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

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Abstract

The offshore area of the Otway Basin (SE Australia) is dominated by a multibranched canyon system where mass-transport complexes (MTCs) are widely distributed. Our study integrates high-resolution multi-beam and seismic data to investigate the importance of MTCs in dictating the evolution of canyons. Our study interprets three regionally distributed MTCs that fail retrogressively and affect almost 70% of the study area. Within the MTCs, seven canyons that initiated from the continental shelf edge and extended to the abyssal plain 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 MTCs have created a series of scarps on the continental shelf and slope regions. In the continental shelf, where terrestrial input is absent, the origin of the canyons is related to the local failures and contour current activities, occurring near the pre-existing larger headwall scarps (c. 120 m high, 3km long). The occurrence of these local failures has provided the necessary sediment input for subsequent gravity-driven, downslope sediment flows. In the continental slope region, the widespread scarps can capture gravity flows initiated from the continental shelf, developing an area of flow convergence, which greatly widens and deepens the canyon system. The gradual diversion and convergence through MTC 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 MTCs has a direct contribution to the initiation, distribution, and evolution of the canyons. The scarps associated with MTCs 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 (MTCs); Submarine canyons; Otway Basin; SE Australia

1. Introduction

Submarine canyons are defined as steep-sided V- or U-shaped valleys that erode into the seabed, they can extend from the continental shelf to the continental slope, with numerous tributaries entering from both sides (Shepard et al., 1966; Twichell and 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 and Whiteway, 2011). Canyons are often associated with sand-rich gravity flows and submarine fans are thus considered as modern analogues for deepwater hydrocarbon reservoirs (Stow and Mayall, 2000; Weimer and Slatt, 2004). Mass-transport complexes (MTCs) are gravity-driven shear failure deposits resulting from creep, spread, slide, slump and debris flow processes (Posamentier and Martinsen, 2011; Wu et al., 2021). MTCs can be extremely erosive, thus containing large volumes of sediments, with single deposits covering areas of >100 km^2 and volumes of >10,000 km^3 (Frey Martinez et al., 2005; Moscardelli and Wood, 2016; Nugraha et al., 2019). MTCs normally fail retrogressively (i.e. backstepping slope failures), the emplacement of MTCs can leave a series of giant slide scars (c.2-5 km wide) on continental slope areas (Figure 1a, 1b; 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 and Krastel, 2006; Lee et al., 2007; Urgeles and Camerlenghi, 2013).

Submarine canyons and MTCs can have a close relationship in terms of their spatial distribution, triggering mechanisms, and preconditioning factors (Micallef 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 the sidewalls to fail depositing MTCs near the canyon walls (i.e. Farre et al., 1983; Green and Uken, 2008). These intra-canyon MTCs can occur retrogressively, increasing the canyon's width (i.e. lateral extension; Pratson and Ryan, 1994) and extending the canyon upslope (i.e. headward incision; Farre et al., 1983; He et al., 2014). Most of the published works have focused on constraining local, coeval, intra-canyon MTCs (sensu detached MTCs; Moscardelli and Wood, 2008) with the evolution of canyons (i.e. Green and Uken, 2008; Gong et al., 2011; He et al., 2014; Su et al., 2020). The relationship between canyons with regional distributed MTCs (i.e. 100s to 100,000s of km^2) (senus attached MTCs; Moscardelli and Wood, 2008) that typically fails retrogressively, have largely been overlooked. Relatively little is known on how regionally distributed MTCs, especially how their retrogressive failure mechanism can influence the initiation, evolution, and morphology of submarine canyons. Therefore, this study uses a high-resolution (c. 10 m vertical resolution) 3D seismic reflection dataset, integrated with 2D seismic and multi-beam data to analyse the spatial and temporal relations between canyons and regionally distributed MTCs in the Otway Basin, south-eastern Australia (Figure 2a, 2b).

2. Geological setting

2.1 Tectonic

The offshore Otway Basin is a broadly NW-SE striking non-volcanic rift basin, located along the south-eastern Australian passive margin (Figure 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 and Stagg, 1990; Perincek and 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 (Figure 3a; Krassay et al., 2004; Holford et al., 2014).

2.2 Sedimentology

The Cenozoic sedimentary successions 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 a mixed siliciclastic-carbonate sediments) (Figure 3a; Dickinson et al., 2002; Krassay et al., 2004; Holford et al., 2014). Our study interval lies in the WBF formation at a time when the study area was in a passive continental margin setting. In the continental slope area, thick, localised sediments deposited in the Pliocene-recent succession, representing marine clastic sediments deposited in submarine canyons (Figure 3b, 3c) (Tassone et al., 2011).

2.3 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) (Figure 2b). The SAC is an eastward-flowing current with high salinity and velocity (0.5 m/s), originating from the centre of the Great Australian Bight Basin (Rochford, 1986). The current operates down to 200 m depth (Middleton and Bye, 2007). The ZC is fed by the South Australian Current, it is a poleward current with low salinity and high current velocity (0.4 m/s), flowing down to 300 m water depth (Ridgway, 2007). The offshore area of the Otway Basin is also periodically affected by seasonal hurricanes and storms (Holland and Gray, 1983; Kuleshov et al., 2002). The above mentioned down-slope and along-slope marine oceanographic processes have jointly influence the sedimentation in the Otway Basin.

As 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 (Figure 3c). As similar seismic facies have been interpreted as contourites that are affected by contourite currents in other submarine settings (i.e. Stow and 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 (Figure 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.

3. Dataset and Methodology

3.1 Multibeam Dataset

The multi-beam echosounder bathymetry data is provided by Geoscience Australia (https://portal.ga.gov.au/persona/marine), covering an area of c. 12,000 km^2 (Figure 4a). The lateral resolution of the data is 50 × 50 m, it enables the identification and interpretation of seafloor morphology and associated canyons and MTCs, especially in areas absent of seismic-reflection data (Figure 4a).

3.2 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 SE Australia (Figure 2b). The survey covers an area of c. 360 km^2 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), is c. 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.

3.3 Methodology

The seismic-stratigraphic framework is correlated with Holford et al. (2014) work in an adjacent area. Seismic and multi-beam data are used to map MTC and canyon related features. The 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; Laberg et al., 2000) (Figure 5). The canyon height is defined as the depth from the canyon shoulder to the canyon base (Figure 5).

4. Result

4.1 Morphology of the seafloor

The study area spans from the continental shelf, to slope, to abyssal plain environment (Figure 4a). The morphology of the study area is characterised as having a narrow (c. 7km) and steep slope (Figure 4b). The continental shelf area dips from 0.4° to 1° with an average water depth of 250 m (Figure 4b). The continental slope area is characterised by a relatively gentle slope of c. 10° in the upper section, to a steep slope gradient of c. 30° near the lower section, with water depths ranging from 600 m to 1500 m, respectively (Figure 4b). The multi-beam reveals several canyons initiated from the continental shelf region, spanning the continental slope, and ultimately terminating in the abyssal plain (Figure 4a). Widely-distributed MTCs and their associated headwall scarps and lateral margins have also been identified, and have a close relationship with the canyons (Figure 4a). The topographic profiles extracted from the multi-beam data in the abyssal plain show dramatic differences in the across-canyon margin morphology (Figure 4c). In the abyssal plain, where the seafloor 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 (Figure 4c, 4d). The width and the height of the canyon increases from c. 5.6- 6.6 km to c. 10.9 km, and c. 300 m to 360 m, respectively (Figure 4c, 4d). The multibeam data used in this study can only investigate the seafloor morphological features with a relatively limited lateral resolution (c. 50 m). It lacks the ability to examine the detailed seafloor structures in 3D and to reveal the characteristics of the buried sediments. Therefore, in the following section, this study use high-resolution seismic reflection datasets to investigate the cause of the canyon converging process, as well as the sedimentary process interactions between canyons and MTCs.

4.2 MTCs and canyons

Three MTCs (MTC-1, MTC-2, and MTC-3) have been interpreted in the study area (Figure 6a, 6b). Seismic data reveals several distinctive NNW-SSE oriented extensional-fault scarps, and NE-SW oriented lateral scarps near the shelf-edge, and within the slope and abyssal plain (Figure 6b). The arcuate NNW-SSE dipping extensional scarps are interpreted as MTC headwall scarps that mark the updip part of an MTC, where extensional deformation dominates (Figure 6b; i.e. Bull et al., 2009). The NE-SW dipping lateral scarps are interpreted as MTCs lateral margins that separate deformed

sediments (MTCs) from the undeformed seabed (Figure 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 (canyon 1-7) spanning from continental shelf to abyssal plain are observed within the MTC influenced area (Figure 6a, 6b). They are oriented NNW-SSW on the continental slope, sub-parallel to the dip direction of the slope. Canyon-1-3 and Canyon-7 are initiated from shelf edge headwall scarps with clear landward incision features, while Canyon-4-6 are restricted in the continental slope (Figure 6b).

4.3 MTC-1

In MTC-1, multiple headwall scarps (HS-1 to HS-5) and their associated lateral margins are observed from the map view and the correlated seismic sections (Figure 7a, 7b). Headwall scarps are recognised as upward concaved lineation with scallop-shaped geometry (Figure 7b). In the seismic dip section, the headwalls are nested in a terraced style, showing a truncated reflector that cuts through upslope sediments (Figure 8a). The heights and angles of the scarps vary considerably throughout MTC-1, with the highest (c. 170 m) and steepest (c. 40^{o}). HS-5 occurring in the upper part of MTC-1 (Figure 8b). The other four headwall scarps (HS-4 to HS-1) are comparatively smaller and gentler than HS-5, with similar morphology and distributed in the central part of the MTC-1 (Figure 8b-d). The middle part of MTC-1 has a hummocky seabed expression in map view and contains chaotic and blocky seismic facies in seismic section (Figure 7b, 8a). A clear basal shear surface with a gentle gradient (c. 3^{o}) that separates the underlying layered seismic facies from the overlying chaotic seismic facies has been observed below the HS-5 and HS-1 (Figure 8a). The chaotic and blocky facies accumulated downdip to the HS-4 and HS-1, showing a wedge-shaped geometry in seismic section (Figure 8a) and a fan shaped geometry in plain view (Figure 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. Our study thus interpret multiple headwall scarps (HS-1 - HS-5) resulting from multiple retrogressive failure events, such as recorded in the Storegga slide and other 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 (Figure 7b), and small-scale faults

or fractures in seismic cross-section (see headwall scarps in Figure 8b-d).

4.4 Canyons in MTC-1

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

This stratigraphic relationship between canyons and MTC-1 indicate that the deposition of the 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 gravity flows are still being initiated, and canyons are remaining active as a sediment pathway today. Quantitative analyses of the canyons indicate 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 the HS-3) indicate headwall scarps has played a key role in dictating the canyon morphology and erosivity. 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 similar process from Mitchell, 2004). Our study thus indicates 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.

4.5 MTC-2 and MTC-3

MTC-2 was deposited at the west of the MTC-1 (Figure 6b). MTC-2 has an E-dipping main headwall scarp located in the lower slope setting, a south-dipping western lateral margin, and its eastern lateral margin has been eroded by the MTC-1 (Figure 10a, 10b). MTC-2 contains four internal headwall scarps (HS-1 to HS-4; Figure 10b) and associated lateral margins. 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 complexed (Figure 10b). The cross-cutting relationship between MTC-1 and MTC-2 reveals MTC-2 occurred after the MTC-1. Similar to MTC-1, the multi-headwall scarps are the result of the retrogressive failure events associated with the emplacement of MTC-2. MTC-3 was deposited in the west of the study area (Figure 6b). Distinctive NNW-ESE dipping headwall scarps can be only identified near the upper boundary of the MTC-3 (Figure 10b). Scarps in MTC-3 are significantly less than those in the MTC-1 and MTC-2 (Figure 10b).

