson et al., 2019).

360   To the east, the sediment pile was primed to fail for the reasons outlined above (i.e. excess

361   pore pressure; Figure 10a). The low gradient (c. 0.4°) of the basal shear surface of MTC 3 likely

362   prevented the failure from accelerating and translating a great distance during emplacement.

363   As a result, the intra-spread blocks stayed relatively intact compared to failures occurring on

364 more steeply dipping slopes (i.e. Hengesh et al., 2013). Onshore and offshore data indicate

365 that even small amounts of unloading near the down-dip part of the slope can trigger the

366 formation of spreads (i.e. Broussard and Sarwar, 2013; Kvalstad et al., 2005; Locat et al., 2011;

367 Micallef et al., 2007).

368 Stage 3: MTC 3 initiation

369 The mass comprising MTC 3 started sliding westward into the new space created by the

370 movement northwards of MTC 2 (Figure 10c). Additional shearing and deformation below

371 MTC 3 ruptured the base-MTC 1 seal layer, promoting liquefaction of the substrate in over-

372 pressured zone, which drove the upward transport of fluids and the formation of large pipe-

373 like structures.

374 The tip angle (α) and the friction angle of the block (β) follow a relationship of $\beta \approx 90°-(\alpha/2)$,

375 which aligns with the failure surface angles observed from triaxial experimental tests on intact

376 natural clays (Locat et al., 2011; Locat et al., 2015). This relationship suggests that internal

377 shear fractures were generated during spreading. Two sets of hydraulic internal shear

378 fractures (primary/secondary internal shear fractures) formed and propagated upward due

379 to the high fluid over-pressure in the substrate (Figure 10c). The primary internal shear

380 fractures developed a 'V'-shaped geometry, consistent with the predictions of numerical

381 models of sediment failure (Andresen, 2001; Buss et al., 2019; Dey et al., 2016; Kvalstad et al.,

382 2005). In between the primary internal shear fractures, smaller secondary shear fractures

383 propagated upward from the basal shear surface of MTC 3 (e.g. see also the formation process

384 of the hydraulic fracturing related pipes from Cartwright and Santamarina, 2015; Løseth et al.,

385 2011). The lateral movement of the spread will increase the shear stress in the substrate of

386 MTC 3, driving growth of the primary and secondary fractures. Overlying material was

387 ultimately broken into fracture-bound blocks flanked by troughs.

388 Stage 4: Internal deformation and lateral spreading

389 Overpressured substrate fluid-sediment mixes flowed upward via the secondary internal

390 shear fractures within sub-circular fluid pipes (e.g. Cartwright and Santamarina, 2015). This

391 extruded material was deposited in depressions above the troughs on the top surface of MTC

392 3 (Figure 10d). Blocks near the distal end of MTC 3 underwent a greater lateral displacement

393 and deformation with increase release of the excess pore pressure from the base of the

394 spread compared to proximal areas that moved less far. Due to the release of overpressure,
395 the shear stress required to drive horizontal motion increased, which may ultimately stop
396 spreading. The spreading may also stop because the mass hit the far (eastern) of the existing
397 MTC 2 lateral margin (Figure 10d). There is an increasing deformation near the headwall of
398 the spread. This is due to the failed sediments of MTC 3 moved west first, this might have
399 ended up with a 'hole' in the east near the initial scarp. The initial scarp was later failed
400 retrogressively, leaving a step-like headwall scarp, and a mass of strongly deformed
401 sediments next to the headwall (Figure 10d).

402 Implications

403 *Preconditioning and triggering of spreads: Unloading and lubrication*

404 We have investigated the geometry and internal structure of an MTC, inferring it was related
405 to a submarine spread. Our study shows that, in these cases, spreading can occur even if the
406 slope gradient is presently low. We propose that the spread was *primed* by the presence of
407 an overpressured layer, which acts as a basal shear surface and promotes sliding on a very
408 low-angle slope. Slope failure was ultimately *triggered* by debuttressing of the slope mass by
409 an earlier slide, which removed downslope and/or lateral confinement. Together these
410 processes resulted in a short run-out but highly deformed slide mass. While the spread shows
411 abundant evidence for intense internal deformation, we relate this deformation to fluid
412 escape from subsurface overpressured strata beneath the failing mass, rather than to
413 landslide disaggregation under rapid, long-distance transport. We suggest that the slide mass
414 may have only moved a relatively short distance (i.e. only a few hundred metres) and that the
415 amount of strain observed in landslides is therefore not necessarily a direct indication of
416 transport distance.

