1   # How do tectonics influence the initiation and evolution of submarine

2   # canyons? A case study from the Otway Basin, SE Australia

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8   ## Abstract

9   The architecture of canyon-fills can provide a valuable record of the link between tectonics,

10   sedimentation, and depositional processes in submarine settings. We integrate 3D and 2D seismic

11   reflection data to investigate the dominant tectonics and sedimentary processes involved in the

12   formation of two deeply buried (c. 500 m below seafloor), and large (c. 3-6 km wide, >35 km long)

13   Late Miocene submarine canyons. We found the plate tectonic-scale events (i.e. continental

14   breakup and shortening) have a first-order influence on the submarine canyon initiation and

15   evolution. Initially, the Late Cretaceous (c. 65 Ma) separation of Australia and Antarctica resulted

16   to extensional fault systems, which then formed stair-shaped paleo-seabed. This inherited seabed

17   topography allowed gravity-driven processes (i.e. turbidity currents and mass-transport complexes)

18   to occur. Subsequently, the Late Miocene (c. 5 Ma) collision of Australia and Eurasia, and the

19   resulting uplift and exhumation, have resulted in a prominent unconformity surface that coincides

20   with the base of the canyons. We suggest that the Late Miocene intensive tectonics and associated

21   seismicity have resulted in instability in the upper slope that consequently gave rise to

22   emplacement of MTCs, initiating the canyons formation. Therefore, we indicate that regional

23   tectonics play a key role in the initiation and development of submarine canyons.

24   Keywords: Submarine buried canyons; Mass-transport complexes; Canyon-fill; Tectonic activity

25   ## 1. Introduction

26   Submarine canyons are ubiquitous in deep-water settings and have long been considered as one

27   of the major conduits for transporting sediment from the shelf edge, across the continental slope,

28 and into the deeper abyssal plain (Shepard, 1981; Normark et al., 2003; Antobreh and Krastel,

29 2006). They are normally characterised by U-shaped cross-sectional geometries, that represents

30 incision of hundreds of metres into the underlying stratigraphy, extend for several kilometres in

31 width, and up to hundreds of kilometres long (i.e. Lewis and Barnes, 1999; Baztan et al., 2005; Su

32 et al., 2020). When buried, the coarse-grained canyon-fill (i.e. sand-rich turbidites) may act as

33 reservoirs for hydrocarbons and/or long-term carbon storage, in many submarine settings (i.e. in

34 the South China Sea, Gulf of Mexico, offshore West Africa, and SE offshore Australia; Moore et al.,

35 2000; Posamentier and Kolla, 2003; Crossey et al., 2006; Gong et al., 2011; Su et al., 2014; Tassone

36 et al., 2014). Submarine canyon-fills have been well studied from large-scale outcrop analogues,

37 which provided valuable information on lithofacies, sedimentary processes, and depositional

38 model of canyon-fills (i.e. Campion et al., 2003; Di Celma, 2011; Hodgson et al., 2011; Zecchin et

39 al., 2011; Figueiredo et al., 2013). However, due to their limited exposures, it is difficult to

40 thoroughly examine the three-dimensional sedimentological and architectural evolution of

41 canyon-fills in the field. Seismic reflection data-based studies have contributed significantly to our

42 understanding of the three-dimensional morphology, internal architecture and stratigraphic

43 evolution of the buried canyons on the continental shelf (i.e. Rasmussen, 1994; He et al., 2013)

44 and continental slope regions (i.e. Gong et al., 2011; Maier et al., 2018; Su et al., 2020). However,

45 the previous canyon-fills related studies lack examples of deeply buried (i.e. > 200m) canyons that

46 deposited in the deeper submarine settings (i.e. continental lower slope or abyssal plain, water

47 depth>200 m), leading to an incomplete assessment of the canyon-fills evolution and, therefore,

48 are generally inadequate to resolve initiation and evolution of canyons in deep marine settings

49 where water depth exceeds 200 m.

50 In this study, we focus on the Otway Basin, located on the south-eastern Australian margin (Figure

51 1a). The modern seabed geometry is characterised by a low gradient (0.4º to 1º) continental shelf

52 in the upper region, a steep (10º to 30º) continental slope that is transacted by multibranched

53 canyons, and mass-transport complexes (MTCs) are also distributed in the middle slope, and a

54 broad Southern Ocean abyssal plain (c. 5-7 km below seafloor) in the lower region (Figure 1b; Leach

55 and Wallace, 2001; Wu et al., 2021b). The high-resolution 3D and 2D seismic reflection data from

56 offshore SE Australia have provided us with a new opportunity to constrain buried canyons

57 sedimentological and architectural evolution in submarine settings. In this study, we present two

58 deeply buried, isolated cut and fill canyons (BC-1 and BC-2) that were formed in the Late Miocene.

59 We aim to investigate the architectural evolution and depositional processes from seismic facies

60 analyses and infer potential links of canyon initiation and evolution to plate tectonic events. A

61 detailed examination conducted in this study can provide valuable information to understand the

62 evolutionary history of buried canyons in the abyssal plain and act as an analogue for comparison

63 to other submarine canyons.

64 ## 2. Geological setting

65 ### 2.1 Structural Framework

66 The Otway Basin is an NW-striking rift basin located on the south-eastern South Australia passive

67 margin (Figure 1a, 1b). The Otway Basin was initiated by rifting during the Late Jurassic to early

68 Palaeogene and formed due to the eventual continental separation between Antarctica and

69 Australia during the break up of Gondwana at the end of the Cretaceous (Figure 2; Willcox and

70 Stagg, 1990; Perincek and Cockshell, 1995; Norvick and Smith, 2001; Krassay et al., 2004). Since

71 the Jurassic, the Otway Basin has had two significant phases of extensional tectonism, including a

72 Late Jurassic- Early Cretaceous rifting phase and a Late Cretaceous rifting phase (Perincek and

73 Cockshell, 1995; Krassay et al., 2004). The post-rift stage of the Otway Basin commenced in the

74 Late Craterous, and most of the major faulting and tectonic activities associated with the final

75 separation of Australia and Antarctica Plate ceased at that time (Krassay et al., 2004; Holford et al.,

