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SEAFLOOR GEOMORPHOLOGY AND SUBMARINE LANDSLIDE HAZARDS ALONG THE CONTINENTAL SLOPE IN THE CARNARVON BASIN, EXMOUTH PLATEAU, NORTH WEST SHELF, AUSTRALIA

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ABSTRACT

3D exploration seismic data were interpreted to investigate the locations and characteristics of submarine slope failures along the continental slope in the offshore Carnarvon Basin on Australia's North West Shelf. Seisnetics™, a patented genetic algorithm was used to process the 3D seismic data to extract virtually all trough and peak surfaces in an unbiased and automated manner. The extracted surfaces were combined in the 3D visual database to develop a seafloor digital terrain model that extends from the continental slope to the Exmouth Plateau. The 3D data were used to map the subsurface extent and geometry of landslide failure planes, as well as to estimate the thickness and volumes of slide deposits. This paper describes the geomorphic characteristics of five of the survey areas.

Geomorphic mapping shows the presence of slope failures ranging from small (<1 km across) to moderate (5–10 km across) scale debris flows, rotational block failures, translational slides, and topple failures, as well as large scale (>20 km across) mass transport complexes (MTC). The features are associated with debris flow chutes, turbidity flow channels, and debris fields. Analysis of failure planes show prominent grooves or striations related to the mobilisation of slide material down both the continental slope and Exmouth Plateau and into the Kangaroo Syncline.

Submarine slope failures can occur at the continental shelf break in about 200–300 m of water and run out to the Exmouth Plateau surface in about 1,100–1,400 m water depths. The largest individual slides in the survey areas have widths of 30 km and minimum run-out lengths of 75 km, though associated turbidity flow deposits likely extend much further. The subsurface expression of the large MTCs illustrates a history of sediment accumulation along the mid-slope followed by repeated slope failure and debris run-out.

Sediment accumulation and slope failure processes are actively occurring along the continental slope and submarine landslides thus are a major driver of hazard to subsea infrastructure development. Smaller more frequent slides may pose a greater hazard than large infrequent MTCs.

KEYWORDS

North West Shelf, Carnarvon Basin, Exmouth Plateau, submarine landslide hazards, slope stability, seafloor geomorphology, depositional environments, pock marks, gas expulsion, geological hazards, Seisnetics.

INTRODUCTION

As Australia's energy demand continues to grow, more and more field developments are being identified in deep water, along the North West Shelf. A significant number of potential developments have been identified at depths of 500 to 1,000 m or more, and several hundred kilometers from shore. Developments at these water depths necessarily mean that infrastructure elements are located below the continental slope, export systems might involve crossing the slope, and as such, system components could potentially be negatively affected by geohazards originating along the slope.

The primary driver of geohazard risk at these water depths will be slope failures and associated mass transport deposits. These types of failures can be among the largest earth movements in the world (Masson et al, 2006) involving thousands of km^3 of material, but it is not necessarily these large catastrophic failures that pose the greatest risk to marine infrastructure. Relatively frequent small failures can impose sufficient loads on infield and export systems to jeopardise system integrity.

The publicly available bathymetric data lacks sufficient resolution to identify these features and so our research is being completed to map and characterise submarine slope failures using open-file 3D exploration seismic data. This paper presents examples of several types of submarine slope failures and processes recognised along part of the continental slope adjacent to the Exmouth Plateau on Australia's North West Shelf.

Geological setting

The Exmouth Plateau encompasses part of the offshore Carnarvon Basin (Fig. 1). This area is located on the northwestern margin of the Australian continent about 800 to 1,000 km south of the tectonically active boundary between the Australian and Eurasian tectonic plates.