417 *The importance of rheology and mobility for geohazard assessments*

418 For offshore geohazard assessments it is important to understand the mobility and rheology
419 of an MTC (Thomas et al., 2010). If the landslide mass of MTC 3 moved only a short distance
420 and at relatively low speed, then the potential for tsunamigenesis will be low, despite the
421 relatively large volume (c. 360 km^3) of the mass. Numerical modelling has shown that very
422 large landslides (volumes of up to 1000 km^3) may not trigger a tsunami if they commence as
423 relatively slow, retrogressive failures (Løvholt et al., 2017).

424 The nature of seafloor and subsurface deformation associated with submarine landsliding

425 control the impact this processes has on different offshore structures. For instance, a seabed-

426 laid pipeline or cable may be able to withstand slow-moving seafloor displacement during a

427 spread, instead being much more vulnerable to the impact of faster-moving slides that

428 become frontally emergent and disaggregate to form more mobile debris flows (Lacroix et al.,

429 2020; Thomas et al., 2010; Zakeri, 2009). Piles or top-hole conductors that support platforms

430 or deep-sea field developments may penetrate tens or hundreds of metres below the seafloor.

431 These deeper foundations are susceptible to i) lateral and vertical movements, which may be

432 relatively limited within intact blocks due to the limited transport distance of the MTC; and ii)

433 changes in subsurface pore pressure and the remoulding of sediments, which together may

434 reduce their lateral capacity (i.e. weakening their support); this particularly property may be

435 prognosed by when an intra-block, fluid vertical fluid venting system is identified

436 (Amaratunga and Grozic, 2009; Hong et al., 2017).

437 *Submarine spreads: Underappreciated agents for seafloor fluid flow*

438 Many studies propose fluid migration at depth as a potential preconditioning or triggering

439 factor for MTCs (e.g. Bünz et al., 2005; Deville et al., 2020; Elger et al., 2018); however, few

440 studies link MTCs to syn- or post-emplacement release of fluids (e.g. Bøe et al., 2012; Browne

441 et al., 2020). It is suggested that significant volumes of methane (an important greenhouse

442 gas) may have been emitted during the disaggregation of the 3000 km^3 Storegga Slide (Paull

443 et al., 2007), and that methane release by widespread submarine landslide activity may have

444 been a contributory mechanism for elevated methane emissions that catalysed the

445 Palaeocene-Eocene Thermal maximum (Higgins and Schrag, 2006). The role of submarine

446 landslides in the release of previously sequestered fluids such as methane remains poorly

447 constrained, and is thus omitted from existing global budgets. Our study shows that fluid

448 escape can play an important role during MTC emplacement, as vertical escape structures act

449 as efficient conduits for fluids and sediments from depth to the seafloor. Similar seafloor fluid

450 expulsions, including that linked to post–MTC emplacement, create cold seeps that support

451 high biomass communities of microbes and chemosynthetic fauna, as the focused fluid flow

452 creates cold seeps (e.g. Deville et al., 2020). Therefore, as well as disturbing the seafloor,

453 MTCs may also provide important hotspots for deep-sea biodiversity, particularly where they

454 create focused zones of fluid flow.

Conclusion

We use 2D and 3D seismic reflection data to investigate processes of submarine spreading, on the Exmouth Plateau, offshore NW Australia. The spread comprises: (i) giant, upward-tapering blocks (c. 300 m-high, c. 1200 m-long, and c. 210 m-wide) which are undeformed, and (ii) intervening troughs (c. 260 m depressions separating the blocks), which are moderately deformed. We interpret that the blocks were only transported minimal lateral distance, and the relatively deformed troughs are formed by the expulsion of fluid and sediment during hydraulic failure of the sediment mass. We then developed a new internal hydraulic fracturing model that accounts for the styles and patterns of blocks and the intervening troughs. The new model requires a low gradient prerequisite over-pressured failure surface/zone, the low gradient of the basal shear surface likely prevented the block from accelerating and translating a great distance during emplacement. The new model suggests that the spread is initiated by the removal of materials in the toe of the otherwise stable strata (i.e. debuttressing). The debuttressing of the adjacent strata results in the decrease of the lateral confining pressure within the pre-spread strata, and subsequently, triggers the spreading process. The underlying overpressured layer is important to prime the spreading and explain the scale and style of fluid escape. An improved understanding of the initiation, emplacement and deposition of submarine spreading failures adds to our broader understanding of deep-water mass failure processes, the risks posed to seafloor infrastructure, and the often-complex interactions with local benthic ecology.

Acknowledgements

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688   Figure caption

689 Figure 1 Schematic diagram showing the classification of mass-transport complexes adopted

690 in this study (modified from Nemec, 1990; Posamentier and Martinsen, 2011; Scarselli et al.,

691 2013).

