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

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ABSTRACT

The offshore area of the Otway Basin (south-eastern Australia) is dominated by multibranched canyons where mass-transport complexes are widely distributed. This study integrates high-resolution multibeam and seismic data to investigate the importance of mass-transport complexes in dictating the evolution of canyons. The study interprets three regionally distributed mass-transport complexes that fail retrogressively and affect almost 70% of the study area. Within the mass-transport complexes, seven canyons that initiated from the continental shelf edge and extended to the lower slope are observed. Although the canyons share common regional tectonics and oceanography, the scales, morphology and distribution are distinctly different. This is linked to the presence of failure-related scarps that control the initiation and formation of the canyons. The retrogressive failure mechanisms of mass-transport complexes have created a series of scarps on the continental shelf and slope. In the continental shelf, where terrestrial input is absent, the origin of the canyons is related to local failures and contour current activities, occurring near the pre-existing larger headwall scarps (ca 120 m high, 3 km long). The occurrence of these local failures has provided the necessary sediment input for subsequent gravity-driven, downslope sediment flows. In the continental slope, the widespread scarps can capture gravity flows initiated from the continental shelf, developing an area of flow convergence, which greatly widens and deepens the canyons. The gradual diversion and convergence through mass-transport complex related scarps have facilitated the canyon confluence process, which has fundamentally changed the canyoning process. Thus, this study concludes that the retrogressive failure mechanism of mass-transport complexes has a direct influence on the initiation, distribution and evolution of the canyons. The scarps associated with mass-transport complexes have greatly facilitated the delivery of sediments and marine plastics from the shelf edge into the deep oceans, especially in areas where fluvial input is missing.

Keywords Mass-transport complexes, Otway Basin, south-east Australia, submarine canyons.
INTRODUCTION

Submarine canyons are defined as steep-sided V-shaped or U-shaped valleys that erode into the seabed; they can extend from the continental shelf to the continental slope, with numerous tributaries (Shepard et al., 1966; Twichell & Roberts, 1982; Obelcz et al., 2014). Canyons are complex geomorphological features formed by erosion from gravity flows occurring near subaqueous slopes (Shepard, 1972; Canals et al., 2006; Harris & Whiteway, 2011). Canyons are often associated with sand-rich gravity flows which develop into submarine fans, which can act as high quality deepwater hydrocarbon reservoirs (Stow & Mayall, 2000; Weimer & Slatt, 2004; Steventon et al., 2021). Mass-transport complexes (MTCs) are gravity-driven shear failure deposits resulting from creep, spread, slide, slump and debris-flow processes (Posamentier & Martinsen, 2011; Wu et al., 2021). MTCs can be extremely erosive, thus containing large volumes of sediments, with single deposits covering areas of >100 km² and volumes of >10 000 km³ (Frey Martinez et al., 2005; Moscardelli & Wood, 2016; Nugraha et al., 2019). MTCs normally fail retrogressively (i.e. backstepping slope failures), and the emplacement of MTCs can leave a series of giant slide scars (ca 2–5 km wide) on continental slope areas (Fig. 1A and B; i.e. Williams, 2016; Li et al., 2017). Both MTCs and canyons can transfer large amounts of sediments between the continental shelf and abyssal plain environments, and are considered important sediment transportation processes in deepwater settings (McAdoo et al., 2000; Popescu et al., 2004; Antobreh & Krastel, 2006; Lee et al., 2007; Urgeles & Camerlenghi, 2013).

Submarine canyons and MTCs can have a close relationship in terms of their spatial distribution, triggering mechanisms and preconditioning factors (Micalef et al., 2012; Watson et al., 2020). The emplacement of MTCs can represent the early phase of submarine canyon initiation, providing early depressions on the continental slopes that extend to the shelf break (Farre et al., 1983). The continuous downcutting process associated with canyon development can steepen the gradient of canyon sidewalls, which preconditions the sidewalls to fail, depositing MTCs near the canyon walls (i.e. Farre et al., 1983; Green & Uken, 2008). These intra-canyon MTCs can occur retrogressively, increasing the canyon’s width (i.e. lateral extension; Pratson & Ryan, 1994) and extending the canyon upslope (i.e. headward incision; Farre et al., 1983; He et al., 2014). However, most of the published works have focused on constraining local, coeval, intra-canyon MTCs (sensu detached MTCs; Moscardelli & Wood, 2008) with the evolution of canyons (i.e. Green & Uken, 2008; Gong et al., 2011; He et al., 2014; Su et al., 2020). The relationship between canyons with regional distributed MTCs (i.e. hundreds to thousands of km²) (sensu attached MTCs; Moscardelli & Wood, 2008) that typically fails retrogressively has largely been overlooked. Relatively little is known about how regionally distributed MTCs, and especially how their retrogressive failure mechanism, can influence the initiation, evolution and morphology of submarine canyons. Therefore, this study uses a high-resolution (ca 10 m vertical resolution) three-dimensional seismic reflection dataset, integrated with two-dimensional seismic and multibeam bathymetry data to analyse the spatial and temporal relations between canyons and regionally distributed MTCs in the Otway Basin, south-eastern Australia (Fig. 2A and B).