4.6 Canyons in MTC-2

Two canyons (Canyon-4 and Canyon-5) that initiated from the lower slope setting, incised across MTC-2, with a little (c. <50 m height) bathymetric expression in plain view (Figure 10a, 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 (Figure 10b). Upslope from the Canyon-5 head, two channels are observed from map view (Figure 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 SE at the site of HS-2, and shifting again to an abrupt SW bend at HS-1 (Figure 10b). After passing through HS-1, Canyon-5 is oriented southward (Figure 10b). Seismic profiles of canyon-5 reveal a U-shaped erosional feature, and the cross-sectional morphology keeps constant along the canyon-5's pathway (Figure 11a-c). The width and height of canyon-5 have a constant variation compared to Canyon-1 (Figure 11d). The upper reach of canyon-5 has a deeper incision and width that can reach 76 m and 565 m, respectively. In the abyssal plain, the width of canyon-5 decreases from 565 m to c. 370 m, and increases to 750 m after passing through HS-3 (Figure 11d). The width of Canyon-5 drops sharply to 343 m after passing through HS-1. The height of the Canyon-5 constantly decreases from c. 58 m near the HS-4 to c. 44 m near the HS-1 (Figure 11d). In summary, from the HS-4 to HS-1, the 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 Canyon-5 pathway indicates the presence of headwall scarps can influence and divert the canyon transport direction. Canyon-5 has a clear backstep (landward) incision and relates to a shelf edge headwall by channels, and this might suggest Canyon-5 is still active during the Holocene. Our study suggests with the headward incision associated with canyon-5, once the canyon head connects to shelf-edge headwall scarps, it will grow into a 'mature' stage akin to the canyons in MTC-1.

4.7 Canyons in MTC-3

Two canyons (Canyon-6 and Canyon-7) are observed in MTC-3. The morphology of Canyon-6 is only visible close to the lower slope (Figure 10b). Further downslope, the Canyon-6 lose its morphology in map view, and there is no visible canyon form in the seismic section as well (Figure 12c). The canyon-7 has a tripartite, concave head that cut c.7 km landward into the shelf (Figure 10b). The cross-sectional geometry of canyon-7 shows a clear V-shaped incision. However, this V-shaped downcutting geometry is only constrained in the lower slope region (Figure 12a, 12b). The width and the height of canyon-7 are constantly low in the abyssal plain, ranging from c. 120 m to 175 m and c. 20 m to 50 m, respectively (Figure 12d).

Canyon-6 and Canyon-7 have a broad flat canyon floor, with less apparent signs of incised channels, which might indicate that the flow contributes to the formation of canyons that 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 (Figure 10b).

5. Discussion

5.1 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 the shelf-edge and are linked with a clear bathymetric connection to fluvial systems, receiving abundant coarse-grained sediment supply and generating erosive canyon morphologies (Jobe et al., 2011). Type II canyons normally indent the continental slope, but have no clear bathymetric connection

to fluvial systems (thus a low sediment supply), exhibiting smooth and aggradational morphologies (Jobe et al., 2011). The study area is disconnected from the modern fluvial system (Leach and Wallace, 2001), which indicates a limited sediment input at or near the canyon heads. The canyons are thus sediment starved when compared to canyons connected with direct fluvial input (e.g. the Type I canyons) or have a high supplies of coarse grained sediment (Smith et al., 2018). Similar canyons (e.g. the Type II canyons) that being isolated from major river input, with linear morphology of low sinuosity, have been documented from other margins (e.g. Harris and Whiteway, 2011; Jobe et al., 2011). The initiation of the type II canyons are connected to the local failures near continental margins or slopes, which is independent of sediment input (i.e. river feed) and sea-level fluctuation (i.e. Normandeau et al., 2014). Other triggers, such as a mixed constructions and modification by turbidity and contour currents near the canyon heads, have also been suggested to the initiation of Type II canyons (i.e. Jobe et al., 2011). As inferred by canyons in the South China Sea (Zhu et al., 2010), and other submarine settings (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 (Figure 13a, 13b). The spatial relation between the shelf-edge headwall scarps and canyon heads suggests the initiation of canyons is closely related to these pre-existing, steep shelf-edge headwall scarps. 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, our study suggests that the canyon systems in the study area are initiated by a combination of multistage retrogressive failure events and contour current activity near the pre-existing headwall scarps (Figure 13c). Although the study area lacks river-sourced sediments, canyon heads can capture sediments from local failure events associated with gravity flows that erode the seabed and form canyons downslope (Figure 13d) (see also similar process from Atlantic canyons; Twichell and Roberts, 1982). Other factors, such as hurricanes, typhoons 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 the turbidity currents, which bring the 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 river input is missing.

5.2 Role of retrogressive failure mechanism on canyon evolution

The headwall scarp of MTCs play an essential role in capturing turbidity currents and facilitating turbidity channelization in submarine settings, as proved by examples from previous seismic- and outcrop-based studies (Loncke et al., 2009; Alves and Cartwright, 2010; Ito, 2013; Qin et al., 2017; Li et al., 2020). The three MTCs presented in this study have indicated the spatial variation of canyon morphology is linked with the MTCs morphometric characteristics. This study further splits these MTCs into two types (Type-1 and Type-2; Table 1) based on their morphology. Type-1 MTCs (e.g. MTC-1 and MTC-2) are characterised as having multiple internal headwall scarps, and the Type-2 MTCs (e.g. MTC-3) are characterised with no visible internal headwall scarps. In the following section, our study 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 seafloor space that greatly changed the slope morphology and created a series of localised seafloor 'ponding' accommodations along the pathway of submarine canyon systems. The gravity-driven downslope processes are sensitive to the slope gradient variations, preferentially deposited 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. Though the headwall scarps within MTC-2 does not widen nor deepen canyons that are transported through, they do play an essential role in changing the canyon direction. Compared to Type-1 MTCs, the Type-2 provides a reversed example of how headwall scarps influence the canyon evolution. Within MTC-3, due to the lack of internal headwall scarps, and hence a lack of ability to trap or capture the turbidity currents that flow through. Though 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; Figure 6a, 6b). Therefore, our study indicates the retrogressive failure mechanism of MTCs is responsible for canyon deepening and confluence process, which can greatly influence the morphology of the canyons.

5.3 Other factors that may influence the evolution of the canyon

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

345 including (i) regional tectonics (i.e. regionally distributed faults), which influence the sediments
346 strength, thus the susceptibility to erosion during the formation of canyons (Covault et al., 2007);
347 (ii) the sea-level variation, which can boost sediment input to canyon heads (Vail, 1977;
348 Posamentier et al., 1991); (iii) downslope and along-slope depositional processes (i.e. gravity flows
349 and contour currents), which erode seafloor and enlarge submarine canyons (Pratson and Coakley,
350 1996; He et al., 2014; Miramontes et al., 2020).
351 In this study, tectonics is unlikely to be of significance for canyon development due to the relatively
352 stable nature of the southern Australian continental margin. The absence of intense tectonics and
353 seismicity may thus have a significant role in the preconditioning of the widely distributed MTCs,
354 as seismicity can actually strengthen sediments and increase stability (i.e. Sawyer and DeVore,
355 2015; DeVore and Sawyer, 2016). Recent studies revealed that the canyon initiation process does
356 not necessarily depend on the sea-level rise and fall, as well-developed canyon systems have been
357 identified during the sea-level rise in many submarine settings (i.e. Xu et al., 2010; Paull et al., 2013;
358 Normandeau et al., 2015). In the study area, the modern canyons are contiguous with Pliocene
359 canyon systems, showing similar geometry and slightly eastward migrated distribution patterns.
360 The similarities between buried Pliocene and modern canyons indicate that the location and
361 distribution of modern canyons are an extension of the infilled Pliocene canyon systems. The
362 overall eastward canyon lateral migration during Pliocene-Recent is interpreted as related to an
363 eastward shelf break parallel paleocurrent (i.e. SAC or LC), which is still active near current-day
364 shelf-edge (Godfrey et al., 1986). Moreover, our study suggests that the types of the underlying
365 deposits can also influence the morphology of the canyons. For example, Canyon-1 to Canyon-3
366 deposit above the slope background deposits (Figure 8b), while Canyon-6 deposits above a buried
367 MTC (Figure 12c). The quantitative analyses reveal that the Canyon-1 to Canyon-3 (immediately
368 above background deposits) are tentatively larger than that of the Canyon-6 (immediately above
369 buried MTCs). This is interpreted as buried MTCs, which are normally more consolidated than
370 undeformed background slope deposits (i.e. Shipp, 2004; Sawyer, 2007; Wu et al., 2021). Thus, the
371 erosivity and scale of the Canyon-6 are smaller than other canyons.
372 *5.4 Canyon evolution model*
373 Our study attempts to build an updated model of canyon formation based on the models proposed
374 by Pratson and Coakley (1996) and Jobe et al. (2011) emphasising the role of headwall scarps

associated with the regional distributed MTCs. Our model consists of three phases, MTC deposition, canyon initiation, and canyon transition.

Phase 1: MTCs deposition

Prevailing eastward-flowing contour currents are continuously depositing sediment near the shelf edge (Figure 14a). Earthquakes (i.e. Bornhold and Prior, 1989), sediment overloading generated overpressure (i.e. Dugan and Flemings, 2000), or tectonic oversteepening (i.e. Moscardelli et al., 2006) may have triggered the initial failures in the lower slope setting. The initial failure creates an open scarp, that leaves the sediments in the up-dip part unstable. As the gravitational strain accumulates, the sediments that 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 (Figure 14a). The failure process will continue up-dip until the final balance between the shear strength of the slope sediments and the shear stress of the gravitational forces (Sawyer et al., 2009). This retrogressive failure mechanism has left a series of headwall scarps and lateral scarps on the continental shelf and slope. The scarp-rich environment represents the initial phase of canyon initiation (Figure 14b).

Phase 2: the initial stage of the canyon system

The erosional processes near the headwall scarps have led to triangular-shaped canyon heads (Figure 14c). The failed sediments 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 and Coakley, 1996; Puga-Bernabéu et al., 2011). Once the canyon has been initiated, sediments collapse from the canyon sidewalls (canyon flank failures) forms downslope flowing turbidity currents, facilitating the canyon flushing process. The failure events associated with headwall scarp and canyon sidewalls permitted the delivery of enough material to enable canyon formation and downward incision. Thus, the initiation mechanism for canyons is the failure of sediments at the headwall scarps of the continental shelf and the downslope eroding flows (Figure 14c) (see also similar process documented by: Pratson and Ryan, 1994; Pratson and Coakley, 1996; Armitage et al., 2010). The mounded shape geometry contourites may fail periodically (e.g. due to seasonal hurricanes or typhoons, contourite deposits creating slope over-steepening, or sediments overpressure generated by rapid deposition of fine-grained contourites) creating local turbulence near the shelf-edge headwall scarps, which further

facilitate the formation of flows that carry sediments into the canyon heads (Figure 14b, 14c; Sequeiros et al., 2019; Brackenridge et al., 2020; Gatter et al., 2020).