692 Figure 2 a) Regional map of the study area showing the location of the Exmouth Plateau Arch,

693 Kangaroo Syncline. The white and grey lines represent 2D seismic reflection data, and the red

694 polygon represents the location of 3D seismic reflection dataset. Shaded relief GEBCO_2014

695 bathymetry map downloaded from https://www.ngdc.noaa.gov/maps/autogrid/; b) location

696 map of the figures demonstrated in this study; c) Stratigraphy column and the major tectonic

697 event of the study interval; d) Sketch map of the regional structures crossing the study area,

698 showing the modern depositional systems, adapted from Nugraha et al. (2018).

699 Figure 3 a) Un-interpreted regional seismic section; b) Interpreted regional seismic section

700 highlighting the key horizons and the seismic units the study area, note that the horizon H1 is

701 the same horizon of Horizon C (see detail from Nugraha et al., 2018) which defines an

702 unconformity of late Miocene (~9 Ma); c) Interpretation sketch of the regional seismic section.

703 See Figure 2b for location.

704 Figure 4 a) Regional structure map interpreted based on the 2D and 3D seismic reflection data,

705 showing the depth structure calculated on horizon H3; b) sketch of the regional structure map

706 showing the distribution of the key intervals in SU-3 (undeformed strata, MTC 3, and MTC 2).

707 Figure 5 a) Variance attribute calculated on Horizon H2 within the 3D seismic reflection data

708 area, revealing pipe-like structures. The dashed line indicates the same boundary in Figure 5d

709 between the undeformed and deformed strata. The upper left map shows the zoom-in view

710 of pipe-like structures, and the upper right seismic section shows the seismic cross-section of

711 the fluid pipe; b) depth structure map calculated on basal shear surface of the MTC 3 within

712 the 3D seismic area; c) variance attribute calculated on Horizon H3 within 3D seismic area; d)

713 sketch of the MTC 3 deposit, revealing the key intervals in SU-3 (undeformed strata, spread,

714 and MTCs).

715   Figure 6 a) Seismic section showing the eastern boundary of the MTC 3 and the undeformed

716   strata; b) seismic section showing the proximal section of the MTC 3; c) seismic section

717   showing the distal section of the MTC 3. See the location from Figure 5d; d) the calculation of

718   the tip angle (α) of the blocks, and the friction angle of the blocks to the failure surface (β); e)

719   the calculation of height and the spacing of the blocks. See block number from Figure 6b and

720   6c, and the blocks number refers to the order in which the blocks are away from the

721   undeformed strata.

722   Figure 7 a) Seismic characteristics of pipe structures in the seismic section with an overlay of

723   the variance attribute, and a zoomed-in view of the VDZs, showing the details of the pipe like

724   fluid escape structures, see the location in Figure 6b; b) variance time slice through the

725   troughs, showing the crater shaped pipes; c) structure map of the horizon H3, showing the

726   top structure of the MTC 3, see the location in Figure 7a. The diameters of the crater-shaped

727   depressions increase upward, from c. 80 m in the variance time slice to hundreds of metres

728   in the structure map.

729   Figure 8 a) Seismic cross-section through the headwall scarp area of MTC 2; b) seismic cross-

730   section through the lateral margins of MTC 2; c) seismic cross-section through the body of

731   MTC 2.

732   Figure 9 Stratigraphic evolution of the study area. a) Seismic unit 1 (SU-1), mainly comprises

733   chaotic seismic reflections and deposited as MTCs; b) seismic unit 2 (SU-2), mainly consist of

734   well-layered seismic section and deposited as carbonate drapes; c) the initial stage of seismic

735   unit 3 (SU-3), consist MTC 1 and carbonate drapes; d) the following stage of SU-3, consisting

736   coherent blocks and chaotic intervening troughs; e) the final stage of SU-3, mainly consist

737   erupted sediments which followed by carbonate drapes.