GEOLOGICAL SETTING

Tectonic

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

Sedimentology

The Cenozoic sedimentary succession in the Otway Basin is composed of marine-related, often calcareous-rich sediments, reflecting an
open marine depositional environment (McGowran et al., 2004). The Cenozoic post-rift sedimentation is represented by the Wangerrip Group (late Palaeocene to middle Eocene, mainly siliciclastic rich), the Nirranda Group (middle Eocene to early Oligocene, mainly containing sandstones and marls), the Heytesbury Group (late Oligocene to late Miocene, mainly contains marls and limestones) and the Whalers Bluff Formation (WBF; Pliocene–Recent, mainly contains mixed siliciclastic–carbonate sediment) (Fig. 3A; Dickinson et al., 2002; Krassay et al., 2004; Holford et al., 2014). The present study interval lies in the Whalers Bluff Formation at a time when the study area was in a passive continental margin setting. In the continental slope area, a thick, localized Pliocene–Recent succession, represents marine clastic sediments deposited in and around submarine canyons (Fig. 3B and C) (Tassone et al., 2011).

Oceanography

Two shelf-break currents dominate ocean circulation in the study area (Duran et al., 2020): (i) the eastward-flowing South Australia Current (SAC); and (ii) the south-eastward-flowing Zeehan Current (ZC) (Fig. 2B). The SAC is an eastward-flowing current with high salinity and velocity (0.5 m s⁻¹), originating from the centre of the Great Australian Bight Basin (Rochford, 1986). The current operates down to 200 m depth (Middleton & Bye, 2007). The ZC (fed by the South Australian Current) is a poleward current with low salinity and high current velocity (0.4 m s⁻¹), flowing down to 300 m water depth (Ridgway, 2007). The offshore area of the Otway Basin is also periodically affected by seasonal cyclones and storms (Holland & Gray, 1983; Kulishov et al., 2002). The above-mentioned downslope and along-slope marine oceanographic....
processes have jointly influenced the oceanography and sedimentation in the Otway Basin.

Because fluvial activity is limited in the study area (McGowran et al., 2004), the elongated mounded seismic facies (sub-parallel to wavy, low to high amplitude, internal truncations) in the WBF Formation have a clear indication of contour current activity (Fig. 3C). Similar seismic facies have been interpreted as contourites that are affected by contourite currents in other submarine settings (i.e. Stow & Faugères, 2008; Rebesco et al., 2014). Moreover, the modern canyons show a clear eastward lateral migration compared to the buried Pliocene canyons in the continental shelf region (Fig. 3C). These observations all indicate that the overall eastward shelf-break parallel currents (SAC and LC) affect the sedimentary processes in the continental shelf region.

**DATASET AND METHODOLOGY**

**Multibeam dataset**

The multibeam echosounder bathymetry data is provided by Geoscience Australia (https://portal.ga.gov.au/persona/marine), covering an area of ca 12 000 km² (Fig. 4A). The lateral resolution of the data is 50 × 50 m, and it enables the identification and interpretation of seabed morphology and associated canyons and MTCs, especially in areas devoid of seismic-reflection data (Fig. 4A).

**Seismic dataset**

The 3D pre-stack time migrated (PSTM) seismic-reflection data were acquired by Santos in 2002, located in the vicinity of Portland, offshore south-eastern Australia (Fig. 2B). The survey covers an area of ca 360 km² with a bin spacing of 25 m × 12.5 m (inline × crossline), and a dominant frequency of 50 Hz at the seabed. The study estimates that the spatial resolution of the seismic data, given an average velocity of the near seabed sediment derived from the seismic report (1824 m s⁻¹), is ca 9 m. The 3D seismic data are zero-phase, and presented in SEG normal polarity with an increase in acoustic impedance expressed as a positive amplitude.

**Methodology**

The seismic-stratigraphic framework is correlated with Holford et al. (2014) work in an adjacent area. Seismic and multibeam data are used to map MTC and canyon related features.
Fig. 3. (A) Stratigraphic and basin event chart for the Otway Basin (modified after Krassay et al., 2004), including lithology interpretation and major tectonic events. The Horizon H1 has been correlated to the intra-Maastrichtian unconformity surface from Holford et al. (2014). The Horizon H2 is correlated to the base of the Whalers Bluff Formation (WBF). (B) Regional along-slope seismic-section showing the overall tectonic of the study area. See location from Fig. 2B. (C) Regional seismic section that is perpendicular to the slope, showing the key seismic horizons (H1 to the seabed) and canyon bearing intervals. See location from Fig. 2B.
key morphometric parameters of the canyons (i.e. canyon width and height) are quantitatively measured and discussed to reveal the sedimentary processes involved in the canyon origin and evolution. In this study, the canyon width is defined as the distance between the canyon shoulders (the point at which the canyon margin begins to dip away from the canyon axis) (Fig. 5; Laberg et al., 2000). The canyon height is defined as the depth from the canyon shoulder to the canyon base (Fig. 5).