Phase 3: 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 (Figure 14c). The failed sediments near the headwall scarps in the continental shelf converged into the channel-shaped conduit that is acting as catchment areas for the canyon evolution. Downward sediment gravity flow 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 settings provided further acceleration and canyon tributary convergence. The canyons are thus progressively propagating to the far side of the lower slope and abyssal plain.

5.5 Implication

Many studies have shown how submarine MTCs rugose top surface 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 and Johnson, 2009; Kneller et al., 2016). These studies are examples of MTCs locates 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 presence of the internal rafted blocks. The rugose topography can be healed quickly by subsequent sand-rich turbidity currents or separate failures. Thus, MTCs have a direct influence in the location and distribution of reservoirs and important implications for hydrocarbon exploration.

Conversely, our study documents MTCs in low sediment supply margins where large-scale sediment bypass is missing. Our study showed strong evidence that the emplace of MTCs has played a key role in influencing the morphology evolution of canyon systems. Our study 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 further abyssal plain. Our study indicates that the retrogressive failure mechanism can facilitate long-distance sediment transportation within canyon systems, and it may be a common and important process in a submarine setting where modern river systems are absent.

Previous studies have revealed that the density of marine plastics in canyons are 2-3 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 and Peng, 2021). Therefore, canyons not only can act as a major conduit for delivering sediments, but they can also receive and carry marine plastics from shallow marine 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 as well as plastics delivered by contour currents near the shelf edge (i.e. Kane et al., 2020; Zhong and 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 and 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 seafloor, and can better constrain the role of MTCs play 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.

6. Conclusion

This study uses multi-beam bathymetry and seismic reflection data to document how the retrogressive failure mechanism of MTCs and related headwall scarps have influenced the origin, geometry, and distribution of canyons in a coarse-grained sediment starved submarine setting. In summary: (i) the emplacement of MTCs have 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, (iv) our study thus indicates that retrogressive failure mechanism can facilitate long-distance sediment transportation

463 and marine plastics within canyon systems in starved submarine settings.

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468 Data Availability

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

473 Figure Captions

474 Figure 1. (a) Model showing the time evolution of retrogressively failed MTCs, modified from
475 Sawyer et al. (2009). (b) Schematic sketch showing the different stages of a retrogressive failure,
476 modified from Locat et al. (2011).
477 Figure 2. (a) Regional map of the study area. (b) Zoom in map of the study area showing the location
478 of the city Portland and the Otway Basin. The white lines represent 2D seismic reflection data, and
479 the red polygon represents the location of the 3D seismic reflection dataset. Shaded relief
480 GEBCO_2014 bathymetry map downloaded from https://www.ngdc.noaa.gov/maps/autogrid/.
481 Abbreviations for the Otway Basin are as follows: SAC: South Australia Current, ZC: Zeehan Current.
482 Figure 3. (a) Stratigraphic and basin event chart for the Otway Basin (modified after Krassay et al.,
483 2004), including lithology interpretation and major tectonic events. The Horizon H1 has been
484 correlated to the intra-Maastrichtian unconformity surface from Holford et al. (2014). The Horizon
485 H2 is corelated to the base of the WBF. (b) Regional along slope seismic section showing the overall
486 tectonic of the study area. See location from Figure 2b. (c) Regional seismic section that

perpendicular to the slope, showing the key seismic horizons (H1 to seabed) and canyon bearing intervals. See location from Figure 2b.

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

Figure 5. Schematic diagram showing the morphological parameters used in the quantitative analyses of the canyons, including the width and height. (a) Uninterpreted cross-section of the canyon system. (b) Interpreted cross-section of the canyon system with parameters used in quantitative analyses.

Figure 6. (a) Contoured seafloor map of the study area extracted from the 3D seismic reflection data. (b) Schematic representation of seafloor geomorphologic interpreted from Figure 6a. See the location of this figure from Figure 2b.

Figure 7. (a) Zoomed in contoured seafloor map showing the region of MTC-1. (b) Interpreted map of Figure 7a, showing the major headwall scarps in MTC-1 and the location of Canyon-1, Canyon-2, and Canyon-3. (c) 3D view of the canyon confluence geometry in MTC-1, and the crescentic bedforms within canyons. See the location of Figure 7c in Figure 7b.

Figure 8. (a) The N-S oriented seismic section of MTC-1 shows backstep shaped headwall scarps and MTC-1's basal shear surface. (b) Seismic cross-section cutting through HS-5 and HS-4, showing the cross-section of the upper part of the Canyon-1, Canyon-2, and Canyon-3. (c) Seismic cross-section cutting through HS-3, showing the cross-section of the proximal part of the Canyon-1, Canyon-2, and Canyon-3. (d) Seismic cross-section cutting through HS-2 and HS-1, showing the cross-section of the post confluence part of the canyon system in MTC-1. See the location of Figure 8a-d in Figure 7a.

Figure 9. (a) Width profile of the canyon system in MTC-1. (b) Height profile of the canyon system in MTC-1.

Figure 10. (a) Zoomed in contoured seafloor map showing the location of MTC-2 and MTC-3. B)

Interpreted map of Figure 10a, showing the headwall scarps in MTC-2 and MTC-3, and the location of Canyon-4, Canyon-5, Canyon-6, and Canyon-7.

Figure 11. (a) Seismic cross-section cutting through HS-5 and HS-4 of MTC-2, showing the upper part of the Canyon-4 and Canyon-5. (b) Seismic cross-section cutting through HS-2 of MTC-2, showing the proximal part of the Canyon-5. (c) Seismic cross-section cutting through MTC-2, showing the distal part of Canyon-5. See the location of Figure 11a-c in Figure 10a. (d) Width and height profile of the Canyon-5 in MTC-2.

Figure 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 Figure 12a-c in Figure 10a. (d) Width and height profile of the Canyon-7 in MTC-3.

Figure 13. (a) 3D view of seafloor morphology showing the head of Canyon-5 and Canyon-7, and the headwall scarps occurring on the shelf-edge. See location in Figure 5a. (b) 3D view of seafloor morphology showing the head of Canyon-3, and the headwall scarps occurring on the shelf-edge. See the location of Figure 13a-b in Figure 6a. (c) Sketch of 2D view of seafloor morphology showing the headwall collapse and the initial stage of canyon evolution on shelf-edge. (d) Sketch of 2D view of seafloor morphology showing the formation of the canyons.

Figure 14. Schematic figure showing the evolution model of the canyon system in the study area. (a) Schematic figure showing that the deposition of contourite drifts near the shelf-edge, and the occurrence of slope attached MTCs and associated headwall scarps near the lower slope. (b) Schematic figure showing that the retrogressively failed MTCs and widely distributed headwall scarps in the continental shelf and slope settings. (c) Schematic figure showing that canyons were captured, converged and re-directed by the pre-existing headwall scarps.

Table Caption

Table 1. Classifications of MTCs and their influence on the canyon evolution.

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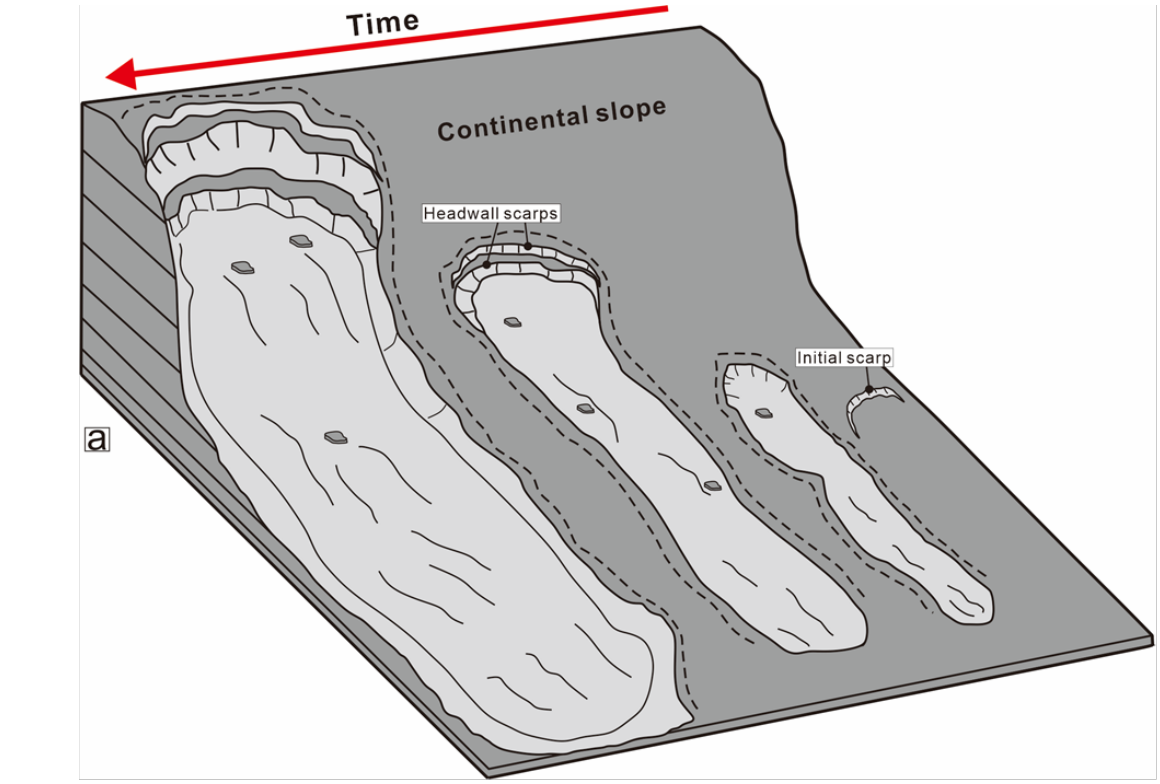
Figure 1