738   Figure 10 Schematic diagram showing the development of the spread: a) Deposition of the

739   undeformed sediments, MTC 1 and down dip evacuation of the MTC 3; b) inferred

740   permeability and shear strength curve through undeformed strata; c) overpressure induced

741   primary and secondary internal fractures propagation stage; d) sediments dislocated into

742   blocks and troughs with extruded sediments deposition stage.
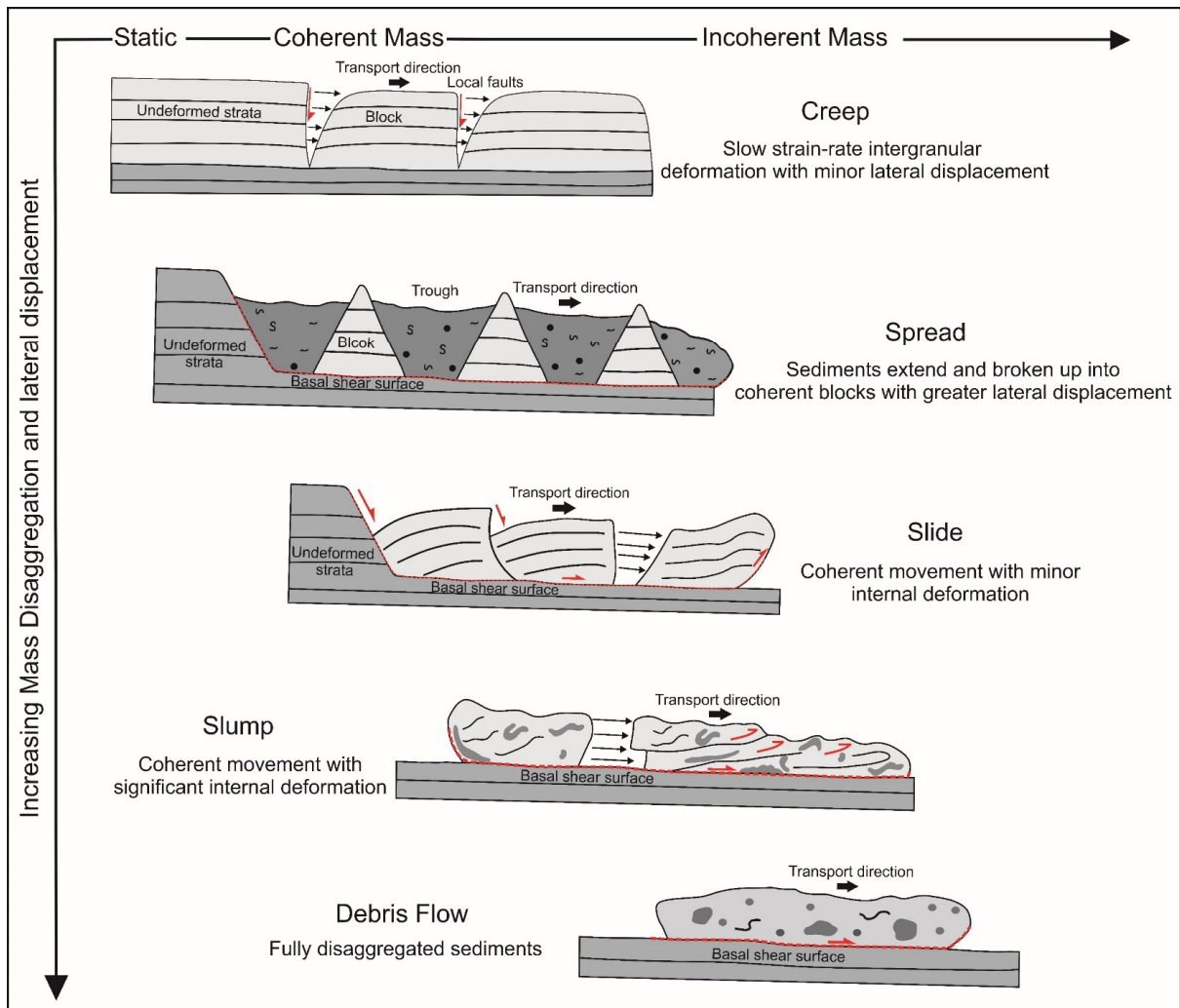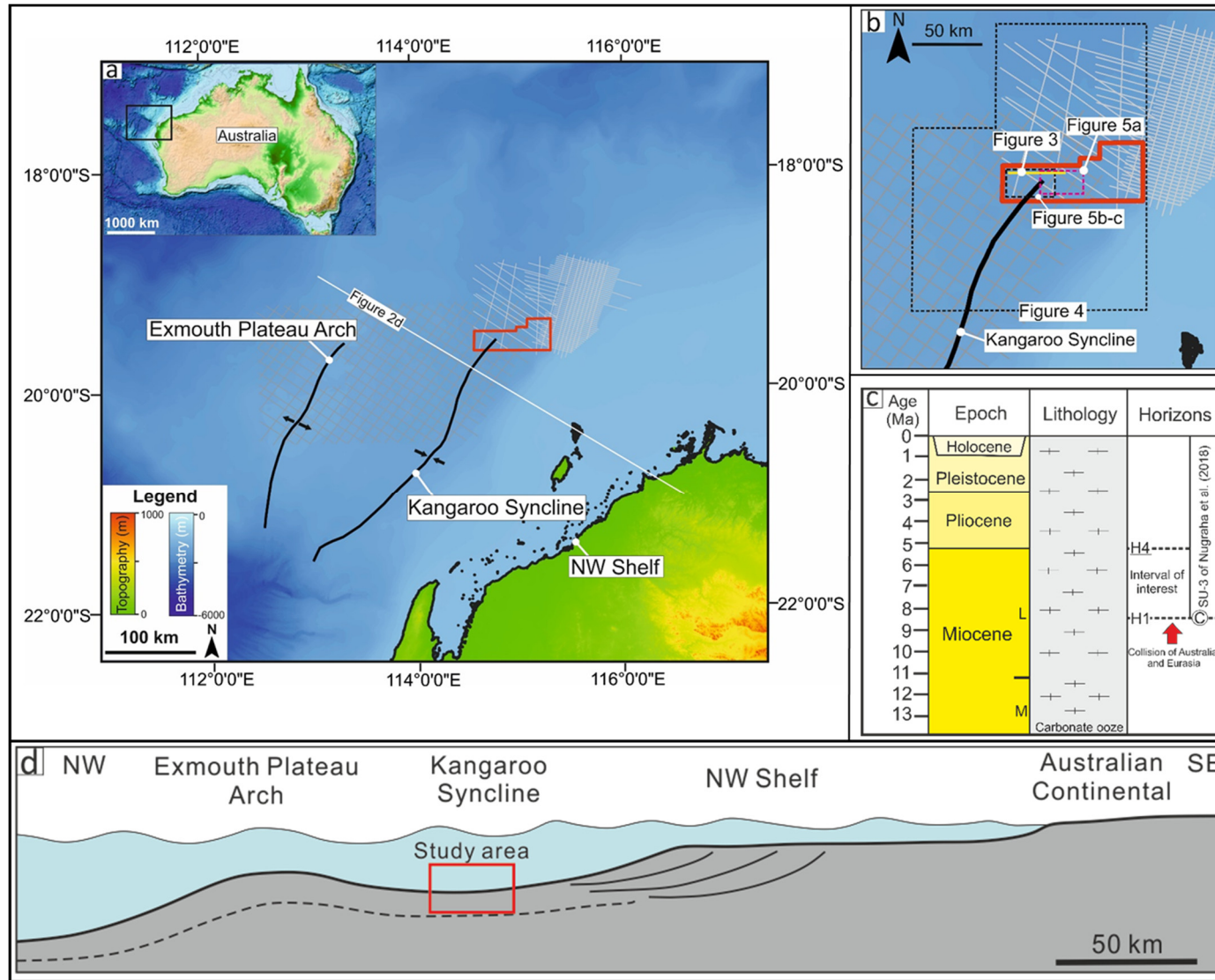
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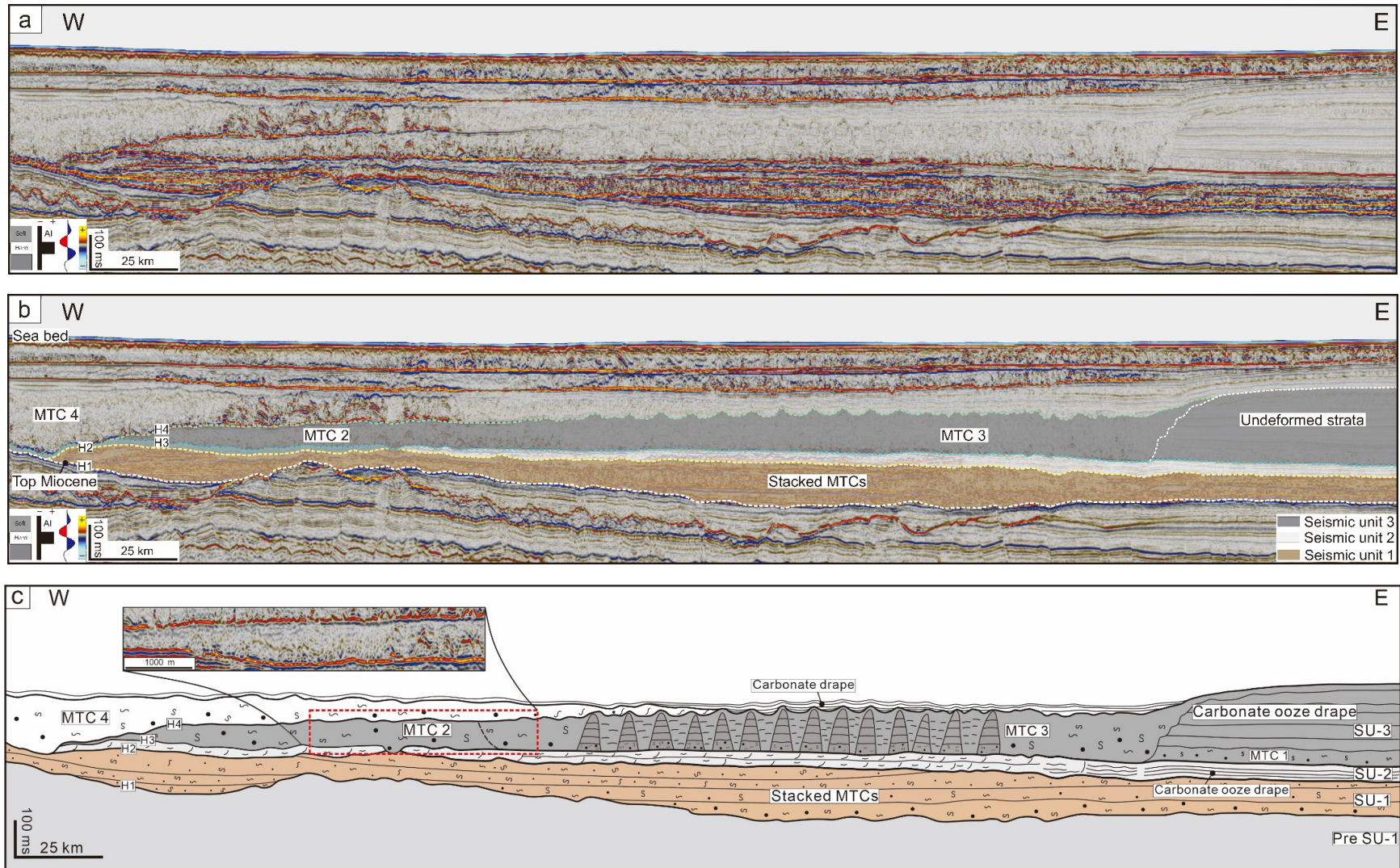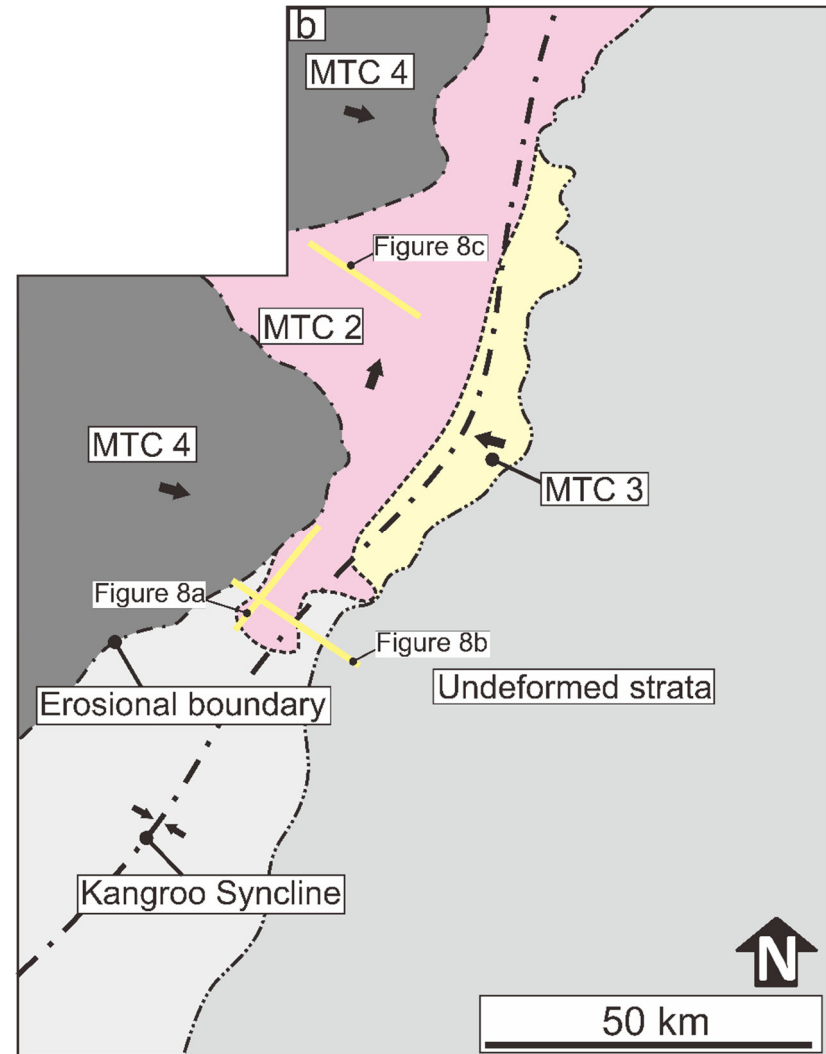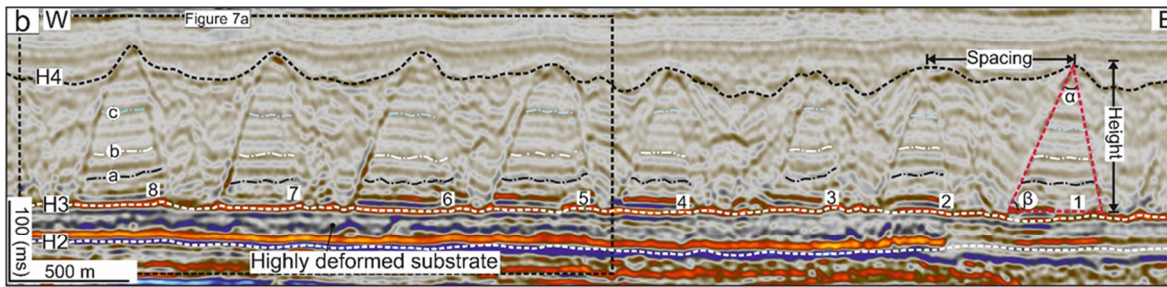
Figure 1