RESULT

Morphology of the seabed
The study area spans from the continental shelf to the continental lower slope environment (Fig. 4A). The morphology of the study area is characterized as having a narrow (ca 7 km) and steep slope (Fig. 4B). The continental shelf area dips from 0.4° to 1.0° with an average water depth of 250 m (Fig. 4B). The continental slope area is characterized by a relatively gentle slope of ca 10° in the upper section, to a steep slope gradient of ca 30° near the lower section, with water depths ranging from 600 to 1500 m, respectively (Fig. 4B). The multibeam reveals that several canyons initiated from the continental shelf region, spanning the continental slope, and ultimately terminating in the abyssal plain (Fig. 4A). Widely distributed MTCs and their associated headwall scarps and lateral margins have also been identified (Fig. 4A). These MTCs have a close relationship with the canyons (Fig. 4A). The topographic profiles extracted from the multibeam data in the abyssal plain show dramatic differences in the across-canyon margin morphology (Fig. 4C). In the abyssal plain, where the seabed gradient is relatively low (<2°), the width and height of the canyons (i.e. Canyon-a and Canyon-b) increase along with the dip of the slope, with canyons converging at the deeper section of the abyssal plain (Fig. 4C and D). The width of the canyon increases from ca 5.6 to 6.6 km to ca 10.9 km, and the height of the canyon increases from ca 300 to 360 m, respectively (Fig. 4C and D). The multibeam data used in this study can only investigate the seabed morphological features with a relatively limited lateral resolution (ca
50 × 50 m). It lacks the ability to examine the detailed seabed structures in 3D and reveal the characteristics of the buried sediments. Therefore, in the following section, this study uses high-resolution seismic reflection datasets to investigate the cause of the canyon converging process and the sedimentary process interactions between canyons and MTCs.

Mass-transport complexes and canyons

Three MTCs (MTC-1, MTC-2 and MTC-3) have been interpreted in the study area (Fig. 6A and B). Within these MTCs, the seismic reflection dataset reveals several distinctive east-trending scarps parallel to the slope strike direction and a set of south-west-oriented lateral scarps parallel to the slope dip direction (Fig. 6B). The arcuate east-dipping extensional scarps are interpreted as MTC headwall scarps that mark the updip part of an MTC, where extensional deformation dominates (Fig. 6B; i.e. Bull et al., 2009). The south-west-dipping lateral scarps are interpreted as MTC lateral margins that separate deformed sediments (MTCs) from the undeformed seabed (Fig. 6B; i.e. Frey Martinez et al., 2005; Bull et al., 2009). Based on the orientation of headwall scarps and lateral margins, the MTCs are predominately transported subparallel to the dip direction of the slope.

Seven major canyons (Canyons 1 to 7) spanning from continental shelf to continental lower slope are observed within the MTC influenced area (Fig. 6A and B). They are oriented NNW–SSE on the continental slope, sub-parallel to the slope dip direction, and the orientation changes to NNE–SSW in the lower slope setting (Fig. 6A and B). Canyons 1 to 3 and Canyon-7 are initiated from shelf edge headwall scarps with clear landward incision features, while Canyons 4 to 6 are restricted in the continental slope (Fig. 6B).

Mass-transport complex-1

In MTC-1, multiple headwall scarps (HS-1 to HS-5; from older to younger) and their associated lateral margins are observed from map view and the correlated seismic sections (Fig. 7A and B). Headwall scarps are recognized as upward concaved lineation with scallop-shaped geometries (Fig. 7B). In the seismic dip section, the headwalls are nested in a terraced style, showing a truncated reflector that cuts through upslope sediments (Fig. 8A). The heights and angles of the scarps vary considerably throughout MTC-1, with the highest (ca 170 m) and steepest (ca 40°) HS-5 occurring in the upper part of MTC-1 (Fig. 8A and B). The scale of the other four headwall scarps (HS-4 to HS-1) are comparatively smaller, and the gradient is gentler than HS-5. HS-1 to HS-4 show similar morphology to HS-5, and they are distributed in the central part of MTC-1 (Figs 7B and 8A to D).
Fig. 6. (A) Contoured seabed map of the study area extracted from the 3D seismic reflection data. (B) Schematic representation of seabed geomorphology interpreted from (A). See the location of this figure from Fig. 2B.
The middle part of MTC-1 has a hummocky seabed expression in map view and contains chaotic and blocky seismic facies in seismic section (Figs 7B and 8A). A clear basal shear surface with a gentle gradient (ca. 3°) separates the underlying layered seismic facies from the overlying chaotic seismic facies, observed below HS-5 and HS-1 (Fig. 8A). The chaotic and blocky facies accumulated downdip of HS-4 and HS-1, showing a wedge-shaped geometry in seismic section (Fig. 8A) and a fan-shaped geometry in plan view (Fig. 7B).