Sediments within the Carnarvon Basin (onshore and offshore) range in age from Silurian to Holocene and comprise 12 primary sedimentary sequences that reflect major depositional episodes (Hocking, 1990). Figure 2 shows two regional scale geological sections that illustrate the stratigraphic and structural relationships across Exmouth Plateau (AGSO, 1994). The sedimentary sequences are each bound by erosional unconformities. There are three Paleozoic sequences that formed during the Silurian, Devonian to early Carboniferous, and Late Carboniferous to Permian (Hocking, 1990). These deposits accumulated in a series of intra-continental rift basins that form the southern part of the late Palaeozoic-early Mesozoic Westralian Superbasin of Yeates et al, (1987).

Late Triassic to earliest Cretaceous, and Early Cretaceous to Late Cretaceous sequences of the northern Carnarvon Basin (Fig. 1) reflect development of the rift system related to fragmentation of Gondwanaland and separation of greater India from the western margin of the Australian craton. The sedimentary sequences formed in a variety of settings including a pre-rift trough during Triassic time, a rift valley in Jurassic time, and post-breakup troughs and trailing margin shelves during

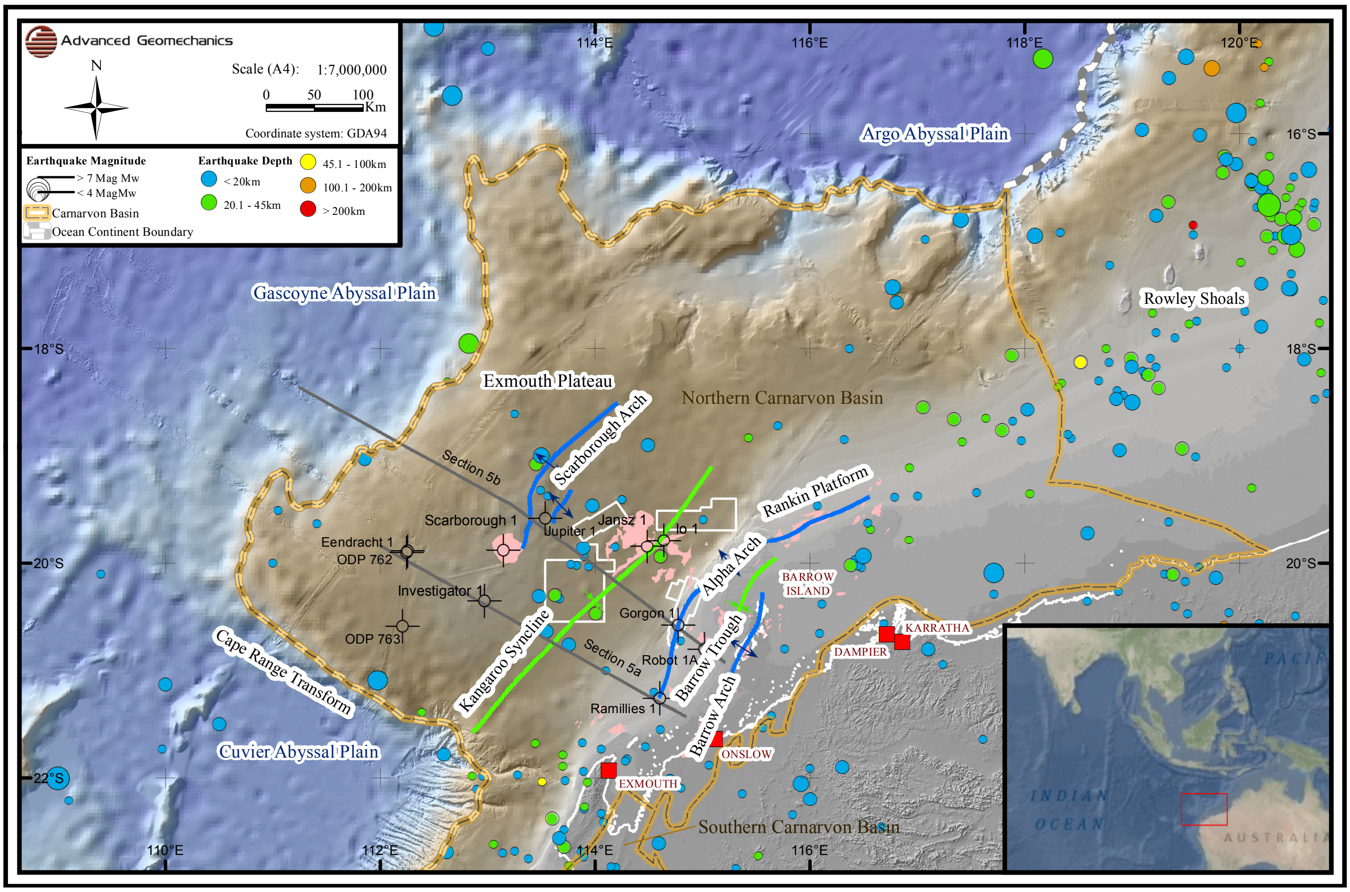
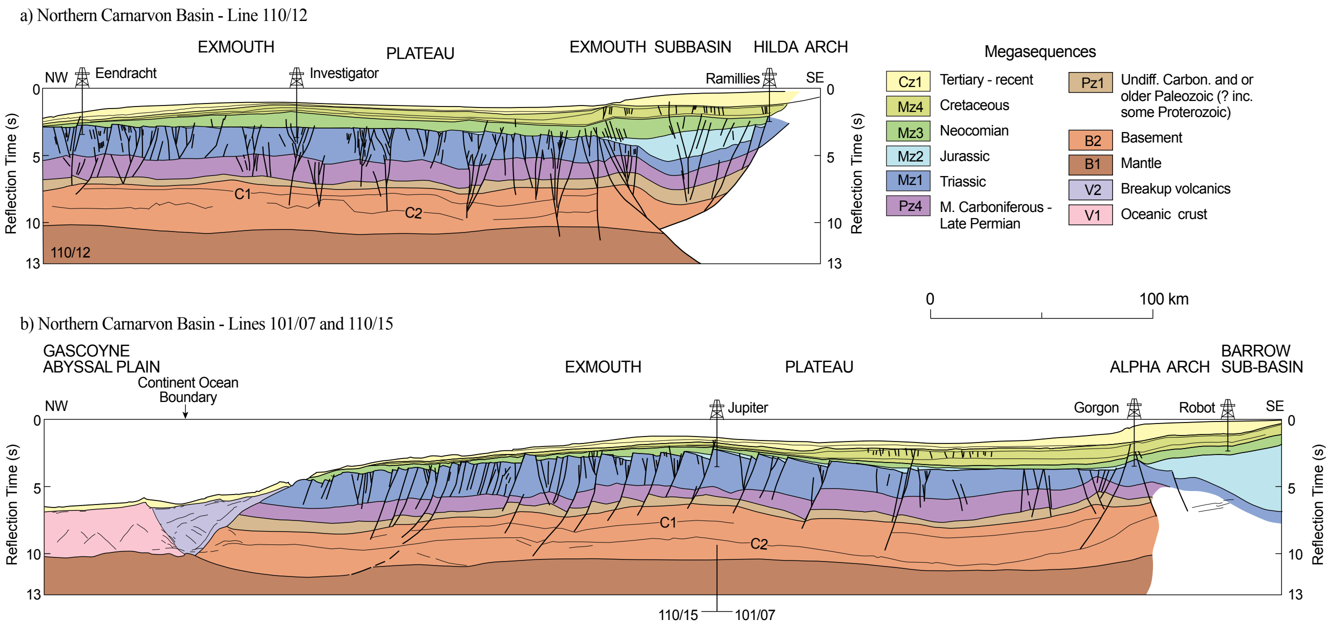


Figure 1. Regional tectonic and physiographic setting of the Exmouth Plateau. White polygons represent survey locations. Dark gray lines represent locations of sections shown on Fig. 2. Coloured circles represent earthquake epicentre locations.



Reference: Australian Geological Survey Organisation (AGSO) North West Shelf Study Group (1994). "Deep reflections on the North West Shelf: changing perspectives of basin formation," in Purcell, P. G. and Purcell, R. R. (eds.), The Sedimentary Basins of Western Australia, Proceedings of the Petroleum Exploration Society of Australia, Perth, p. 63-74.