76 2014). The Late Jurassic- Early Cretaceous rifting phase has created an intense faulting event that

77 affects the entire Cretaceous succession (Figure 3; Moore et al., 2000). The Cretaceous faults are

78 generally NW-SE striking normal faults with an average dip of 60° (Figure 3; Ziesch et al., 2017). The

79 final breakup of the Australia and Antarctica Plates has resulted in a regionally distributed

80 unconformity surface (Horizon H1 in this study; Figure 2, Figure 3) which separates the underlying

81 Cretaceous and overlying Cenozoic successions (Krassay et al., 2004). These extensional faults

82 normally terminate in the overlying thin Cenozoic succession and are characterised with high-angle

83 extensional faults that dominant the shallower part of the basin, lower angle listric faults are

84 common in the deeper part of the basin (Figure 3). During the Late Miocene to Early Pliocene, the

85 collision between Australia and the subduction zones of the Indo-Australian plate has generated

86 long-wavelength (of the order 10^3 km) intraplate forces (Hillis et al., 2008; Tassone et al., 2012;

87 Tassone et al., 2014). The Southern Australia margin has recorded this intraplate force and

88 experienced an intensive uplift, exhumation and deformation (Figure 3; Dickinson et al., 2002;

89 Sandiford, 2003; Hillis et al., 2008). The onset of this late Miocene tectonic phase is marked by a

90 regional unconformity (Horizon H2 in this study; Figure 2) that is widely distributed along the deep-

91 water sedimentary basins in SE Australia (Dickinson et al., 2002).

92 ***2.2 Sedimentology***

93 The study interval lies in the Cenozoic stratigraphy in a passive continental margin setting. During

94 the Cenozoic, the Otway Basin was in an open marine depositional environment, characterised by

95 marine-related, calcareous-rich sediments (McGowran et al., 2004). The strata of the Cenozoic

96 succession comprises of: the Wangerrip Group, the Nirranda Group, the Heytesbury Group, and

97 the Whalers Bluff Formation (Figure 2; Perincek and Cockshell, 1995; Krassay et al., 2004; Totterdell

98 et al., 2014). The Wangerrip Group (late Palaeocene to middle Eocene) represents the beginning

99 of the passive margin sedimentation after the cessation of Late Cretaceous rifting (Figure 2). It

100 unconformably overlies the regional Late Cretaceous unconformity (Horizon H1) and comprises of

101 siliciclastic rich sediments (Figure 2). The Nirranda Group (middle Eocene to early Oligocene) is a

102 succession of fine-grained siliciclastic in the lower section and marls in the upper section (Figure

103 2). The Heytesbury Group (late Oligocene to late Miocene) is deposited in fully marine conditions

104 dominated by a combination of calcareous mudstone and sandy limestone (Figure 2; Ziesch et al.,

105 2017). The Late Miocene to Pliocene tectonic inversion induced the deposition of fluvial sands,

106 which continues up to the present day (Norvick and Smith, 2001). The Whalers Bluff Formation

107 (WBF, Pliocene-Recent; Figure 2) mainly consists of siliciclastic-rich sediments and is mostly

108 developed near the continental slope area (Tassone et al., 2011).

109 ## 3. Dataset and Methodology

110 ***3.1 Dataset***

111 A Geoscience Australia Database is used as the primary data source for this work, including high-

112 resolution 2D and 3D seismic reflection data (Figure 1b). The seismic reflection data encompass

113 the modern continental shelf, continental slope, and abyssal plain area (Figure 1b). As shelf

progradation occurs seaward since Miocene times, the Miocene shelf edge is located c. 50 km

landward of the modern shelf edge (Figure 1b; Leach and Wallace, 2001). Therefore, the seismic

datasets provide the opportunity to investigate the evolutional history of buried canyons and the

tectonic features in the deep submarine setting. The 3D seismic-reflection dataset (OS02 3D)

covers an area of c. 360 km^2, with a bin spacing of 25 m × 12.5 m (inline × crossline). The 3D seismic

data is zero-phase and presented in SEG normal polarity with an increase in acoustic impedance

expressed as a positive amplitude (Figure 4). The dominant frequency within the stratigraphic

interval of interest is c. 35 Hz, giving an average velocity of the buried sediment of 2450 m/s, and

a vertical resolution of approximately 17.5 m.

3.2 Methodology

The age of the buried canyons was determined by correlations with offset wells (Figure 3) described

in nearby studies (Leach and Wallace, 2001). We identified and interpreted three key horizons (H1,

H2, and seabed), based on their high continuity (which extend throughout the study area) and

strong amplitude. Horizon H1 (Figure 3, Figure 4) is a regionally mappable unconformity that has

been correlated to the intra-Maastrichtian unconformity surface (Holford et al., 2014), and which

records the eventual separation of the Australian and Antarctic Plates (Krassay et al., 2004; Holford

et al., 2014). Horizon H2 (Figure 4, Figure 5) is another regionally mappable unconformity that

defines the base of the Middle Miocene, which formed due to the tectonic uplift and the associated

canyon erosion (Holdgate et al., 2000; Dickinson et al., 2001; Leach and Wallace, 2001).

Five seismic facies are identified based on their external geometry, internal configuration, seismic

amplitude, continuity, and seismic reflection termination patterns (Figure 6). The seismic facies

interpretation is further guided by comparing their expression with previous seismic facies analysis

schemes developed for buried submarine canyon-fills in the nearby area (Leach and Wallace, 2001)

and in similar basin settings (Mayall et al., 2006; Gong et al., 2011; Mauffrey et al., 2017; Maier et

al., 2018). A variance (coherency) attribute was calculated to illustrate and delineate the

morphology and internal structures of the intra-canyon depositional elements. Variance attribute

calculates the variability of a trace to its neighbour over a particular sample interval and produces

interpretable lateral changes in acoustic impedance (Van Bemmel and Pepper, 2000), low variance

response represents similar traces, and high variance response represents discontinuities (Brown,

2011). Therefore, coupled with seismic facies analyses, variance attributes can contribute to better

144 imaging and mapping intra-canyon deposits.