The presence of the backstepping stair shape geometry, the relative flat basal shear surface, and the deposition of chaotic seismic facies near the distal part of HS-4, HS-3 and HS-2, suggests that the initial failure started at the lowermost part of MTC-1 and propagated retrogressively towards the upper slope area. This study thus interprets multiple headwall scarps (HS-1 to HS-5) resulting from multiple retrogressive failure events, such as recorded in the Storegga slide and other well-studied MTCs (i.e. Bryn et al., 2005; Sawyer et al., 2009; Badhani et al., 2020). The occurrence of retrogressive failure has resulted in linear to sinuous depression features in plan-view (Fig. 7B) and small-scale faults or fractures in seismic cross-sections (see headwall scarps in Fig. 8B and D).
Canyons in mass-transport complex-1

In the upper section of MTC-1, the canyon system comprises three tributaries (Canyon-1 to Canyon-3; Figs 6B and 7B), which terminate to the scarps near the shelf edge (Fig. 6B). Canyon-1 and Canyon-2 are developed in the north-eastern part of MTC-1, while Canyon-3 is in the north-western part (Fig. 7B). Canyons 1 to 3 have more pronounced seabed erosion than MTC-1. Near HS-5, clear seabed incision and truncations can be observed in the seismic sections that image the canyons (Fig. 8A and B). Canyons 1 to 3 have a linear geometry in map view. The cross-sectional geometry of the canyons is generally U-shaped, with a gently sloping base surface (ca 1°) and steep canyon sidewalls (ca 60°) (Fig. 8B and C). Canyons 1 to 3 trend downslope from the continental shelf towards HS-5 and converge near HS-3 (the confluence point; Fig. 7B and C); ultimately converging into a broad canyon after passing through HS-2, at a water depth of 1522 to 1595 m (Figs 7B, 7C and 8D). Numerous crescentic bedforms and axial incisions are observed along the axis of Canyons 1 to 3 (Fig. 7B and C). In the pre-confluence region, Canyons 1 to 3 range from ca 100 to 670 m wide and ca 20 to 134 m high (Fig. 9A and B). In the post-confluence area, the width increases from ca 370 to 1140 m, which is two to three times wider than that of the pre-confluence region (Fig. 9A). The canyon height increases from ca 90 to 140 m in the post-confluence area, slightly larger than the canyons in the pre-confluence area (Fig. 9B).

This stratigraphic relationship between canyons and MTC-1 indicate that the deposition of MTC-1 occurred prior to the initiation of canyons. The crescentic bedforms are possibly associated with supercritical currents (i.e. Zhong et al., 2015), suggesting that gravity flows are still being initiated, and canyons are remaining active as a sediment pathway today. Quantitative analyses of the canyons indicate that a strong correlation exists between the canyon width/height with distance along the different MTC-1 headwall scarps. The increase of the canyon’s width and depth after the confluence point (near HS-2) indicate that headwall scarps have played a key role in dictating the canyon morphology and incision depth. The abrupt increase in canyon width after the confluence can be interpreted as an increase in discharge, because the converged canyon can be subjected to gravity flows from multi-sources (see the similar process from Mitchell, 2004). The present study thus indicates that the topography within MTC-1 was established as a function of topographic confinement imposed by the backstep.
headwall scarps. The existence of the headwall scarps can facilitate the canyon widening and deepening process.

**Mass-transport complex-2 and Mass-transport complex-3**

MTC-2 was deposited at the west of MTC-1 (Fig. 6B), it contains four internal headwall scarps (HS-1 to HS-4; from older to younger) and associated lateral margins (Fig. 10A and B). Along the proximal part of the western lateral margin, the sidewall displays up to at least three levels of local retrogressive failures that make the west lateral margin complex (Fig. 10B). The cross-cutting relationship between MTC-1 and MTC-2 reveals that MTC-2 occurred after MTC-1. Similar to MTC-1, the multi-headwall scarps are the result of retrogressive failure events associated with the emplacement of MTC-2. MTC-3 was deposited in the west of the study area (Fig. 6B). Distinctive NNW–ESE dipping headwall scarps can only be identified near the upper boundary of MTC-3 (Fig. 10B). The number of scarps in MTC-3 are significantly less than those in MTC-1 and MTC-2 (Fig. 10B).

**Mass-transport complex-2**

Two canyons (Canyon-4 and Canyon-5) that initiated from the lower slope setting, were observed and incised across MTC-2, with a small (ca <50 m height) bathymetric expression in plan view (Fig. 10A and B). Upslope from the Canyon-4 head, a channel is observed from map view (Fig. 10B). The morphology of Canyon-4 is only visible in map view near the lower slope, and it loses surface expression at the location of HS-4 (Fig. 10B). Upslope from the Canyon-5 head, two channels are observed from map view (Fig. 10B). The morphology of Canyon-5 meanders around the headwall scarps within MTC-2, being initially WNW–SE strike at the location of HS-4 and HS-3, shifting to the south-east at the site of HS-2, and shifting again to an abrupt south-west bend at HS-1 (Fig. 10B). After passing through HS-1, Canyon-5 is oriented southward (Fig. 10B). Seismic profiles of Canyon-5 reveal a U-shaped erosional feature, and the cross-sectional morphology keeps constant along the Canyon-5 pathway (Fig. 11A to C). The width and height of Canyon-5 varies compared to Canyon-1 (Fig. 11D). The upper reach of Canyon-5 has a deeper incision and width that can reach 76 and 565 m, respectively. In the lower slope, the width of Canyon-5 decreases from 565 m to ca 370 m and increases to 750 m after passing through HS-3 (Fig. 11D). The width of Canyon-5 drops sharply to 343 m after passing through HS-1. The height of Canyon-5 constantly decreases from ca 58 m near HS-4 to ca 44 m near HS-1 (Fig. 11D). In summary, from HS-4 to HS-1, Canyon-5 becomes narrower and less incised.