Figure 2. Regional geological sections showing major stratigraphic and structural relations across the Exmouth Plateau.

Cretaceous time (Hocking, 1990; Exon and Buffler, 1992; Exon et al, 1992; Baillie et al, 1994). The Upper Cretaceous, Paleocene to Early Eocene, Eocene, Oligocene to Middle Miocene, and Late Miocene to Holocene sequences are dominated by carbonate sediments that formed through progradation of the continental shelf (Hocking, 1990) and carbonate-dominated hemipelagic sedimentation (von Rad and Haq, 1992; Boyd et al, 1992).

Many continental slopes define the transition from continental crust to oceanic crust. However, the Carnarvon Basin deposits that form the Exmouth Plateau represent a fragment of continental material that was stranded during the rifting process. As such the continental slope on the Exmouth Plateau represents the transition from the continental shelf (proper) to a stranded continental fragment that stalled during the rifting process. Geological evidence of syn-rifting lava flows at the ocean-continent boundary (COB) (Figs 1 and 2), fluvial/subarial depositional environments for pre-rift sedimentary sequences, as well as subsidence modeling (Kaiko and Tait, 2001) indicate that 1–4 km of syn- and post-rift subsidence has occurred (from east to west) across the Exmouth continental margin. Total subsidence is suggested to be a combination of tectonic subsidence and thermal sagging during rifting and cooling of the Late Jurassic to Early Cretaceous seafloor. It is this tectonic subsidence and thermal sagging that has led to the depressed elevation (i.e., deeper water depths) of the continental fragment that forms the Exmouth Plateau part of the Carnarvon Basin.

Former rift related extensional structures have undergone Neogene to Recent transpression leading to both transform and contractional reactivation and structural inversion of basin sequences (Fig. 3) (Boyd et al, 1992; Cathro and Karner, 2006; Keep and Moss, 2000; Kaiko and Tait, 2001; Keep et al, 2007). Some of these inversion structures underlie the continental slope and are targets for exploration activity. These inversion structures also are sources of gas and fluid venting as well as potential earthquake sources. Thus, slopes above inversion structures are susceptible to failure from several different triggering mechanisms (Hengesh et al, 2011).

Physiography of the Exmouth Continental Slope

The location and general physiography of the Exmouth Plateau is shown on Figures 1 and 4. The primary physiographic features in the Exmouth Plateau area include: (a) the continental shelf; (b) upper, middle, and lower continental slope; and (c) Kangaroo Syncline and Scarborough Arch. The continental shelf is generally defined as extending from the nearshore environment to the shelf break at about 200 m water depth. The continental slope is characterised by submarine canyon systems, smooth sedimentary fans, and abrupt landslide scars. The elevation change across the slope is typically 400 to 600 m. Average slopes along the canyon systems are on the order of 3 to 7 degrees (following interfluves), while the average slopes across the landside complexes are much higher with common 30–70 degree slopes.

The continental slope extends from the shelf break to the Kangaroo Syncline at about 1,400 m water depth, where the lower slope adjoins the Exmouth Plateau. The plateau is a 350 km wide arch (in an east-west direction) that extends from the Kangaroo Syncline at the base of the continental slope (~1,400 m depth), across the arch (~1,000 m depth), to the continent-ocean boundary at about (~5,000 m depth).

Two important factors must be kept in mind when assessing the marine geomorphology and physiography in this region: (1) sedimentation rates in the pelagic environment are exceedingly low (von Rad and Haq, 1992) and thus even pronounced features in the landscape can have significant antiquity; and (2) hemipalagic sedimentation mantles former seafloor features and thus the present seafloor geomorphology may in fact be mimicking a relict buried seabed. Relict seabed morphology can retain expression even under 10's of metres of sediment.