4. Result

4.1 Seismic facies

Seismic facies-1: Turbidite complexes

Seismic facies-1 (SF-1) consists of parallel to sub-parallel, continuous, high amplitude seismic reflections (Figure 6). SF-1 typically displays onlapping or pinching out geometries toward the canyon sidewalls (Figure 6). SF-1 can be observed in most of the canyon cross-sectional profiles, it comprises approximately 5-10% of the buried canyon stratigraphy. SF-1 is c. 60-90 m thick and preferentially occurs at the base of the canyon fill. It is abundant in the lower section of the buried canyons and becomes less obvious in the middle and upper sections. Based on the seismic characteristics and previous seismic facies-based studies, SF-1 is interpreted as primarily coarse-grained turbidite complexes, representing multiple episodes of turbidity currents deposition (i.e. Cross et al., 2009; Gong et al., 2011; Wu et al., 2021a).

Seismic facies-2: Background slope deposits

Seismic facies-2 (SF-2) is characterised by sheet-like, medium- to low-amplitude, laterally continuous reflections that cap SF-1 and SF-3 (Figure 6). SF-2 consists of a flat base and top surface with fair cross-sectional continuity, and no erosive features have been observed. In general, the SF-2 preferentially occurs at the middle part of the canyon-fill, and makes up c. 20% of the buried canyon stratigraphy. The thickness of SF-2 is constant, ranging from 150-190 m. Based on the seismic characteristics and previous seismic facies-based studies, SF-2 is interpreted as a mix of fine-grained turbidite complexes and mud-rich hemipelagic deposits (Symons et al., 2017; Maier et al., 2018), representing a low-energy depositional environment (Prather et al., 1998).

Seismic facies 3: Mass transport complexes (MTCs)

Seismic facies-3 (SF-3) consists of a discontinuous to chaotic reflection package with high- to medium-amplitude seismic reflections (Figure 6). The SF-3 is c. 170-300 m thick, has a rugose top surface and a relatively flat base surface (Figure 6). It dominates the middle to upper canyon-fill, representing nearly 60% of the buried canyon stratigraphy. The chaotic nature of the SF-3, combined with the rugose upper surface, indicates SF-3 has been remobilised and transported, mostly as MTCs (Prather et al., 1998; Posamentier, 2005; Maier et al., 2018). Based on its seismic

173 reflection character, we propose that SF-3 was initially deposited as and ultimately sourced from

174 the remobilisation of SF-1 and SF-2.

175 *Seismic facies 4: Turbidite channel*

176 Seismic facies-4 (SF-4) is defined by medium-high amplitude, and has a bowl-shaped external form

177 with an erosional base (Figure 6). Internal reflections of SF-4 are characterised by chaotic, medium

178 amplitude reflection. Seismic reflections outside the SF-4 are of fare continuity and medium-high

179 amplitude reflections (Figure 6). The thickness of SF-4 ranges from 130-170 m, it is observed

180 primarily in the upper section of the canyon-fill, representing c. 5% of the buried canyon

181 stratigraphy. The internal amplitudes of SF-4 are higher than that of the surrounding seismic facies,

182 which indicates a higher acoustic impedance contrast when compared with surrounding facies. The

183 erosional nature at the base of SF-4 suggests incisions, and the high amplitude of the fill might

184 suggest that SF-4 is dominated by sandstone-rich deposits. We interpret SF-4 as turbidite channel

185 deposits, as indicated by studies from Perov and Bhattacharya (2011) and Posamentier and Kolla

186 (2003).

187 *Seismic facies 5: Contourite channel*

188 Seismic facies-5 (SF-5) is defined by sub-parallel to wavy, low-high amplitude seismic reflections,

189 with truncated internal reflections (Figure 6). SF-5 can be easily recognised in the uppermost

190 section of the buried canyons, near the continental shelf edge, having an elongated mounded

191 shape and an adjacent concave moat (Figure 6). Based on its seismic reflection character, SF-5 is

192 interpreted as contourites that are affected/reworked by contourite currents (Stow et al., 2002;

193 Stow and Faugères, 2008; Rebesco et al., 2014).

194 ***4.2 The buried canyons***

195 The buried canyons (BC-1 and BC-2) are deposited in the Oligocene to Miocene Heytesbury Group,

196 and belong to Miocene Canyon systems which are defined by Leach and Wallace (2001). The BC-1

197 and BC-2 oriented NNE-SSW, subparallel to the paleo-slope direction (Figure 7a, 7b). The BC-1 is

198 broad U-shaped canyons in seismic cross-section, ranging from c. 3 km to 5 km wide and cutting

199 approximately c. 300 m to 500 m deep (Figure 8a-d). It is bounded by a lower undulatory erosional

200 surface (Horizon H2) that truncates the underlying strata, showing a distinct seismic amplitude

201 with negative polarity (Figure 4, Figure 8). The U-shaped erosional surfaces represent the oldest

202 period of erosion and can be identified on most of the canyon cross-sectional profiles. The canyon

203 sidewalls are steep, ranging from 20° to more than 30° (Figure 8). A series of sliding blocks are

204 locally modified and truncated the steep canyon sidewalls, and located along the canyon margin

205 (Figure 8c, 8d).

206 The seismic facies assemblage of the sliding blocks is similar and can be correlated to the

207 undeformed strata adjacent to the canyon walls, and is therefore interpreted to fail along the

208 canyon sidewalls (Figure 8d). After the formation of the U-shaped erosional canyon base, the

209 accommodation is filled by several different seismic facies. Based on the seismic facies infill pattern

210 and their location toward the slope, the BC-1 is divided into two transverse segments (Upper

211 segment and Lower segment; Figure 7b). The Upper segment starts from the upper (NW) gap of

212 the 3D seismic data to the lower edge of the paleo-slope. The Lower segment covers most of the

213 3D seismic data area, expanding from the lower slope to the abyssal plain. In the following section,

214 we take BC-1 (the biggest buried canyon in the study area) as an example to further investigate its

215 facies association and infill patterns.