Time
Continental slope
Headwall scarps
Initial scarp
a

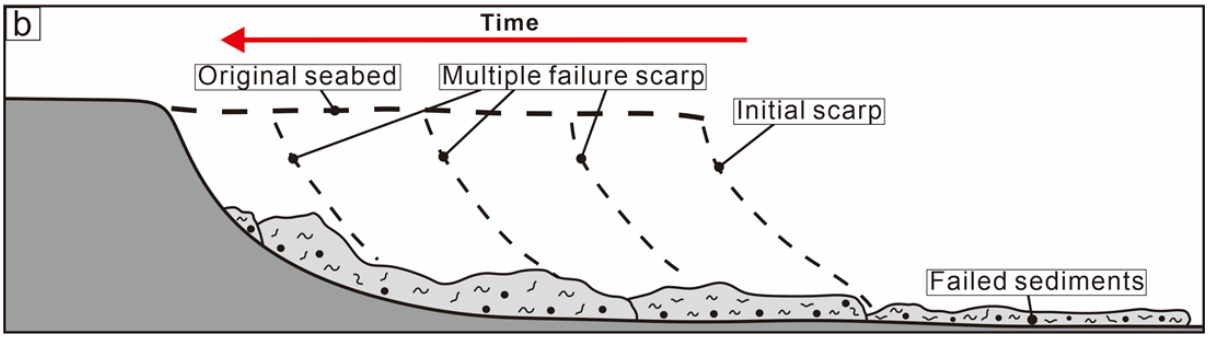

b
Time
Original seabed
Multiple failure scarp
Initial scarp
Failed sediments

Figure 2

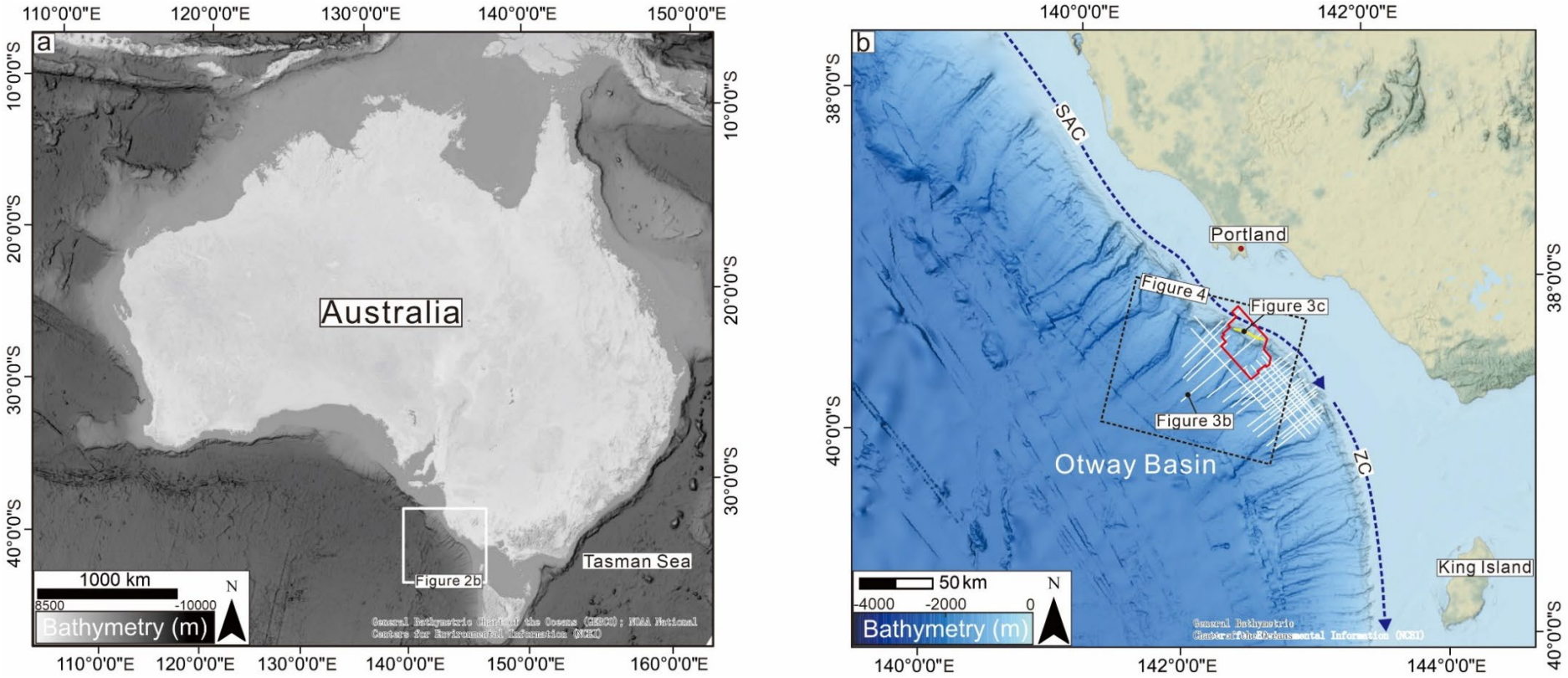

a
110°0'0"E
120°0'0"E
130°0'0"E
140°0'0"E
150°0'0"E
160°0'0"E
10°0'0"S
20°0'0"S
30°0'0"S
40°0'0"S
Australia
Tasman Sea
Figure 2b
1000 km
8500
-10000
N
Bathymetry (m)
b
140°0'0"E
142°0'0"E
144°0'0"E
38°0'0"S
40°0'0"S
SAC
Portland
Figure 4
Figure 3c
Figure 3b
Otway Basin
ZC
King Island
50 km
-4000
-2000
0
N
Bathymetry (m)

Figure 3

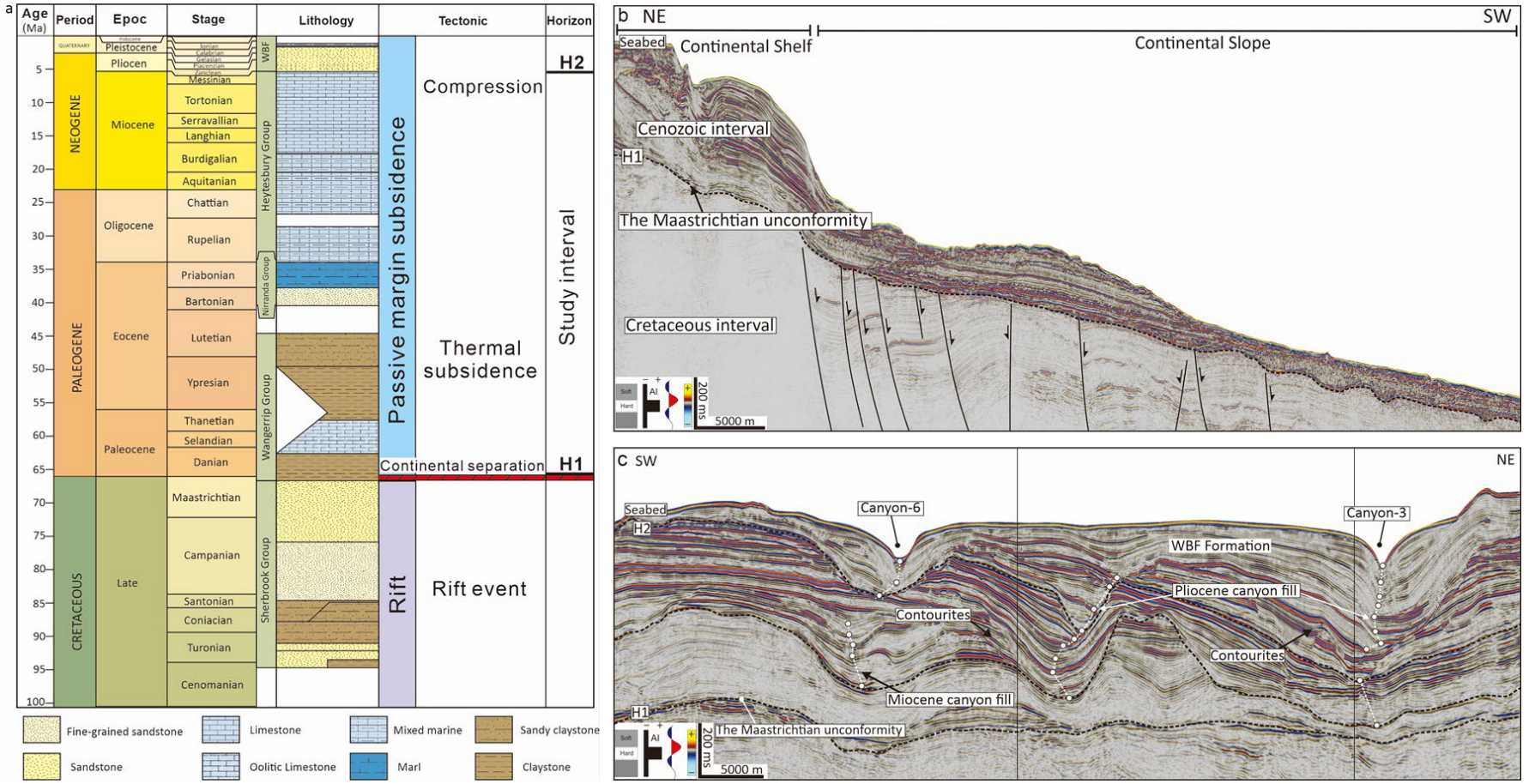

a
Age (Ma)
Period
Epoc
Stage
Lithology
Tectonic
Horizon
QUATERNARY
NEOGENE
PALEOGENE
CRETACEOUS
Pleistocene
Pliocen
Miocene
Oligocene
Eocene
Paleocene
Late
Messinian
Tortonian
Serravallian
Langhian
Burdigalian
Aquitanian
Chattian
Rupelian
Priabonian
Bartonian
Lutetian
Ypresian
Thanetian
Selandian
Danian
Maastrichtian
Campanian
Santonian
Coniacian
Turonian
Cenomanian
WBF
Heytesbury Group
Nirranda Group
Wangerrip Group
Sherbrook Group
Passive margin subsidence
Rift
Compression
Thermal subsidence
Rift event
Study interval
Continental separation
H2
H1
Fine-grained sandstone
Sandstone
Limestone
Oolitic Limestone
Mixed marine
Marl
Sandy claystone
Claystone
b NE
SW
Seabed
Continental Shelf
Continental Slope
Cenozoic interval
H1
The Maastrichtian unconformity
Cretaceous interval
200 ms
5000 m
c SW
NE
Seabed
H2
Canyon-6
Canyon-3
WBF Formation
Pliocene canyon fill
Contourites
Contourites
Miocene canyon fill
H1
The Maastrichtian unconformity
200 ms
5000 m

Figure 4

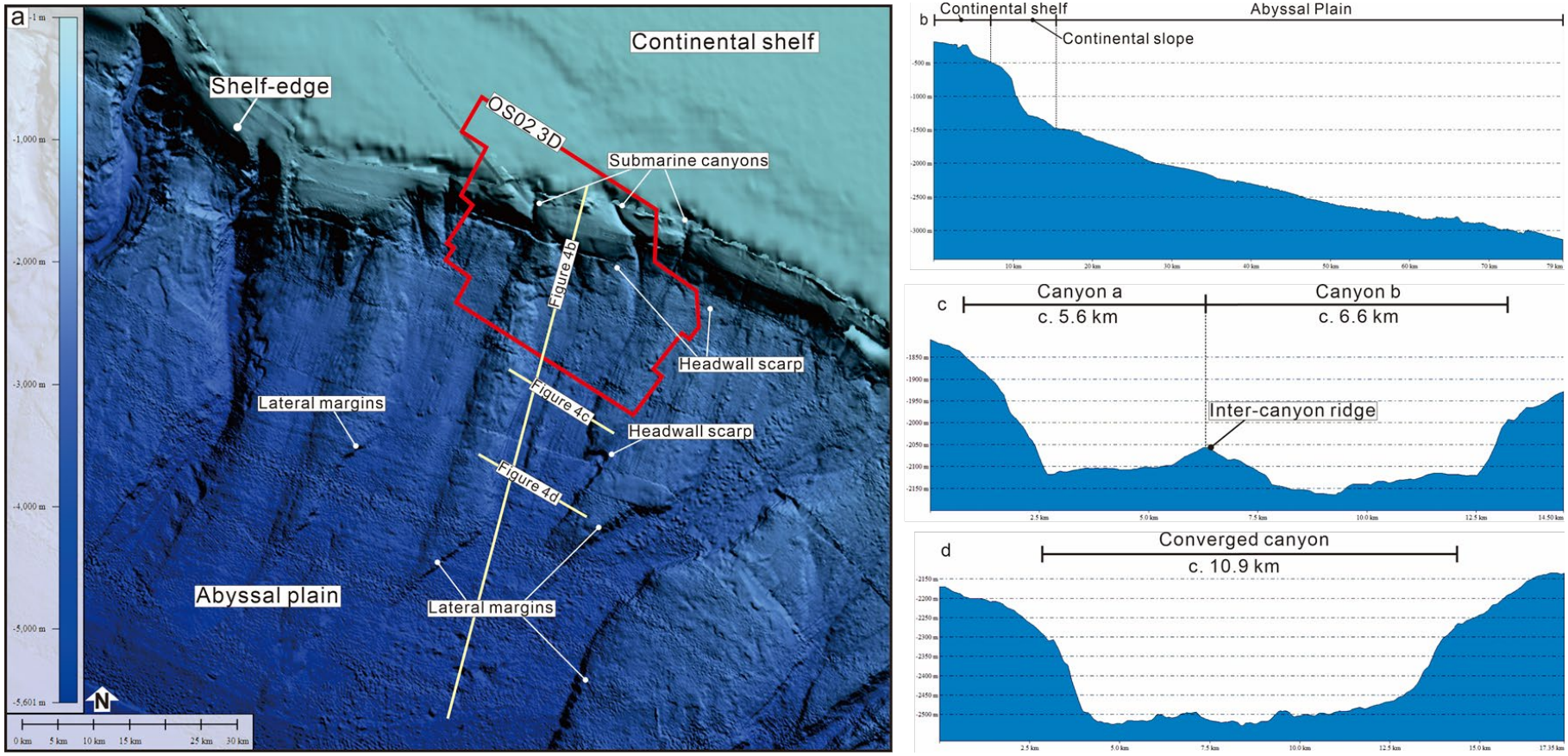

a
Continental shelf
Shelf-edge
OS02 3D
Submarine canyons
Figure 4b
Figure 4c
Figure 4d
Headwall scarp
Headwall scarp
Lateral margins
Abyssal plain
Lateral margins
N
b
Continental shelf
Abyssal Plain
Continental slope
c
Canyon a
c. 5.6 km
Canyon b
c. 6.6 km
Inter-canyon ridge
d
Converged canyon
c. 10.9 km