Landslide processes along Exmouth Continental Slope

The locations of submarine landslides along the North West Shelf are largely controlled by the relict seafloor topography that formed following Jurassic to Cretaceous continental rifting. The main relict topographic features where landslides occur include the continental slope and submarine canyons, the outer margins of the Exmouth Plateau, and along both the east and west facing limbs of Scarborough Arch (Fig. 4).

Post-Neogene to recent collisions and tectonic re-organisation on the northern plate boundary has resulted in the reactivation of some faults along the former rifted margin. The reverse reactivation of some of the former normal faults has resulted in the structural inversion of post-rift basin infills and has caused local arching and warping of the former relict seafloor. Structures such as the Scarborough Arch and Kangaroo Syncline (Fig. 4) have increased seafloor slope gradients and reduced the stability of shallow, unconsolidated sediments.

Submarine landslides along the North West Shelf generally occur in Quaternary hemipelagic foraminiferal nanno-fossil ooze. These deposits have very high porosity, water content, void ratios, and low strength profiles (Fig. 5) (von Rad and Haq, 1992). Typical shear strength gradients in these shallow Quaternary age calcareous sediments are in the order of ~1–2 kPa per metre. These low shear strengths result in low residual stability of slopes and, given a triggering opportunity, a high slope hazard potential. Near the ODP sites shown on Figure 1 the weak calcareous deposits overlie more competent Eocene and older sediments, such as polygonally faulted nanno-fossil chalk (von Rad and Haq, 1992). Near the continental slope, however, the Neogene and younger section includes landslide deposits. The modern landslide complexes provide an analogy for these older deposits along the base of the continental slope. Figure 6 shows examples of a stacked series of large mass transport complexes (MTC) in the Willem survey area.

In other locations, such as the outer Exmouth Plateau, submarine landslides appear to be ancient features now draped by 10's of metres to a few 100's of metres of pelagic sediment. The large amount of sedimentary drape can indicate significant antiquity to these former landslide features. Because the sedimentation rates across the deep water parts of the Exmouth Plateau can be as low as 0.02 mm/yr (von Rad and Haq, 1992), the overlying sedimentary drape can be several million years old in these areas.

SEAFLOOR GEOMORPHOLOGY

Sea-floor digital terrain models (DTM) were developed from open-file 3D exploration seismic data using Seisnetics™ (Dirstein and Fallon, 2011), a patented genetic algorithm that extracts virtually all trough and peak surfaces from 3D seismic data in an unbiased and automated manner. The extracted surfaces were combined in the 3D visual database and then the x,y,z data were imported to Fledermaus to develop the seafloor DTMs. The exploration 3D seismic data typically have bin spacing of 12.5–25 m and thus provide good resolution of seafloor features. The DTM's were used as a basis to map geomorphic features and assess processes occurring along the Exmouth Plateau continental slope. 2D profiles and 3D horizon maps also were used to assess the subsurface stratigraphy and characteristics of submarine landsides. Examples are shown for the Gorgon/Acme, Willem, Chandon, and Glencoe surveys.

Gorgon/Acme survey areas

The Gorgon survey covers an area of about 75 km × 17 km area along the Exmouth continental slope (Figs 4 and 7). This has been combined with the smaller Acme survey, which provides partial coverage of the lower slope beneath the Gorgon survey area. The continental slope in the Gorgon area extends from about 200–700 m water depth and includes four distinct morphologies including (from north to south): (a) a 20 km long, 250 m high landslide headscarp; (b) an area of incipient slope failure lying above both submarine canyons and the landslide headscarp; (c) a 20 km long system of submarine canyons and