216 **_4.3 Canyon architecture_**

217 _Upper segment_

218 The upper segment of the BC-1 truncates into the paleo-lower continental slope (Figure 7a, 7b).

219 The maximum width and relief of the buried canyon is c. 3 km and 300 m, respectively. In this

220 segment, the lowermost and the uppermost section of the buried canyon is commonly filled with

221 SF-1, suggesting that turbidite complexes are the most dominant depositional elements during the

222 initial and final phase of the buried canyon-fill (Figure 8a, 8b). The upper section of the buried

223 canyon filled is commonly SF-2, suggesting that hemipelagic deposits are deposited shortly after

224 the turbidite complexes (Figure 8a, 8b). In the uppermost part of the canyon-fill, the SF-5 are

225 present, indicating the contourite current activities have influenced the final stage of the canyon-

226 fill (Figure 8a).

227 _Lower segment_

228 The Lower segment is SSW-oriented and constitutes the portion of the buried canyons where major

229 accumulation took place. The width of the canyon in this segment is up to c. 7 km, with maximum

230 sidewall reliefs of c. 500 m (Figure 8c, 8d). In the 3D seismic data area, most of the canyon-fill of

231 the BC-1 is characterised by SF-3, which can constitute more than 70% of the canyon stratigraphy,

232 with only thin (c. 30 m) deposition of SF-1 and SF-2 deposited in the middle or upper parts of the

233 stratigraphy (Figure 8c, 8d). Further downslope, regional 2D seismic lines image several other

234 buried canyons that deposited in the deeper submarine setting, with the percentage of the SF-3

235 infill increasing to nearly 90% of the total canyon stratigraphy (Figure 9a, 9b). The large percentage

236 SF-3 infill show MTCs are the largest component of the Lower segment infill. A relatively thin fill (c.

237 90 m to 200 m) of turbidite complexes and background slope deposits appears in the upper section

238 of the buried canyons.

239 The thick accumulation of MTCs indicate the Lower segment represents the part of the buried

240 canyons where the intensity of erosion reached its peak (Figure 9a, 9b). The lower section of the

241 canyon-fill was likely eroded by MTCs and preserved as erosional remnants scattered throughout

242 the canyon-fill lower section (Figure 8c). The presence of the erosional remnants indicates the

243 erosive MTCs has been initiated and transported from the Upper segment, and ultimately

244 deposited in the Lower segment where extensive erosion is normal.

245 **4.4 Intra-canyon MTCs**

246 Several vertically stacked MTCs have been observed from the seismic sections cutting through the

247 Lower segment of the BC-1. We map three seismically distinctive MTCs (MTC-1 to MTC-3; Figure

248 8c, 8d) to investigate the morphological and kinematic properties of these intra-canyon MTCs.

249 MTC-1 is bounded by horizons H2.1 and H2.2, it is laterally confined by the canyon base surface

250 (Horizon H2) and mainly consisting of chaotic seismic facies with high amplitude seismic reflections

251 (Figure 8c, 8d). MTC-1 is 90 to 130 m thick, being thickest near the canyon centre, and progressively

252 thins towards and onlaps onto the canyon sidewalls (Figure 8c, 8d). In plain view, the distribution

253 of MTC-1 is spatially confined within the BC-1, the lateral margins of MTC-1 follow an NNE-

254 orientated direction, coinciding with the orientation of BC-1 sidewalls (Figure 10a). MTC-2 is 120

255 to 190 m thick and bounded by horizon H.2.2 and H2.3, and it contains chaotic seismic facies with

256 medium amplitude reflections (Figure 8c, 8d). The lateral margins of MTC-2 follows an NNE-

257 orientated direction, subparallel to the orientation of canyon sidewalls. Similar to MTC-1, MTC-2 is

258 laterally confined by the Horizon H2 and spatially distributed within the area of the BC-1 (Figure

259 10b). MTC-3 is 130 to 210 m thick, and it is bounded by horizon H2.3 and H2.4, mainly consisting

260 of chaotic seismic facies with medium amplitude reflections (Figure 7c, 7d). MTC-3 has NNE-

261 orientated lateral margins, and the distribution of this MTC is nearly the same extent as the BC-1

262 (Figure 10c).

263   The orientation of NNE-striking lateral margins suggests these MTCs were transported towards the

264   SSE. Although there is no direct evidence indicating the source area of MTCs, the overall

265   distribution (confined within the lower section of canyon-fills) and the nature of the seismic facies,

266   together suggest MTC-1, MTC-2, and MTC-3 may derive from the failures of turbidite complexes or

267   background sediments that originally deposited in the Upper canyon segment. The strictly confined

268   nature of the intra-canyon MTCs indicates that the distribution of these failures is controlled by the

269   canyons' morphology (i.e. the width and the height). Compared with MTC-1, the areal extent of

270   MTC-2, and MTC-3 is larger, which suggests mass failure processes become more dominant with

271   the evolution of canyon-fill. The vertically stacked deposition pattern of these MTCs suggests the

272   intense erosion and sediment failure in the buried canyons were enhanced by tectonic deformation.

273   The reoccurrence of the intra-canyon MTCs may be associated with the intensive faulting activities

274   during Late Miocene–Pliocene fault reactivation, which has been variously ascribed to the

275   contemporaneous collision of Australia's northern margin with the island arc in New Guinea (Hill

276   et al., 1995).

277   5. Discussion

278   *5.1 Sedimentological evolution of buried canyons*

279   Based on the canyon-fill pattern, the evolutionary model of the buried canyons identified in the

280   Otway Basin can be summarised into three stages: (i) mass-transport complexes (MTCs) dominated

281   the erosional stage, (ii) turbidites dominated the depositional stage, and (iii) an interbedded MTC-

282   turbidite dominated erosional-depositional stage.