Figure 5

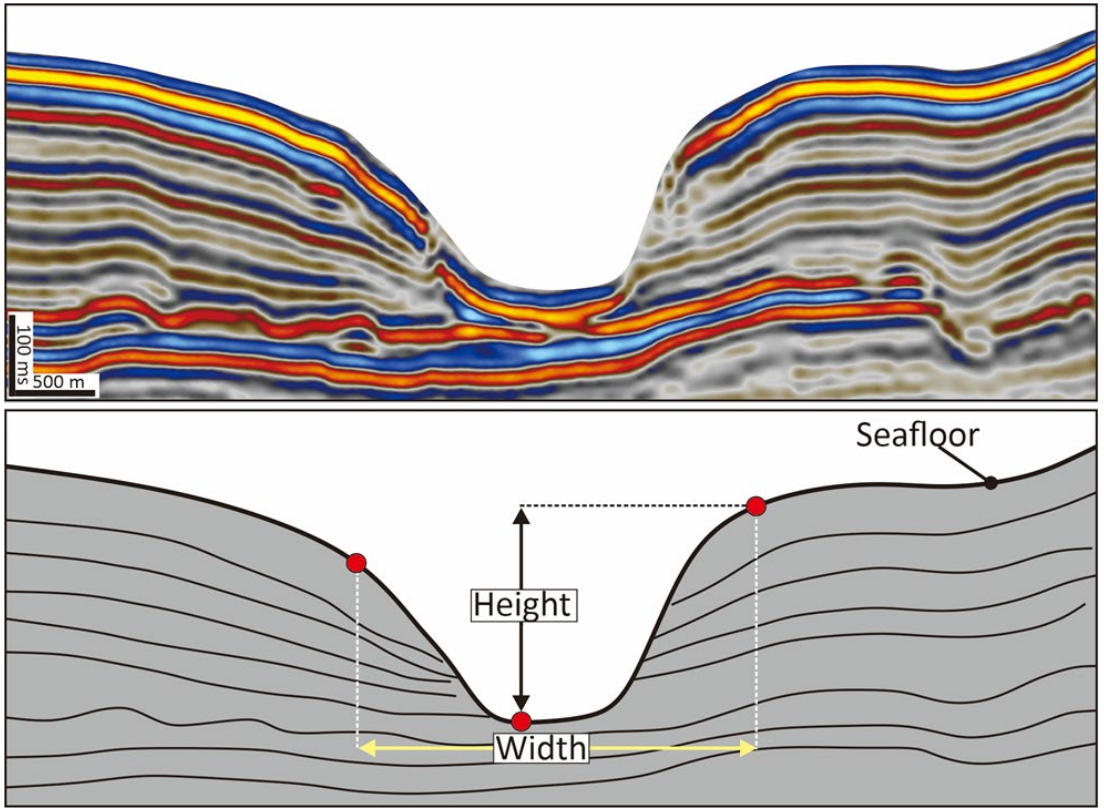


Figure 6

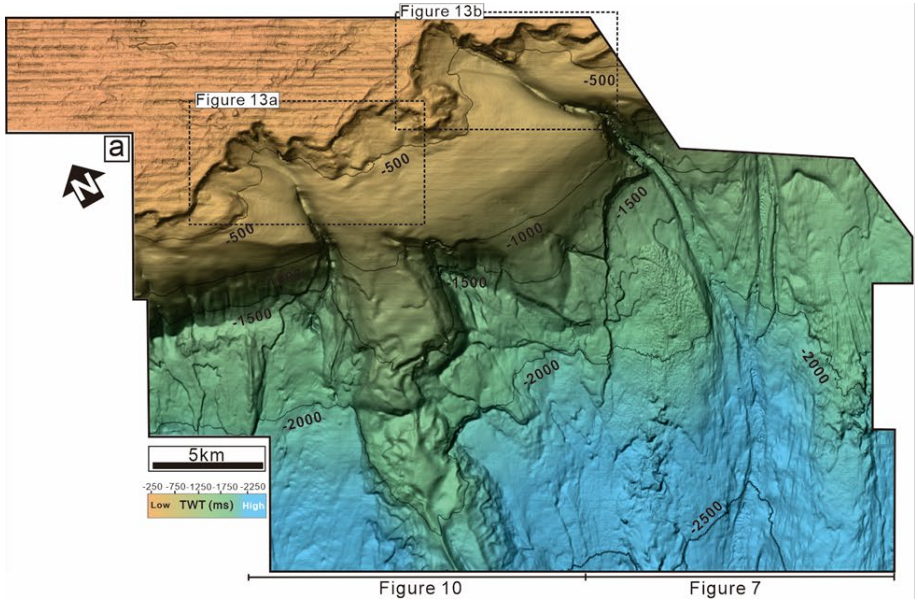


Figure 13b
Figure 13a
a
-500
-1000
-1500
-2000
-2500
5km
-250 -750 -1250 -1750 -2250
Low TWT (ms) High
Figure 10
Figure 7

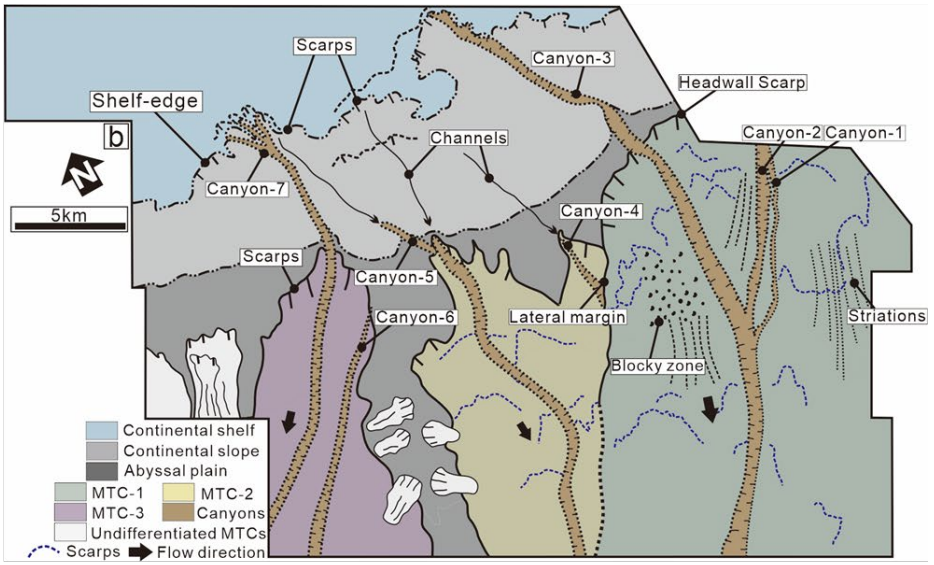
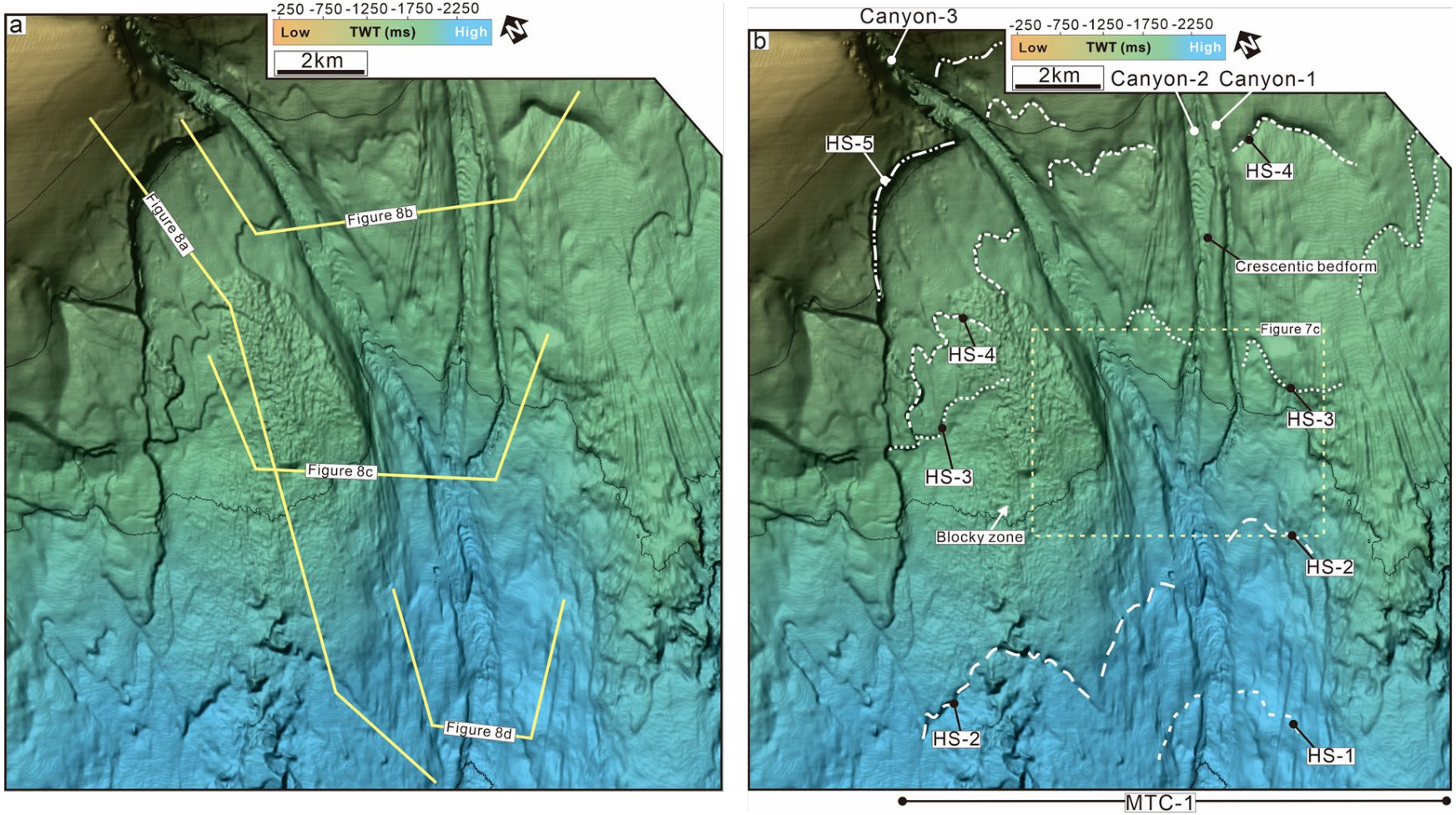

b
5km
Scarps
Canyon-3
Headwall Scarp
Shelf-edge
Channels
Canyon-2
Canyon-1
Canyon-7
Canyon-4
Scarps
Canyon-5
Canyon-6
Lateral margin
Striations
Blocky zone
Continental shelf
Continental slope
Abyssal plain
MTC-1
MTC-2
MTC-3
Canyons
Undifferentiated MTCs
Scarps
Flow direction