Figure 2

Figure 3

Panel a (seismic section): W — E; scale bars 100 ms, 25 km

Panel b (interpreted seismic section): W — E
- Sea bed
- MTC 4
- H4, H3, H2, H1
- Top Miocene
- MTC 2
- Undeformed strata
- MTC 3
- Stacked MTCs
- Seismic unit 3
- Seismic unit 2
- Seismic unit 1
- scale bars 100 ms, 25 km

Panel c (line drawing): W — E
- MTC 4
- H4, H3, H2, H1
- MTC 2
- Carbonate drape
- Carbonate ooze drape
- SU-3
- MTC 3
- MTC 1
- SU-2
- Carbonate ooze drape
- Stacked MTCs
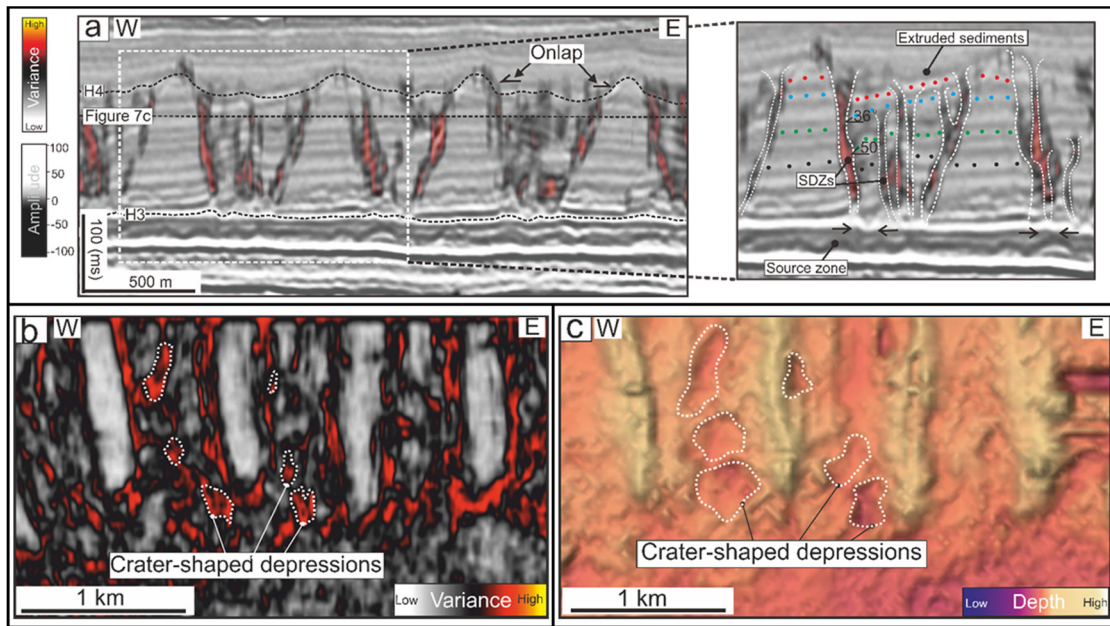- SU-1
- Pre SU-1
- inset scale bar 1000 m
- scale bars 100 ms, 25 km