283   At the initial erosional stage, the morphology of the U-shaped canyon base has been attributed to

284   the erosion by multiple mass failure events, as recorded by the thick deposition of MTCs in the

285   distal section of the canyon-fill (Figure 9a, 9b). Another interpretation for the formation of the

286   canyon base is the turbidity currents shaped the canyon and where then remobilised as MTCs. As

287   turbidite complexes (or channel lags; Mayall et al., 2006) were observed at the lowermost section

288   of the canyon-fill (Figure 9a). Due to the steep angle of the canyon sidewall (dips from c.40° to 60°),

289   sidewall initiated sliding also occurs at the initial erosional stage. In the second depositional stage,

290   processes such as turbidity currents and background sedimentations take place. The repeated

291   cutting and filling by turbidity currents is one of the major features of canyon-fill, and the canyon-

292   fill remains stable, similar to depositional patterns that have been recorded in other fills (i.e.,

293   Deptuck et al., 2007; Gong et al., 2011; Liang et al., 2020). In the final erosional-depositional stage,

294   the canyon fill is dominated by the deposition of MTCs and turbidite channels. Contourite currents

295   may play a role in the final stage of the canyon evolution. However, it is confined to the upper slope

296   region, where the contourite currents are stronger than other current regimes (i.e. turbidity or

297   mass-transport processes). For example, in the Upper segment of the canyon-fill (Figure 8a), the

298   uppermost of the canyon-fill contains a large portion of contourite drifts and shows a distinct

299   pattern similar to other area where contourite activities are intense (i.e. He et al., 2013; Warratz

300   et al., 2019).

301   *5.2 Origin of the buried canyons*

302   The causal mechanisms by which submarine canyons in the shallow submarine settings are

303   initiated are generally a combination of near shelf-edge fluvial erosion during periods of relative

304   sea-level fall/and or higher sediment flux (i.e. Posamentier et al., 1991) and retrogressive slope

305   failure events occurring near the upper slope (i.e. Coleman et al., 1983; Goodwin and Prior, 1989;

306   Pratson and Coakley, 1996; He et al., 2014). The strong contourite current, tidal current activities,

307   and hurricanes and typhoons, that occur near the coast may also play a role in the canyon initiation

308   (i.e. Shepard et al., 1974; Sequeiros et al., 2019).

309   In the study area, the oldest buried Miocene canyons are tied to occur near the base of the

310   Heytesbury Group (Leach and Wallace, 2001). Therefore, the initiation of the buried canyons likely

311   started during the Late Miocene, when cool-water carbonates dominated (Leach and Wallace,

312   2001). The canyon bases are with high rugosity and show clear erosional features that are similar

313   to those (i.e. grooves or scours) observed from the basal shear surface of MTCs (i.e.Bull et al., 2009;

314   Butler et al., 2016). The Lower segment of the buried canyon-fill is characterised by a dominant

315   deposition of MTCs, and the proportion of MTCs infill constantly increases toward to the farther

316   distal part. Therefore, the origin of the buried canyons is tied to the occurrence of erosive gravity-

317   driven processes (most likely mass failure events) during Late Miocene.

318   *5.3 How do Late Miocene tectonics dictate the canyon initiation?*

319   During Miocene, the SE Australia margin has experienced an extremely intense episode of uplift

320   event, where the study area has experienced the most (Dickinson et al., 2001; Dickinson et al.,

2002; Tassone et al., 2012). The driving mechanism for this uplifting episode is crustal shortening controlled intra-plate stresses, triggered by the northward movement of Australia towards the subduction zones along the northern boundary of the Indo-Australia plate (i.e. Sandiford, 2007; Hillis et al., 2008). Such a momentous uplift event has generated a significant net exhumation around the deep-water Otway Basin during Late Miocene. For example, the gross exhumation in the submarine Otway Basin is more than 1000 m during Late Miocene to Pliocene (Green et al., 2004), near the study area, the gross exhumation could reach more than 1500 m (Duddy, 1997; Tassone et al., 2014). The significant exhumation has created an increase in onshore sediment supply and elevated levels of seismicity in the continental region (Dickinson et al., 2001). These changes likely increased sediment instability in the upper slope and, consequently, gave rise to mass failure events (Sandiford, 2003; Sandiford et al., 2004). The above mentioned processes associated with the continental margin uplifting are marked by a regional erosion surface (Horizon H2 in this study) that can be traced for c. 1500 km along with SE Australia (Dickinson et al., 2002; Tassone et al., 2012). This is especially the case in the deep submarine where the regional erosion surface is corresponded to the extremely irregular canyon base surface (H2), and the canyon-fills are observed to display a thick package of chaotic seismic facies, indicating deposition of MTCs.

The Late Miocene erosion period corresponds to the time when the entire shelf was exposed and thus heavily incised by frequent deposition of MTCs, that were transported down to the deeper part of the basin. We infer that mass failures during episodes of intense tectonic, rather than other factors, caused of incision on the continental slope to initiate the development of buried canyons. The Late Miocene tectonics have helped establish a mature sediment conduit system that extended from shallower marine down to the abyssal plain.

5.4 How do Late Cretaceous tectonics influenced the canyon evolution?

The late Cretaceous fault systems are generally NW-SE striking (Figure 11a, 11b; Ziesch et al., 2017). The dip- and cross-seismic sections have revealed these faults cutting vertically beneath the thalwegs of the BC-1 and BC-2 (Figure 4b, 5b, 9b). The seismic dip line along the canyon axis shows the presence of the faults has created a stair-shaped structure within the Lower segment, which is truncated by the canyon (Figure 5b, 9b). The seismic dip line along the area outside the buried canyons show that after deposition of the pre-canyon succession (sedimentation between horizon H1-H2), the paleo-seafloor (at the time of H2) may have inherited the geometry created by the

351 Cretaceous fault systems, showing a stair-shaped structure with a high-gradient (Figure 11c). This

352 can be clearly seen from the onlapping patterns of sediments onto the local topographically high

353 created by buried faults (Figure 11c).