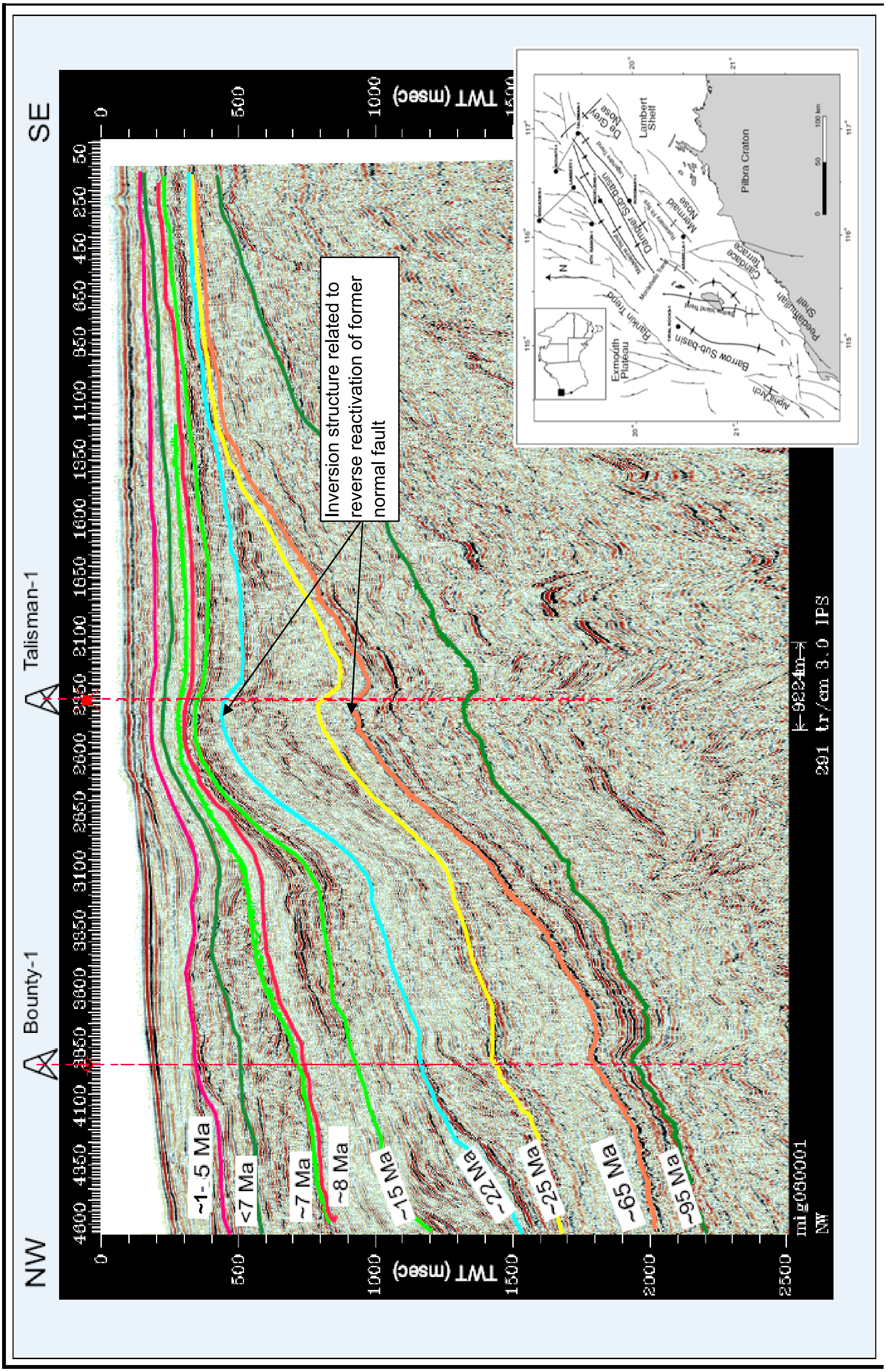


Figure 3. Example of late to post-Neogene inversion structure underlying the continental slope. Source: Kaiko and Tait, 2001.