Figure 7


a
-250 -750 -1250 -1750 -2250
Low TWT (ms) High
2km
Figure 8a
Figure 8b
Figure 8c
Figure 8d
b
Canyon-3
-250 -750 -1250 -1750 -2250
Low TWT (ms) High
2km
Canyon-2
Canyon-1
HS-5
HS-4
Crescentic bedform
Figure 7c
HS-4
HS-3
HS-3
Blocky zone
HS-2
HS-2
HS-1
MTC-1

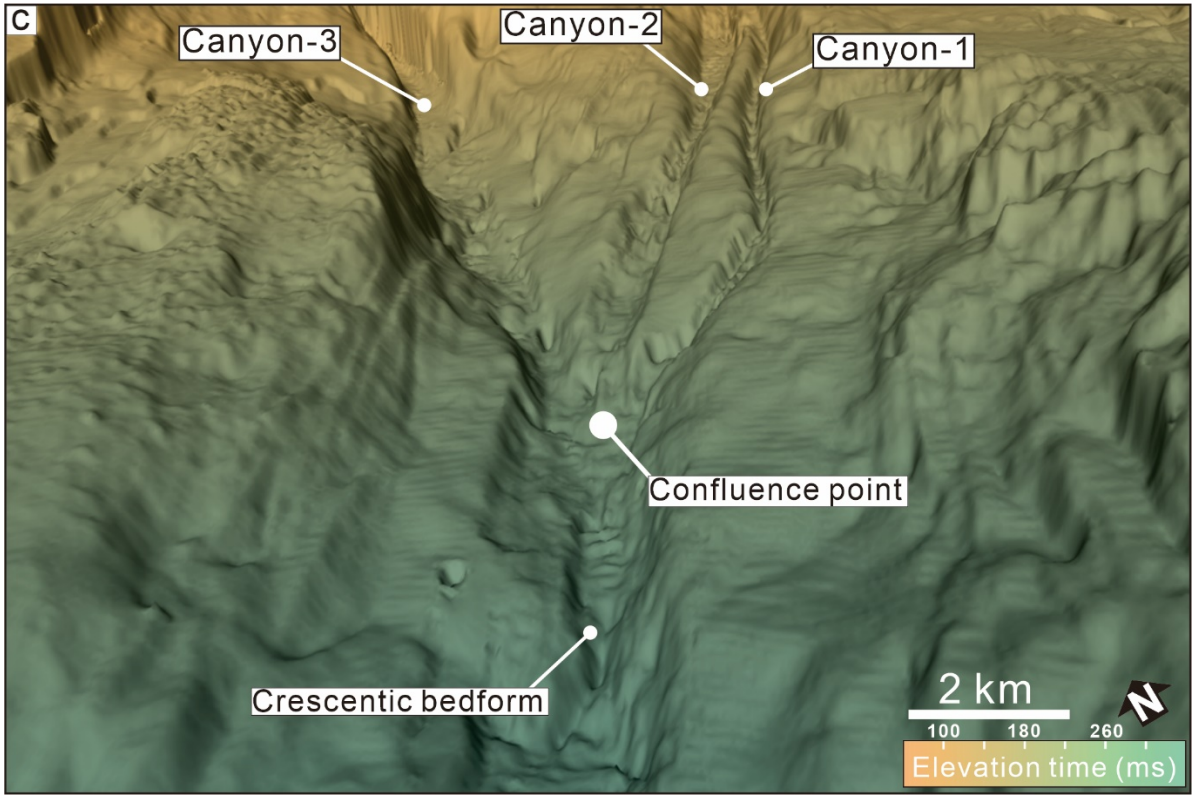

C
Canyon-3
Canyon-2
Canyon-1
Confluence point
Crescentic bedform
2 km
N
100
180
260
Elevation time (ms)

Figure 8

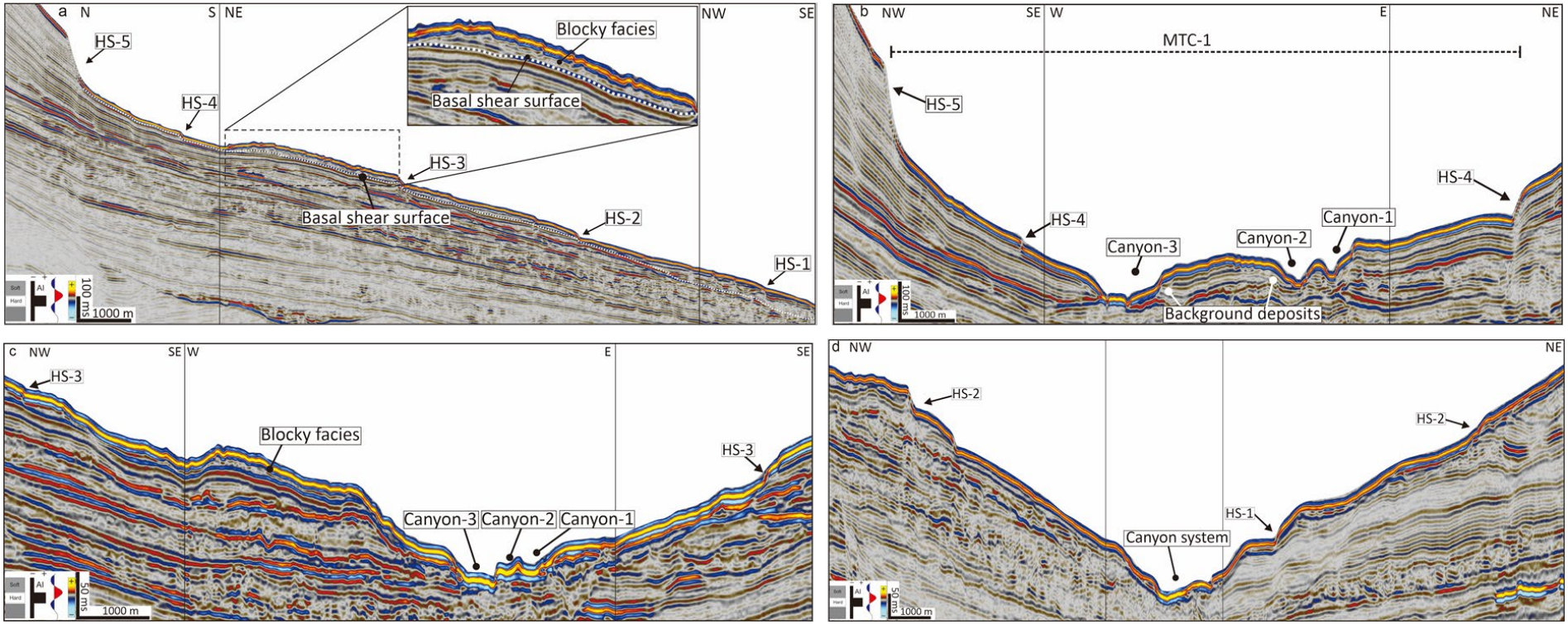

a N S NE NW SE
HS-5
HS-4
Blocky facies
Basal shear surface
HS-3
Basal shear surface
HS-2
HS-1
100 ms
1000 m
b NW SE W E NE
MTC-1
HS-5
HS-4
Canyon-3
Canyon-2
Canyon-1
HS-4
Background deposits
100 ms
1000 m
c NW SE W E SE
HS-3
Blocky facies
HS-3
Canyon-3
Canyon-2
Canyon-1
50 ms
1000 m
d NW NE
HS-2
HS-2
HS-1
Canyon system
50 ms
1000 m

Figure 9

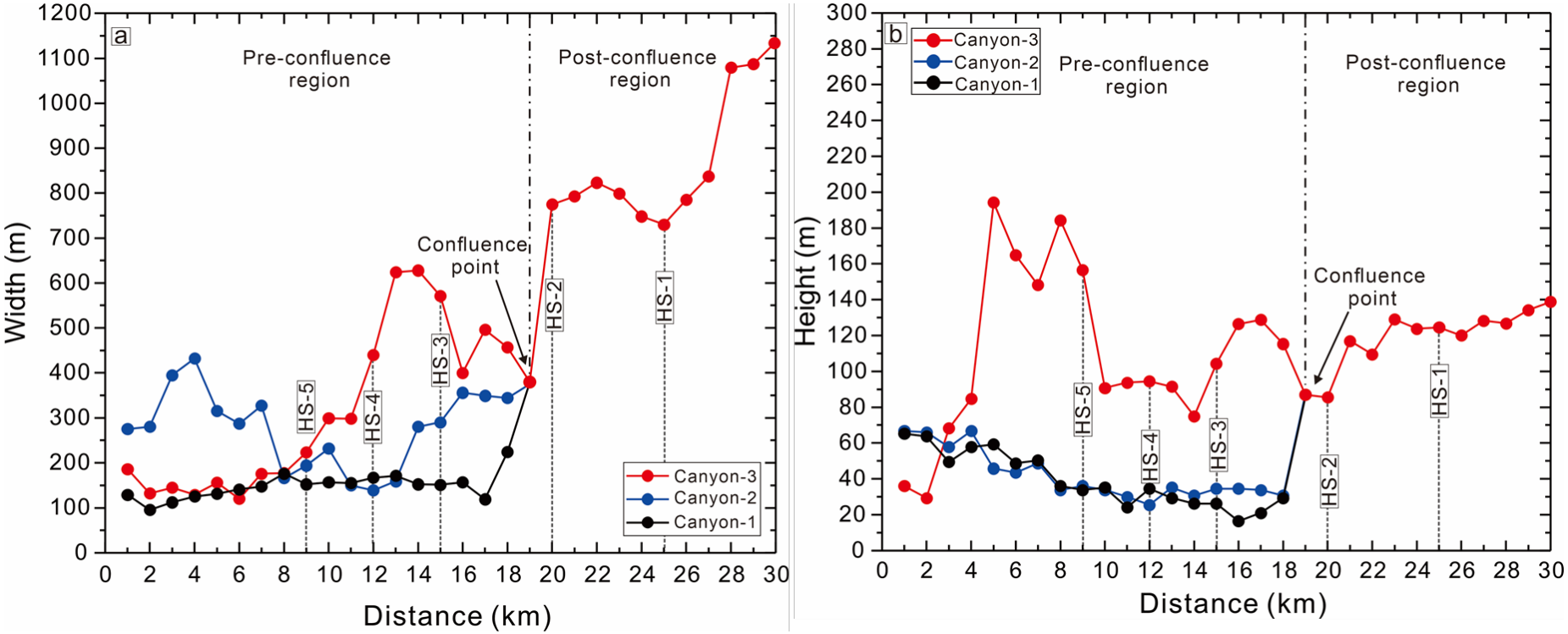

a
Pre-confluence region
Post-confluence region
Confluence point
HS-5
HS-4
HS-3
HS-2
HS-1
Canyon-3
Canyon-2
Canyon-1
Width (m)
Distance (km)
b
Pre-confluence region
Post-confluence region
Confluence point
HS-5
HS-4
HS-3
HS-2
HS-1
Canyon-3
Canyon-2
Canyon-1
Height (m)
Distance (km)