Limited distribution of Canyon-4 indicates that the canyon incision has been isolated to the lower slope. The rapid shifting of the Canyon-5 pathway orientations indicates that the presence...
of headwall scarps can influence and divert canyon transport direction. Canyon-5 has a clear backstep (landward) incision and connects with the shelf edge headwall scarp by channels, and this might suggest that Canyon-5 is still active during the Holocene. This study suggests that, with the headward incision associated with Canyon-5, once the canyon head connects to shelf edge headwall scarps, it will develop into a ‘mature’ stage akin to the canyons in MTC-1.

Canyons in mass-transport complex-3

Two canyons (Canyon-6 and Canyon-7) are observed in MTC-3 (Fig. 10B). The morphology of Canyon-6 is only visible close to the lower slope (Fig. 10B). Further downslope, Canyon-6 loses its morphology in map view, and there is no visible canyon form in the seismic section (Fig. 12B and C). Canyon-7 has a tripartite, concave head that cuts ca 7 km landward into the shelf (Fig. 10B). The cross-sectional geometry of Canyon-7 shows a clear V-shaped incision (Fig. 12A and B). However, this V-shaped downcutting geometry is only constrained in the lower slope region. The width and height of Canyon-7 are low in the lower slope setting, ranging from ca 120 to 175 m and ca 20 to 50 m, respectively (Fig. 12D).

Canyon-6 and Canyon-7 have a broad flat canyon floor, with less signs of incised channels. The flat canyon floor might indicate that the gravity flow contributes to the formation of canyons have been largely displaced due to the absence of headwall scarps. Moreover, due to the absence of the scarps, Canyon-6 and Canyon-7 show a low sinuosity and a subparallel pathway. No major canyon diverting nor converging has been observed in the MTC-3 region (Fig. 10B).

DISCUSSION

Origin of the canyons

Based on the morphology and depositional process, submarine canyons can be classified into two main types (Type I and Type II from Jobe et al., 2011). Type I canyons normally indent
Fig. 11. (A) Seismic cross-section cutting through HS-5 and HS-4 of MTC-2, showing the upper part of Canyon-4 and Canyon-5. (B) Seismic cross-section cutting through HS-2 of MTC-2, showing the proximal part of Canyon-5. (C) Seismic cross-section cutting through MTC-2, showing the distal part of Canyon-5. See the location of (A) to (C) in Fig. 10A. (D) Width and height profile of Canyon-5 in MTC-2.

Fig. 12. (A) Seismic cross-section cutting through the headwall of MTC-3, showing the upper part of the Canyon-7. (B) Seismic cross-section showing the proximal part of the Canyon-6 and Canyon-7. (C) Seismic cross-section showing the distal part of Canyon-6 and Canyon-7. See the location of (A) to (C) in Fig. 10A. (D) Width and height profile of the Canyon-7 in MTC-3.
the shelf edge and are linked with a clear bathymetric connection to fluvial systems. These canyons can receive abundant coarse-grained sediment supply and generate erosive canyon morphologies (Jobe et al., 2011). Type II canyons normally indent the continental slopes, and they do not have a clear bathymetric connection to fluvial systems (thus a low sediment supply). Therefore, the Type II canyons normally exhibit smooth and aggradational morphologies (Jobe et al., 2011). In this study, the study area is disconnected from the modern fluvial system (Leach & Wallace, 2001), which indicates a limited sediment input at or near the canyon heads. The canyons are thus sediment starved when compared with canyons connected to direct fluvial input (for example, the Type I canyons) or canyons which are in close proximity to high supplies of coarse-grained sediment (Smith et al., 2018). Similar canyons (for example, the Type II canyons) that are isolated from major river input, with linear morphology of low sinuosity, have been documented from other margins (e.g. Harris & Whiteway, 2011; Jobe et al., 2011). The initiation of the Type II canyons is connected to local failures near continental margins or slopes, which is independent of sediment input (i.e. river feed) and sea-level fluctuation (Normandeau et al., 2014). Other triggers, such as mixed constructions and modification by turbidity and contour currents near the canyon heads have also been suggested as potential initiation mechanisms for Type II canyons (i.e. Jobe et al., 2011). This has also been inferred for canyons in the South China Sea (Zhu et al., 2010) and other submarine localities (i.e. Rebesco et al., 2007). In this study, the morphology of the canyon heads is strictly constrained within the headwall scarps near the shelf edge (Fig. 13A and B). The spatial relation between the shelf edge headwall scarps and canyon heads suggests that the initiation of canyons is closely related to these pre-existing, steep shelf edge headwall scarps (Fig. 13A and B). Moreover, as the contour current is active near the shelf edge area, the movement of the contour current along the topographically low scarps may induce local turbulence and produce down-canyon sediment transportation (i.e. Fenner et al., 1971; Warratz et al., 2019). Thus, the present study suggests that the canyon systems in the study area are initiated by a combination of multistage