Figure 4

Figure 5

Figure 6
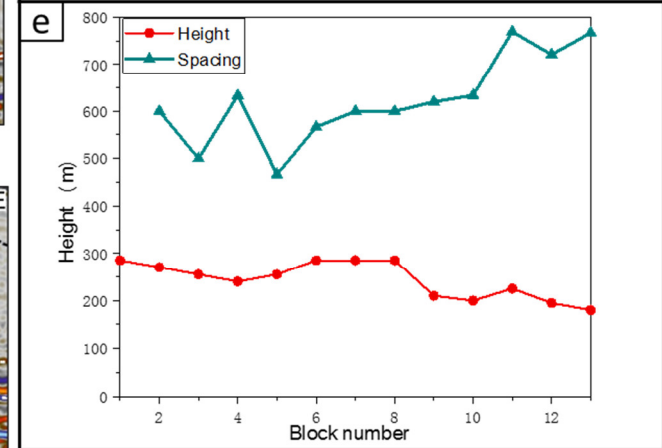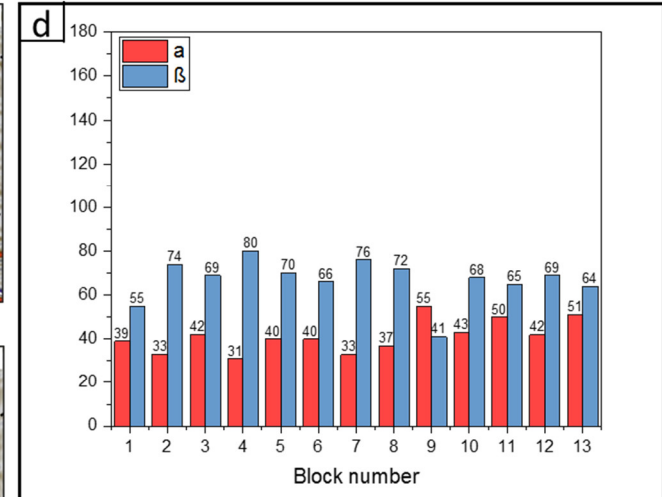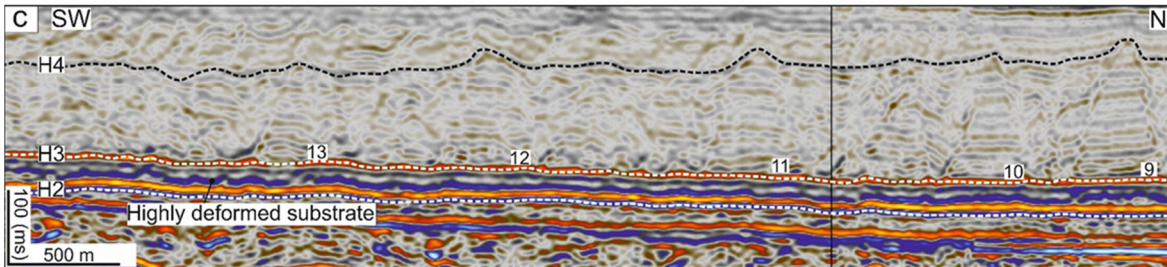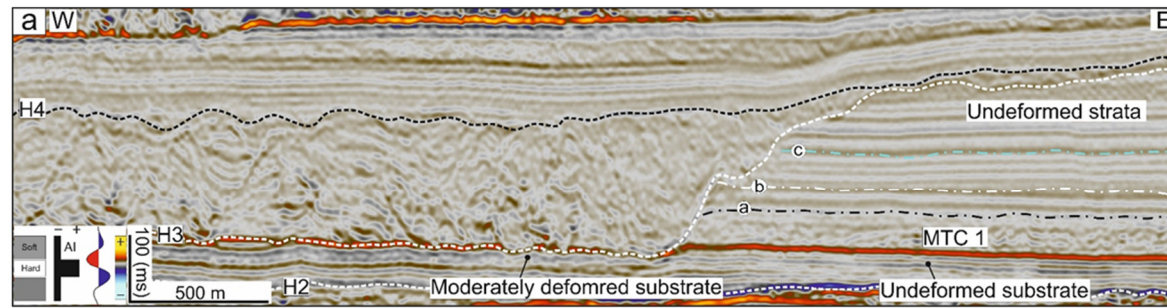
Figure 7

Figure 8

Figure 9

Figure 10