354 The stair shaped geometry is interpreted as the hanging walls of the deeply sourced fault systems

355 may have created a local structure high on the Late Cretaceous seafloor when horizon H1 is

356 deposited. The footwalls of the deeply sourced fault systems have created a local structure low on

357 the Late Cretaceous seafloor (Figure 12a). After the burial, the buried footwalls acted as a local

358 high (buried hanging walls are locally low), causing an elevation difference between two adjacent

359 footwalls and hanging walls (Figure 12a). When the canyon initiates, the stair-shape paleo

360 geometry can cause an immediate increase in currents (e.g., turbidity currents or debris flow)

361 energy and erosivity, thus facilitating the canyon development (Figure 12b). The subsequent

362 canyon-fills was also influenced by the inherited topography created by the previous canyon infill

363 and the stair-shape canyon base (Figure 12c). In modern analogues, the local gradient variation of

364 the seabed has played a key role in canyon evolution (e.g., expansion in canyon width and depth),

365 as demonstrated by modern canyon systems (Qin et al., 2017; Wu et al., 2021b). Therefore, we

366 suggest that the late Cretaceous fault-controlled zones may have pre-determined the location of

367 the canyons by facilitating the erosional downcutting during the formation of the canyon base, this

368 influence has not been instantaneous, instead the impact on the canyon evolution can be felt as

369 late as tens of million years (or more).

370 ***5.5 Implication***

371 Previous studies show that the tectonically active settings tend to develop small-scale, short-lived

372 canyons (Eyles and Lagoe, 1998), while canyons in tectonically stable passive margin settings tend

373 to develop relatively large scale canyons which are active for longer periods (Coleman et al., 1983).

374 However, we reveal that in the tectonically active regions, uplift and tilting due to tectonic

375 deformation induce an increased in sediment supply and seismicity, which can promote mass

376 failure events thus contribute significantly to the formation of large-scale submarine canyons.

377 Therefore, we indicate that the factors which preconditioned and triggered mass-transport

378 complexes can also induce canyon initiation and facilitate canyon development. We suggest that

379 the plate tectonic scale events (i.e. continental breakup and shortening) have a first-order influence

380 on the submarine canyon initiation and evolution. The impact from the regional tectonics to the

381 buried canyons can be instantaneous (i.e. directly trigger canyoning processes), or their influence

382 can also be postponed (i.e. indirectly influence the seabed topography thus the canyon geometry).

6. Conclusion

384 1. The interpretation of the seismic data reveals that the sedimentological evolution of buried

385 canyons can be divided into: (i) a mass-transport complex (MTC) dominated erosional stage, (ii) a

386 turbidite dominated depositional stage, and (iii) a mixed MTC-turbidite dominated the erosional-

387 depositional stage. We indicate that in the deeper submarine settings (i.e. lower continental slope

388 or abyssal plain), the interplay of turbidity currents and mass failure events control the canyon

389 sedimentological and architectural patterns.

390 2. The intimate association of the buried canyon base with the Late Miocene uplift events suggest

391 that canyon inception was triggered by Miocene uplifting and associated upper slope instability.

392 We suggest that repeated mass failure is the most likely driving mechanism of the buried canyon

393 inception, in conjunction with increased sediment flux due to exhumation of the margin.

394 3. We interpret the extensional faults associated with the late Cretaceous plate separation

395 between Australia and Antarctica as responsible for the inception and evolution of the buried

396 canyons by increasing the steepness of the paleo-seabed, thus controlling the canyon geometry

397 and location.

398 4. Plate-scale tectonic events have a close link with the submarine canyon initiation and evolution

399 processes. The influence from regional tectonic movements to the initiation of canyons may have

400 been almost instantaneous (i.e. directly triggering canyoning processes), or their influence can also

401 be delayed (i.e. indirectly influence the canyon geometry).

Figure Caption

403 Figure 1. Location map of the study area. (a) Regional map of Australia. The black box marks the

404 area shown in Figure 1b. (b) Zoom-in map of the study area showing the location of the city of

405 Portland and the Otway Basin. The white lines represent 2D seismic reflection data, the black

406 dotted line represents the location of the modern shelf edge and the inferred location of the

407   Miocene continental shelf edge (modified from Leach and Wallace, 2001), and the red box

408   represents the extent of the 3D seismic reflection dataset. The GEBCO_2014 bathymetry map is

409   downloaded from https://www.ngdc.noaa.gov/maps/autogrid/.

410   Figure 2. Stratigraphic and tectonic event chart for the study area, showing the key horizons

411   mapped in the seismic data and major tectonic events in the study interval. This figure is modified

412   from Krassay et al. (2004) and Perincek and Cockshell (1995). The Horizon H1 has been correlated

413   to the late-Cretaceous unconformity surface from Holford et al. (2014). The Horizon H2 has been

414   correlated to the late-Miocene unconformity surface from Hillis et al. (2008).

415   Figure 3. Large scale regional seismic section across the inner SE Australian shelf to the deeper

416   abyssal plain, highlighting Unconformity surface (H1), and basinward thickening of the Upper

417   Cretaceous supersequence. See the location of this regional seismic profile in Figure 1b. Figure 3 is

418   originally downloaded and modified from Geoscience Australia official website

419   (https://www.ga.gov.au/scientific-topics).

420   Figure 4. (a) W-E seismic cross-section through the 3D seismic data area (see Figure 1b for location).

421   (b) Interpreted seismic cross-section, showing the key horizons, major faults, and the location of

422   the buried canyons.

423   Figure 5. (a) N-S seismic dip-section through the 3D seismic data area (see Figure 1b for location).

424   (b) Interpreted seismic dip-section, showing the key horizons and the major faults.

425   Figure 6. Seismic facies classification figure.

426   Figure 7. (a) Depth structure map of Horizon H2 within OS02 3D area. (b) interpreted sketch of

427   Figure 7a, showing the morphology of Buried canyons (BC-1 and BC-2).

428   Figure 8. (a) Seismic section cutting across the Upper Segment of the BC-1, showing the location

429   of BC-1 and Horizons H1 and H2. (b) Seismic section cutting across the Upper Segment of the BC-

430   1, showing the location of BC-1 and Horizons H1 and H2. (c) Seismic section cutting across the

431   Lower Segment of the BC-1, showing the location of BC-1 and BC-2, and Horizons H1 and H2. (d)

432   Seismic section cutting across the Lower Segment of the BC-1, showing the location of BC-1 and

433   BC-2, and Horizons H1 and H2. See the location of this figure in Figure 7b, and see the uninterpreted,

434   clean seismic sections in the supplementary material.