![Fig. 13.](image-url)
retrogressive failure events and contour current activity near the pre-existing headwall scarps at the continental shelf edge (Fig. 13C). Although the study area lacks river-sourced sediments, canyon heads can still capture sediments from local failures associated with the contour current activities. These local failures and the associated gravity flows can erode the seabed and facilitate canyon development from upper slope to lower slope (Fig. 13D) (see also similar processes from Atlantic canyons; Twichell & Roberts, 1982). Other factors, such as cyclones (hurricane or typhoon) and tidal currents occurring in the continental shelf area, may also contribute to canyon initiation (Shepard et al., 1974; Sequeiros et al., 2019). Hurricanes and typhoons can trigger waves and currents, thus resuspending and carrying sediment. These processes will directly play a role in initiating turbidity currents, which bring sediments into the canyon heads and enhance the canyoning process (Sequeiros et al., 2019). Tidal currents can act as an efficient force for reworking and carrying sediments in submarine settings (Shepard et al., 1974). Tidal currents can thus transport sediments into the canyon heads, especially at places where fluvial input is missing.

Role of the retrogressive failure mechanism on canyon evolution

The headwall scarps of MTCs play an essential role in capturing turbidity currents and facilitating turbidity channelization in submarine settings, as demonstrated by examples from previous seismic and outcrop-based studies (Loncke et al., 2009; Alves & Cartwright, 2010; Ito, 2013; Qin et al., 2017; Li et al., 2020). The three MTCs presented in this study have indicated that the spatial variation of canyon morphology is linked with the MTCs morphometric characteristics. This study further splits these MTCs into two types based on their morphology (Type-1 and Type-2; Table 1). Type-1 MTCs (for example, MTC-1 and MTC-2) are characterized as having multiple internal headwall scarps, and Type-2 MTCs (for example, MTC-3) are characterized with no visible internal headwall scarps. The following section attempts to define the possible mechanisms influencing different types of MTCs and their impact on canyon evolution.

For Type-1 MTCs, the retrogressive failure events associated with MTC-1 have left a pronounced negative seabed space that greatly changed the slope morphology and created a series of localized seabed ‘ponding’ accommodation spaces along the pathway of submarine canyon systems. The gravity-driven downslope processes are sensitive to the slope gradient variations, preferentially depositing where the gradient decreases the most (Kneller et al., 2016). The varied hierarchies of headwall scarps can therefore trap or divert subsequent turbidity currents and facilitate canyon systems’ incision and development. Although the headwall scarps within MTC-2 do not widen nor deepen canyons that are transported through, they do play an essential role in changing the canyon direction. Type-2 MTCs have less influence on the canyoning process, providing a different example of how headwall scarps can influence canyon evolution. MTC-3 demonstrates that an absence of internal headwall scarps produces a lack of ability to trap or capture the turbidity currents that flow through. Although Canyon-7 has connections to the shelf edge headwall scarps, the scale of the canyon is smaller than those in the other two MTCs (i.e. Canyon-3 in MTC-1; Fig. 6A and B). Therefore, this study indicates that the retrogressive failure mechanism of MTCs is responsible for the canyon deepening and confluence process, which can greatly influence the canyon morphology.

| Table 1. Classification of MTCs and their influence on the canyon evolution (note that MTCs is the abbreviation of mass-transport complexes, and HS equals headwall scarps). |
|-----------------|-----------------|-----------------|-----------------|
| Classification  | MTC              | Headwall scarps | Canyons         | Influences imposed on canyons                        |
| Type-1          | MTC-1            | HS-1 to HS-5    | Canyons 1 to 3  | Canyon confluence, widening and deepening            |
|                 | MTC-2            | HS-1 to HS-5    | Canyon-5        | Canyon transport direction diversion                  |
| Type-2          | MTC-3            | None            | Canyons 6 and 7 | No canyon confluence nor diversion                    |

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sediiments strength, thus the susceptibility to erosion during the formation of canyons (Covault et al., 2007); (ii) the sea-level variation, which can vary sediment input into canyon heads (Vail, 1977; Posamentier et al., 1991); and (iii) downslope and along-slope depositional processes (i.e. gravity flows and contour currents), which erode the seabed and enlarge submarine canyons (Pratson & Coakley, 1996; He et al., 2014; Miramontes et al., 2020).