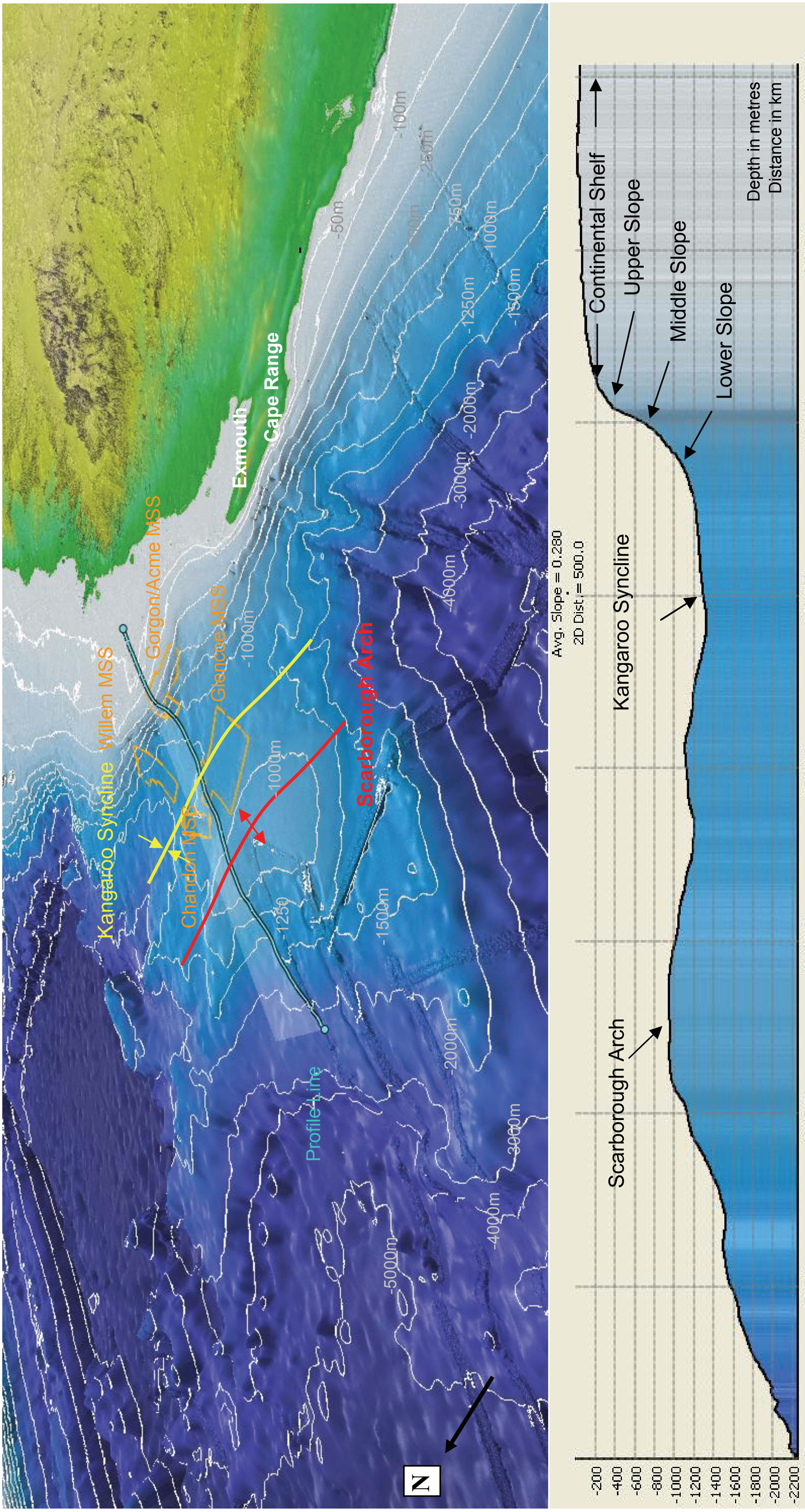


Figure 4. Oblique view to northeast across Exmouth Plateau showing major physiographic features and survey locations. Bathymetric data from Geoscience Australia. Vertical exaggeration 20 times.