435   Figure 9. (a) 2D seismic section in the deep submarine settings showing the cross-section of the

436   buried canyons. (b) 2D seismic section in the deep submarine settings showing the dip-section of

437   the buried canyons. See location of this figure from Figure 1b, and see the uninterpreted, clean

438   seismic sections in the supplementary material.

439   Figure 10. (a) Variance attribute calculated on horizon H2.1, showing a map view of MTC-1. Note

440   that the white dotted lines indicate the boundary of the buried canyon, and the yellow dotted lines

441   indicate the boundary of MTCs. (b) Variance attribute calculated on horizon H2.2, showing a map

442   view of MTC-2. (c) Variance attribute calculated on horizon H2.3, showing the map view of MTC-3.

443   See the location of this figure in Figure 7b.

444   Figure 11. (a) Variance attribute map calculated on the horizon a (see the location of this horizon

445   in Figure 11c), showing the extensional faults formed during the Late Cretaceous. (b). Interpreted

446   view of Figure 11a, showing the location of the extensional faults (white dotted lines) and the

447   location of the buried canyons (blue dotted lines). (c) Seismic cross-section through the area

448   outside of the buried canyons (see Figure 11b for location). See the uninterpreted Figure 11c in the

449   supplementary material.

450   Figure 12. Schematic figure showing the evolution model of the buried canyons. (a) Schematic

451   figure showing that the regionally distributed, Late Cretaceous extensional faults. (b) Schematic

452   figure showing the initiation of the MTCs that formed the canyon bases during the Late Miocene.

453   (c) Schematic figure showing the canyon-fill pattern after the formation of the canyon base.

Data Access

454

Acknowledgements

458

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Figure 1

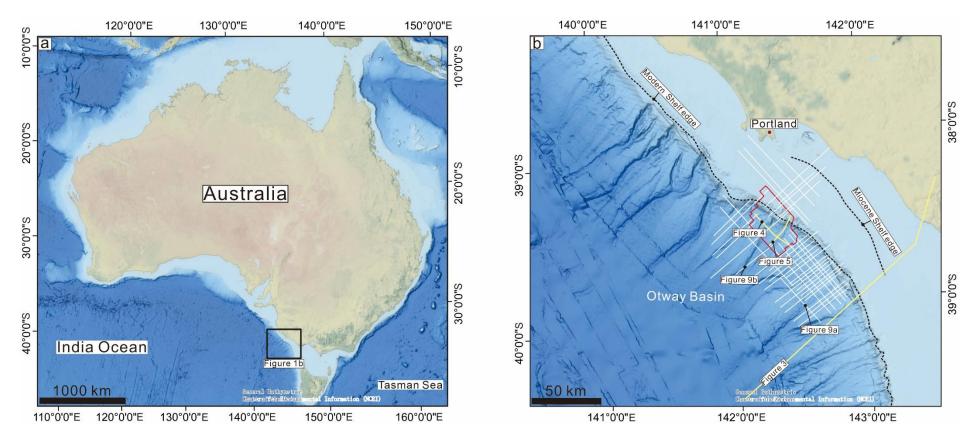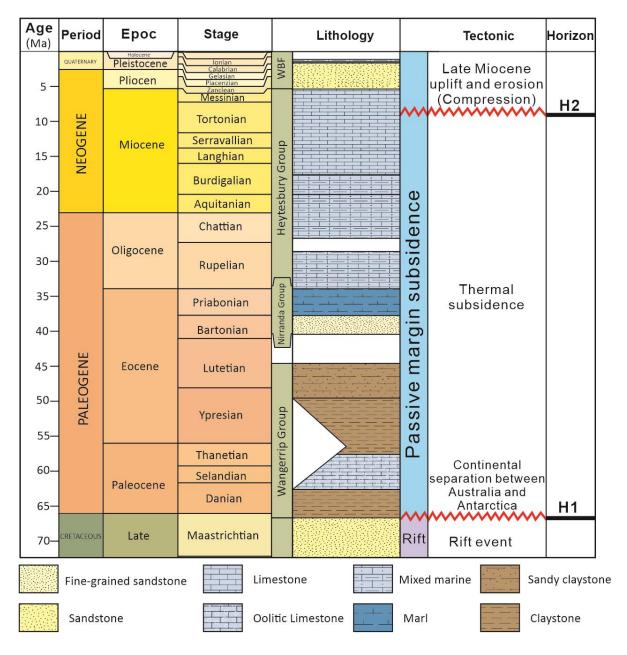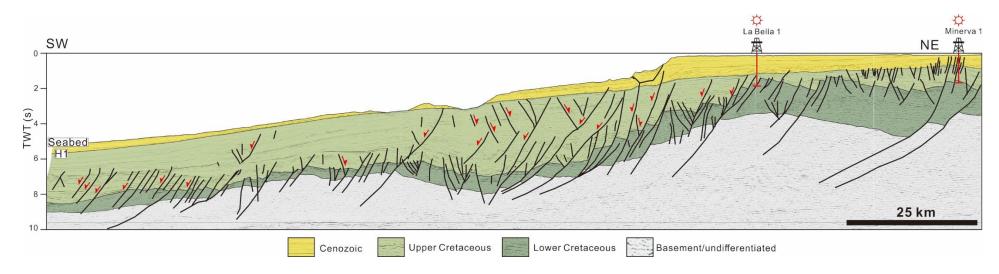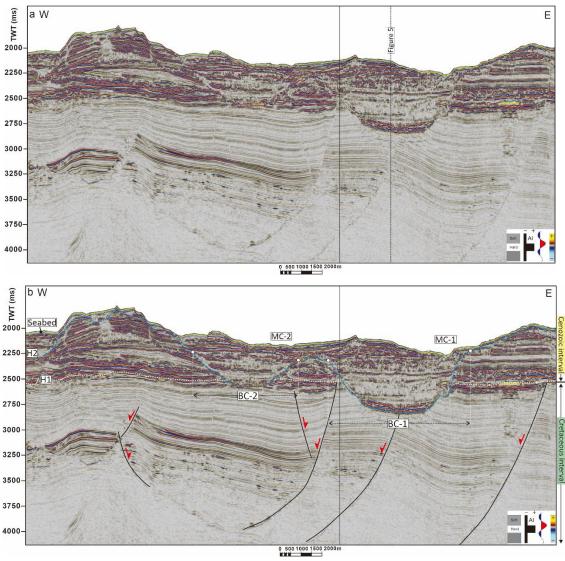Figure 2