In this study, tectonics is unlikely to be of significance for canyon development due to the relatively stable nature of the southern Australian passive margin. Sediments in such a stable setting typically exhibit lower shear strength as compared to their active margin counterparts (Sawyer & DeVore, 2015; DeVore & Sawyer, 2016). In active margins, the higher sediment shear strength is interpreted to be due to the repeated exposure to earthquake energy that gradually increases shear strength by shear-induced compaction and dewatering processes (i.e. seismic strengthening, sensu Sawyer & DeVore, 2015). Therefore, the absence of intense tectonics and seismicity may have a significant role in preconditioning slope failures in passive margins, resulting in widely distributed MTCs (i.e. Sawyer & DeVore, 2015; DeVore & Sawyer, 2016). Recent studies have revealed that the canyon initiation process does not necessarily depend on sea-level rise and fall, because well-developed canyon systems have been identified during highstands in many submarine settings (i.e. Xu et al., 2010; Paull et al., 2013; Normandeau et al., 2015). In the study area, the modern canyons are contiguous with Pliocene canyon systems, showing similar geometries and slightly eastward migrated distribution patterns. The similarities between buried Pliocene and modern canyons indicate that the location and distribution of modern canyons are an extension of the infilled Pliocene canyon systems. The overall eastward canyon lateral migration during Pliocene–Recent is interpreted to be related to the eastward shelf break parallel palaeocurrent (i.e. South Australia Current or Zeehan Current), which is still active near the current-day shelf edge (Godfrey et al., 1986). Moreover, the present study suggests that the types of the underlying deposits can also influence the morphology of the canyons. For example, Canyon-1 to Canyon-3 deposit above the slope background deposits (Fig. 8B), while Canyon-6 deposits above a buried MTC (Fig. 12C). The quantitative analyses reveal that the scale of Canyon-1 to Canyon-3 (immediately above background deposits) is larger than that of the Canyon-6 (immediately above buried MTCs). The scale contrast is interpreted to be due to buried MTCs, which are typically more consolidated than undeformed background slope deposits (i.e. Shipp et al., 2004; Sawyer, 2007; Wu et al., 2021). Thus, the incision depth and scale of Canyon-6 is smaller than other canyons.

**Canyon evolution model**

This study attempts to build an updated model of canyon formation based on the models proposed by Pratson & Coakley (1996) and Jobe et al. (2011), emphasising the role of headwall scarps associated with regionally distributed MTCs. The model herein consists of three phases, the occurrence of retrogressive failures, the initiation stage of the canyons and the canyon transition stage.

**Phase 1: the occurrence of retrogressive failures**

Prevailing eastward-flowing contour currents continuously deposit sediment near the shelf edge (Fig. 14A). Seismicity (i.e. Bornhold & Prior, 1989), sediment overloading generated overpressure (i.e. Dugan & Flemings, 2000), or tectonic oversteepening (i.e. Moscardelli et al., 2006), or other triggering mechanisms (i.e. Tal ling et al., 2014) activated the initial failures in the lower slope setting (Fig. 14A). The initial failure creates an open scarp, that leaves the sediments in the up-dip area unstable. As the gravitational strain accumulates, the sediments near the initial scarp weaken. A new extensional failure (the second scarp) will occur behind the initial scarp once the sediments become weaker than the along-slope gravity-induced stress (Fig. 14A). The failure process will continue up-dip until final balance has been achieved between the shear strength of the slope sediments and the shear stress of the gravitational forces (Fig. 14B and C; Sawyer et al., 2009). This retrogressive failure mechanism has left a series of headwall scarps and lateral scarps on the continental shelf and slope (Fig. 14C). The scarprich environment represents the preliminary phase of canyon initiation.

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

The erosional processes near the headwall scarps have led to triangular-shaped canyon heads (Fig. 14D). The failed sediments
Fig. 14. Schematic figure showing the evolution model of the canyon system in the study area. (A) The schematic figure shows that the initial failure was created in the lower slope area, and a series of headwall scarps occurred updip of the initial failure. (B) The schematic figure shows the deposition of contourite drifts near the shelf edge, and the occurrence of slope attached MTCs near the lower slope. (C) The schematic figure shows the retrogressively failed MTCs and widely distributed headwall scarps in the continental shelf and slope settings. (D) The schematic figure shows that canyons were captured, converged and re-directed by the pre-existing headwall scarps.
associated with erosional processes near the shelf edge could excavate the pre-existing headwall scarps and contribute to the initial sediment influx for canyon initiation (see the similar process from Pratson & Coakley, 1996; Puga-Bernabéu et al., 2011). There are other erosional processes that could also account for the initial sediment influx, and therefore may have also contributed to canyon initiation. Firstly, sediments collapsed from the canyon sidewalls (canyon flank failures) can form downslope-flowing turbidity currents, facilitating the canyon flushing process. The failure events associated with the pre-existing headwall scarps and canyon sidewalls allow the delivery of sediment, enabling canyon formation and downward incision (Pratson & Ryan, 1994; Pratson & Coakley, 1996; Armitage et al., 2010). Secondly, contourites may fail periodically, due to the seasonal cyclone (hurricane or typhoon) activities, or sediment overpressure generated by rapid deposition of fine-grained sediments (Sequeiros et al., 2019; Brackenridge et al., 2020; Gatter et al., 2020). The periodical failure processes can create local turbulence near the shelf edge headwall scarps, which further facilitate the formation of flows that carry sediments into the canyon heads (Fig. 14D).