Figure 10

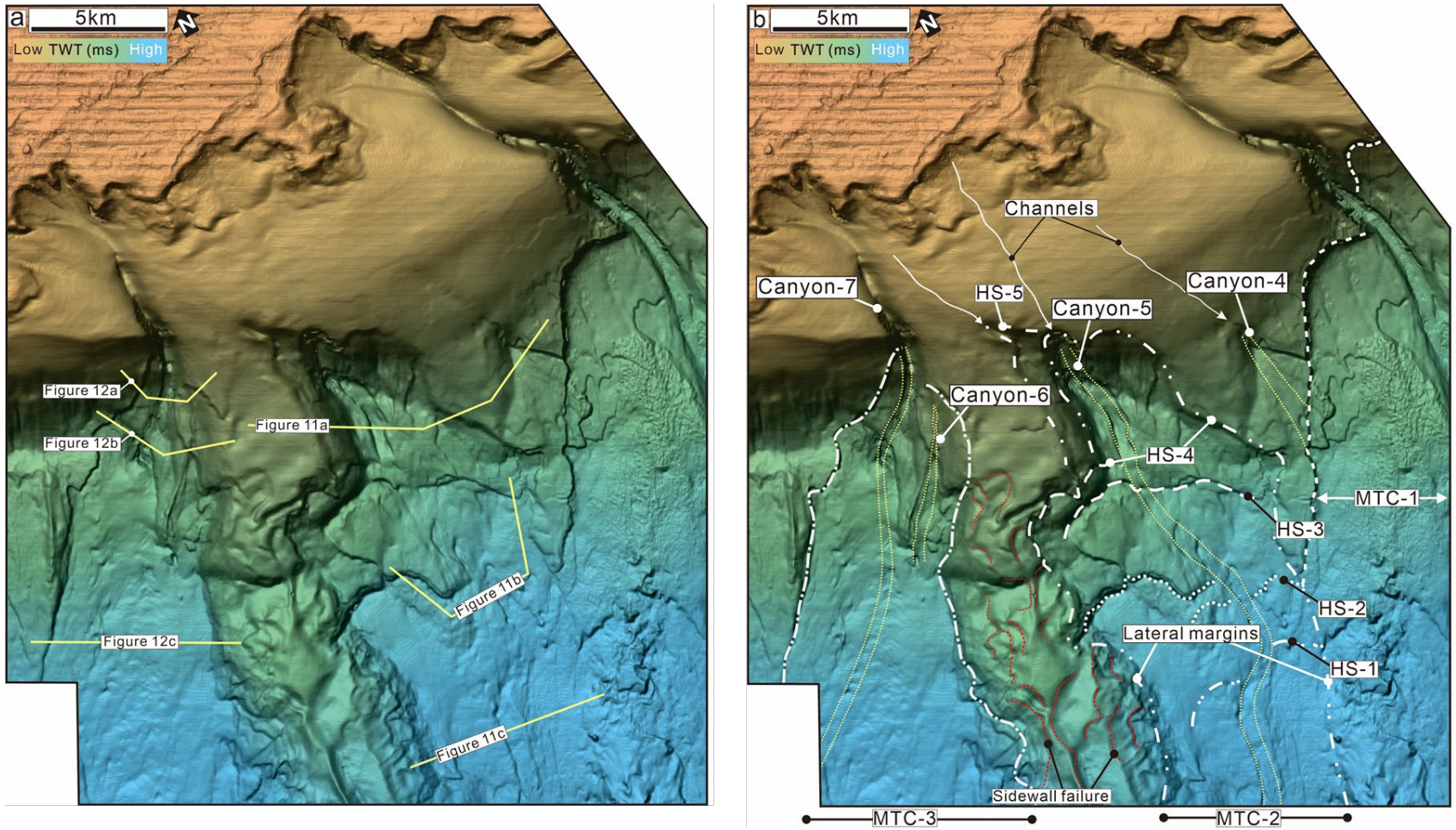

a
5km
N
Low TWT (ms) High
Figure 12a
Figure 12b
Figure 11a
Figure 11b
Figure 12c
Figure 11c
b
5km
N
Low TWT (ms) High
Channels
Canyon-7
HS-5
Canyon-5
Canyon-4
Canyon-6
HS-4
MTC-1
HS-3
HS-2
Lateral margins
HS-1
Sidewall failure
MTC-3
MTC-2

Figure 11

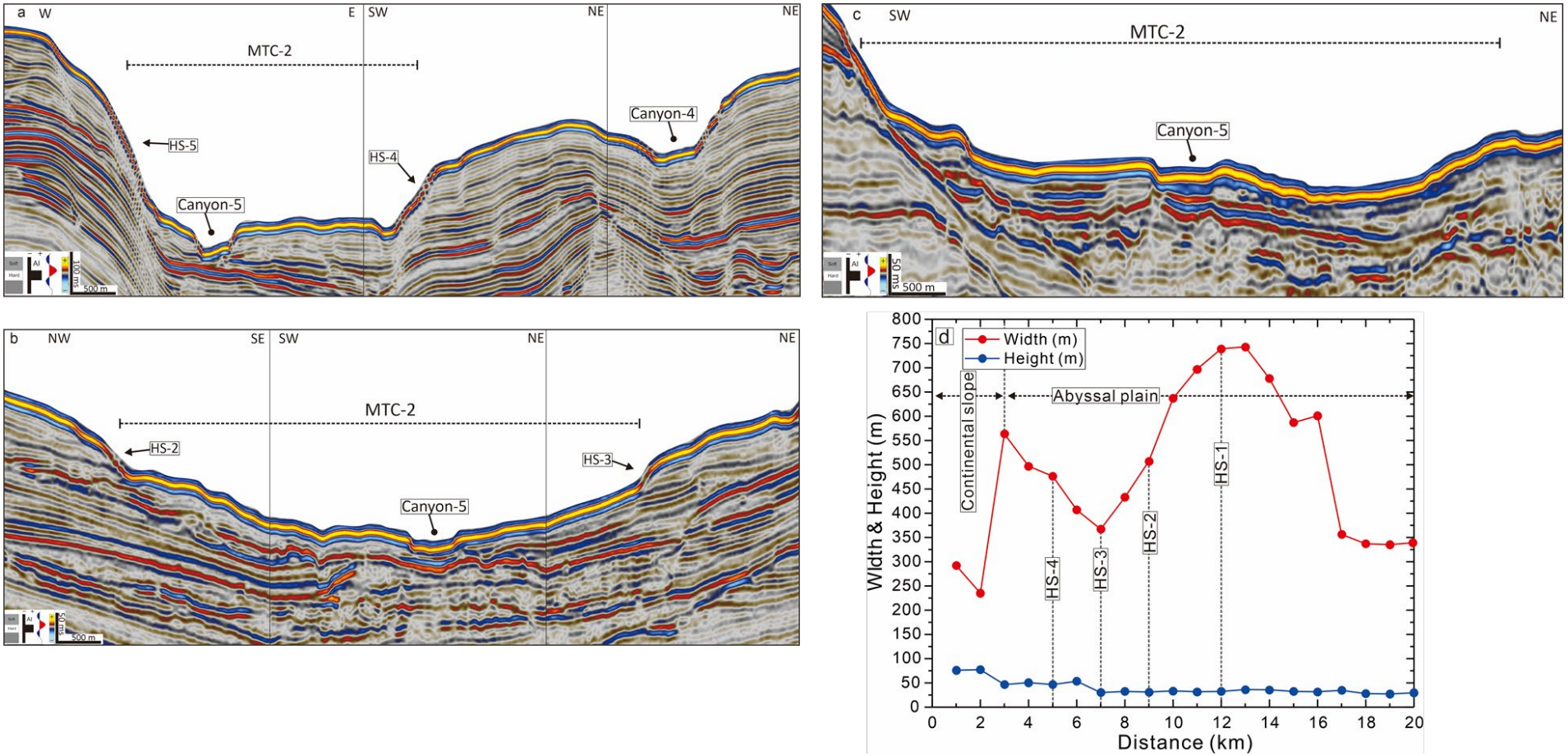
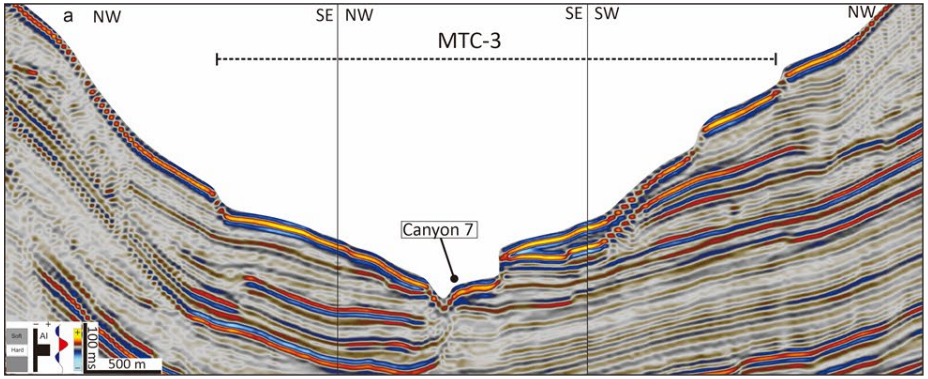
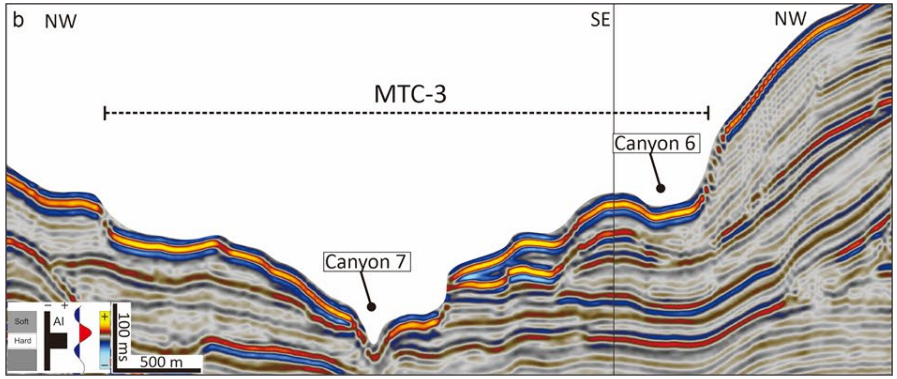
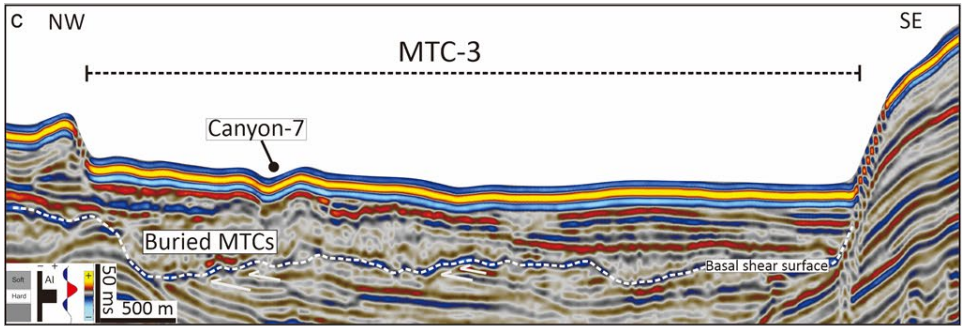

a W
E SW
NE
NE
MTC-2
HS-5
HS-4
Canyon-4
Canyon-5
500 m
c SW
NE
MTC-2
Canyon-5
500 m
b NW
SE SW
NE
NE
MTC-2
HS-2
HS-3
Canyon-5
500 m
d
Width (m)
Height (m)
Continental slope
Abyssal plain
HS-1
HS-2
HS-3
HS-4
Width & Height (m)
Distance (km)