Figure 3

Cenozoic   Upper Cretaceous   Lower Cretaceous   Basement/undifferentiated

Figure 4

Figure 5

Figure 6

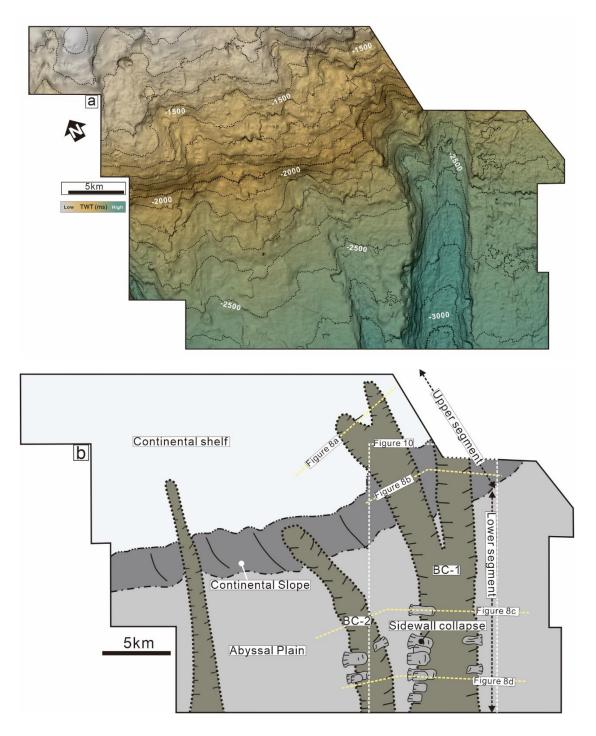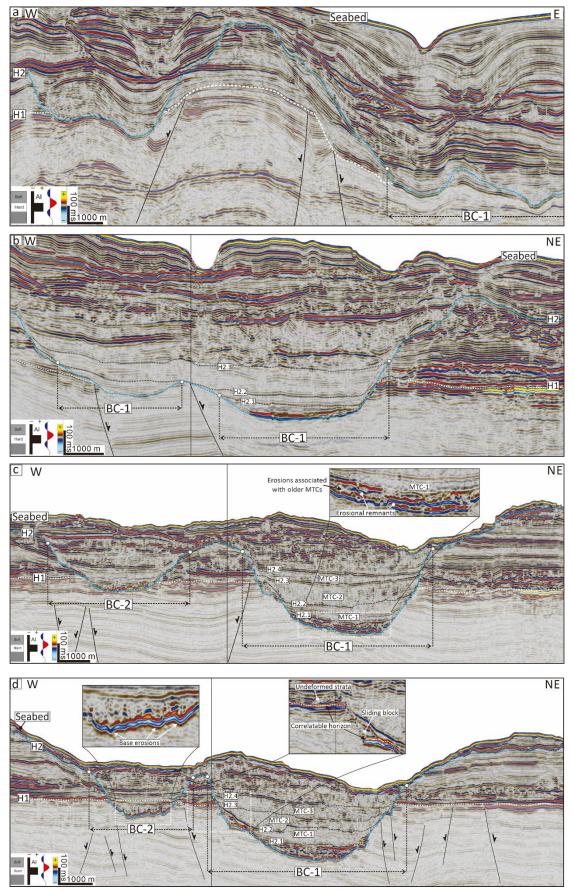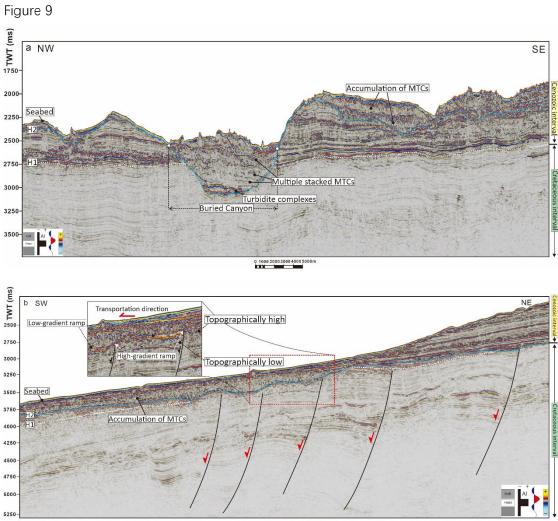| Facies	Description	Interpretation
SF-1	Internally coherent, high- to medium-amplitude, continuous seismic facies.	Turbidite complexes
SF-2	Internally coherent, medium- to low-amplitude, continuous seismic facies.	Hemipelagic sediment
SF-3	Internally deformed, medium- to high- amplitude reflections, trough-shaped seismic facies.	Mass-transport complexes (MTCs)
SF-4	Internally chaotic, medium- to high- amplitude reflections, bowl-shaped external form with an erosional base.	Turbidite channel
SF-5	Internally sub-parallel to wavy, low-high amplitude seismic reflections with truncated base surface.	Contourite channel

Figure 7

a

-1500
-1500
-2000
-2000
-2500
-2500
-2500
-3000

5km
Low   TWT (ms)   High

b

Continental shelf

Continental Slope

Abyssal Plain

BC-2

BC-1

Sidewall collapse

Figure 8a

Figure 10

Figure 8b

Figure 8c

Figure 8d

Upper segment

Lower segment

5km

Figure 8

Figure 9

Figure 10

Figure 11

Figure 12