Phase 3: the canyon transitional stage
With the continuous failures near the shelf edge headwall scarps, the canyon heads gradually establish into triangular or dendritic shapes. These triangular or dendritic shape structures facilitate canyon head capture and funnel larger volumes of sediments into the canyon, and the canyoning process becomes self-propagating (Fig. 14D). The failed sediments near the headwall scarps in the continental shelf converged into the channel-shaped conduit, acting as catchment areas for sediments. Downward sediment gravity flows generated by the failed sediments can contribute significantly to the ongoing canyon excavation and downslope propagation (Popescu et al., 2004; Baztan et al., 2005). The presence of the headwall scarps on the slope provide further sediment input and canyon tributary convergence (Fig. 14D). The canyons are thus progressively propagating to the lower slope and abyssal plain.

Implication
Many studies have shown how the rugose top surface of submarine MTCs can capture/reroute subsequent sediment pathways based on seismic data (Loncke et al., 2009; Ortiz-Karpf et al., 2015; Qin et al., 2017) and outcrops (Armitage et al., 2009; Jackson & Johnson, 2009; Kneller et al., 2016). These studies are examples of MTCs located near the shelf edge where the sediment supply is high. The rugose top surfaces developed along the upper surface of MTCs is caused by the cohesive nature of the failures, along with the presence of internal structures, such as megaclasts, fold-thrust systems, and pressure ridges (see Bull et al., 2009; Steventon et al., 2021). The rugose topography can be healed quickly by subsequent sand-rich turbidity currents or separate failures. Thus, MTCs have a direct influence on the location and distribution of reservoirs and important implications for hydrocarbon exploration.

Conversely, the present study documents MTCs in low sediment supply margins where large-scale sediment bypass is missing. This study shows strong evidence that the emplacement of MTCs has played a key role in influencing the evolution of canyon systems; and develops a generic model of the MTCs headwall scarps, as a function of triggering and influencing the morphological evolution of canyons, thus controlling the sediment bypass from the shelf edge to lower slope and abyssal plain. The study indicates that retrogressive failure mechanisms can facilitate long-distance sediment transportation within canyon systems, and may be a common process in a submarine setting where modern river systems are absent.

Previous studies have revealed that the density of marine plastics in canyons are two to three times larger than the adjacent slopes or shelves (Pham et al., 2014; Cau et al., 2017; Kane et al., 2020). The plastic pollutants can be transported across the shelf by contour currents and delivered to submarine canyon heads formed far from terrestrial input (i.e. 150 km away from the coastline; Zhong & Peng, 2021). Therefore, canyons not only can act as a major conduit for delivering sediments, but they can also receive and transport marine plastics from shallow marine environments into the deep ocean (Kane et al., 2020).

In this study, the canyon heads are subjected to episodic turbidity currents. Therefore, they can receive sediments and plastics delivered by contour currents near the shelf edge (i.e. Kane et al., 2020; Zhong & Peng, 2021). Moreover, as the MTCs can facilitate longer transport distance of sediments and plastics within canyons into the
deep ocean, plastics delivered by canyon systems may thus have the ability to travel into the deep Southern Ocean, with associated environmental impacts (Zhong & Peng, 2021). Therefore, a combination of a high-resolution bathymetry dataset with manned submersible dives is needed to further study this subject. The high-resolution bathymetry dataset can provide detailed imaging of the seabed and better constrain the role of MTCs during the canyon evolution. The manned submersible dives can establish plastic and/or microplastic density in the deeper marine region, which will help to understand and mitigate against anthropogenic impacts on the marine environment.

CONCLUSION

This study uses multibeam bathymetry and seismic reflection data to document how the retrogressive failure mechanism of mass-transport complexes (MTCs) has influenced the origin, geometry and distribution of canyons in sediment starved submarine settings. In summary: (i) the emplacement of MTCs has left multi-scaled headwall scarps and lateral margins on the continental margin and slope area; (ii) the local failures developed associated headwall scarps near the continental shelf-edge have provided the initial sediment supply for canyon evolution; (iii) the headwall scarps which developed in the slope setting may act as the preferential pathways for sediment gravity flows and facilitate canyon development; and (iv) the study thus indicates that retrogressive failure mechanisms can facilitate long-distance sediment transportation within canyon systems in starved submarine settings.

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DATA AVAILABILITY STATEMENT

The seismic reflection data (OS02 3D survey and OS02 2D survey) and bathymetric data used in this study can be requested from the Geoscience Australia Repository https://www.ga.gov.au/data-pubs. The GEBCO_2014 bathymetry map can be downloaded from the Gridded Bathymetry Data Repository https://www.ngdc.noaa.gov/maps/autogrid/.

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Supporting Information

Additional information may be found in the online version of this article:

Appendix S1. Uninterpreted seismic sections.

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