Figure 12


a
NW
SE
NW
SE
SW
NW
MTC-3
Canyon 7
100 ms
500 m


b
NW
SE
NW
MTC-3
Canyon 6
Canyon 7
100 ms
500 m


c
NW
SE
MTC-3
Canyon-7
Buried MTCs
Basal shear surface
50 ms
500 m

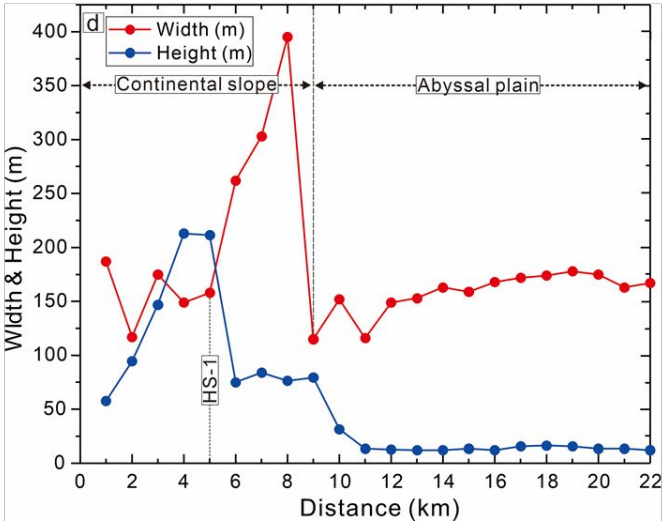

d
Width (m)
Height (m)
Continental slope
Abyssal plain
HS-1
Width & Height (m)
Distance (km)
0
50
100
150
200
250
300
350
400
0
2
4
6
8
10
12
14
16
18
20
22

Figure 13

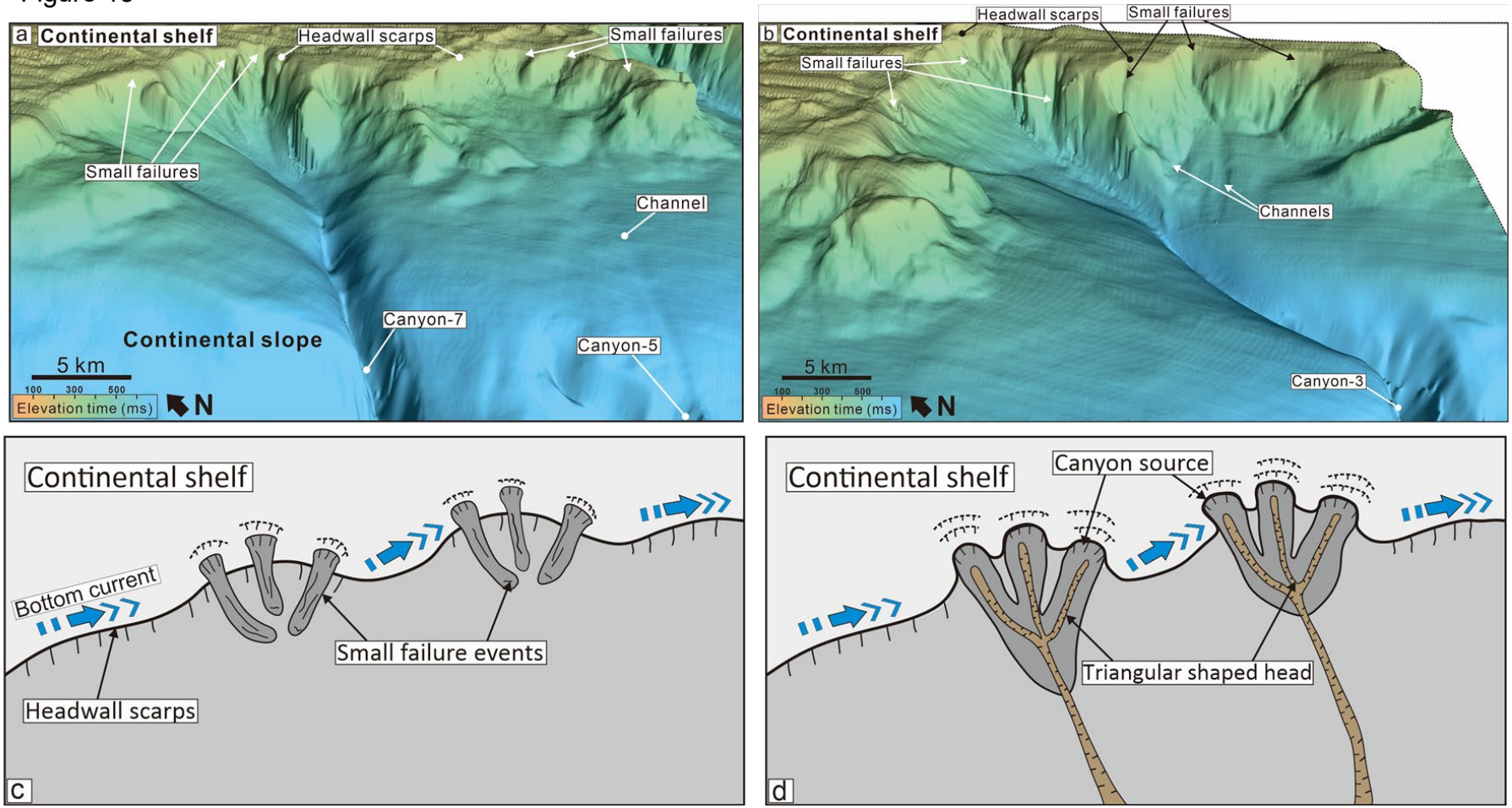
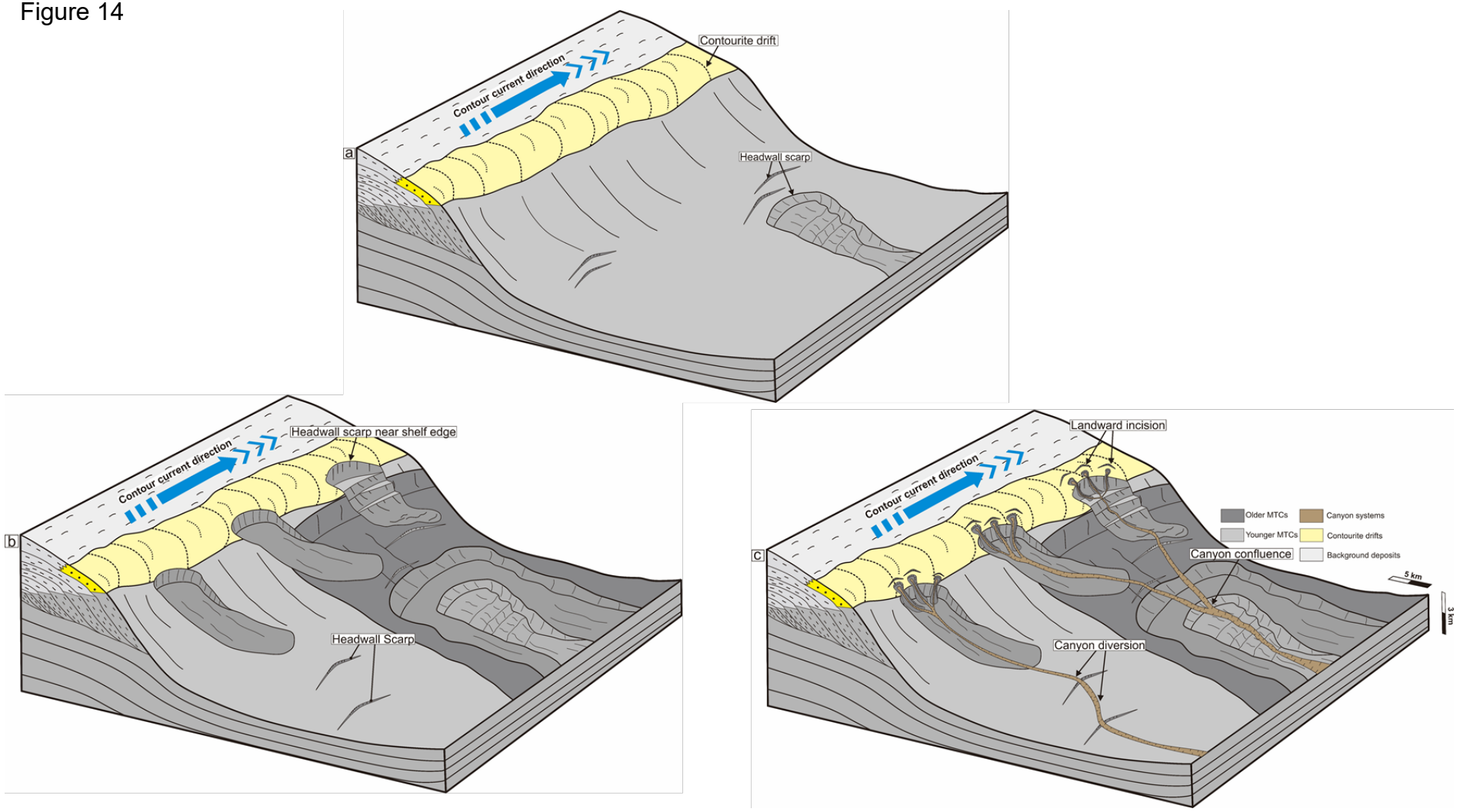

a Continental shelf
Headwall scarps
Small failures
Small failures
Channel
Continental slope
Canyon-7
Canyon-5
5 km
100 300 500
Elevation time (ms)
N
b Continental shelf
Headwall scarps
Small failures
Small failures
Channels
Canyon-3
5 km
100 300 500
Elevation time (ms)
N
Continental shelf
Bottom current
Small failure events
Headwall scarps
c
Continental shelf
Canyon source
Triangular shaped head
d

Figure 14


a
Contourite drift
Contour current direction
Headwall scarp
b
Contour current direction
Headwall scarp near shelf edge
Headwall Scarp
c
Landward incision
Contour current direction
Older MTCs
Younger MTCs
Canyon systems
Contourite drifts
Background deposits
Canyon confluence
5 km
3 km
Canyon diversion

Classification	MTC	Headwall scarps	Canyons	Influences imposed on canyons
Type-1	MTC-1	HS-1 to HS-5	Canyons 1-3	Canyon confluence, widening and deepening
	MTC-2	HS-1 to HS-5	Canyon-5	Canyon transport direction diversion
Type-2	MTC-3	None	Canyons 6-7	No canyon confluence nor diversion

Table 1. Classification of MTCs. Note that MTCs are the abbreviation of mass-transport complexes, and HS equals headwall scarps.