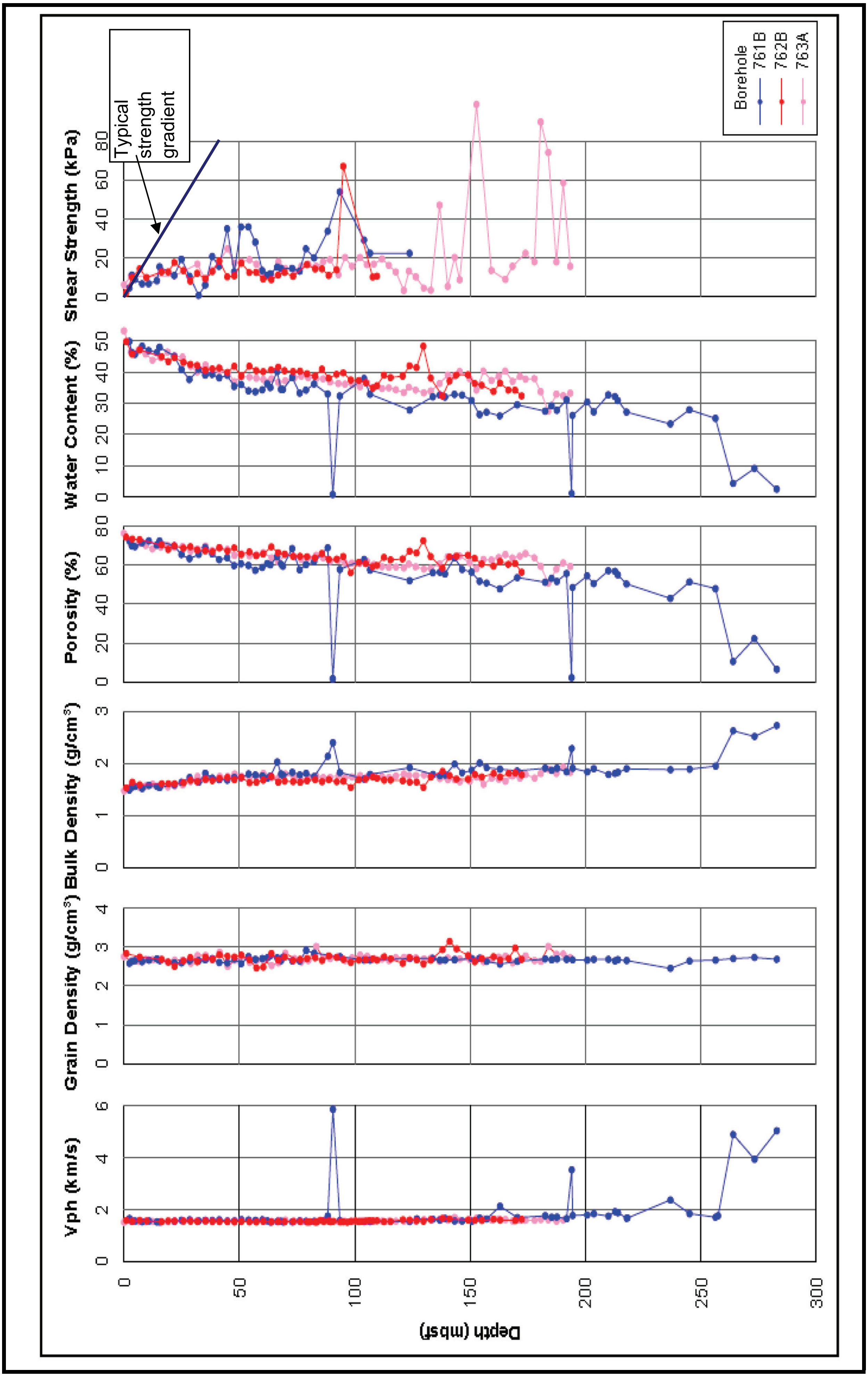


Figure 5. Sediment data from Ocean Drilling Project borings (ODP 761, 762 and 763 (von Rad and Haq, 1992). ODP boring locations are shown on Figure. Note that the ODP definition of water content is water/total not water/soil. Therefore the 50% shown is 100% by conventional definition. Strength data from ODP are atypical possibly due to sample disturbance. A more common strength profile for Exmouth Plateau is shown by line.

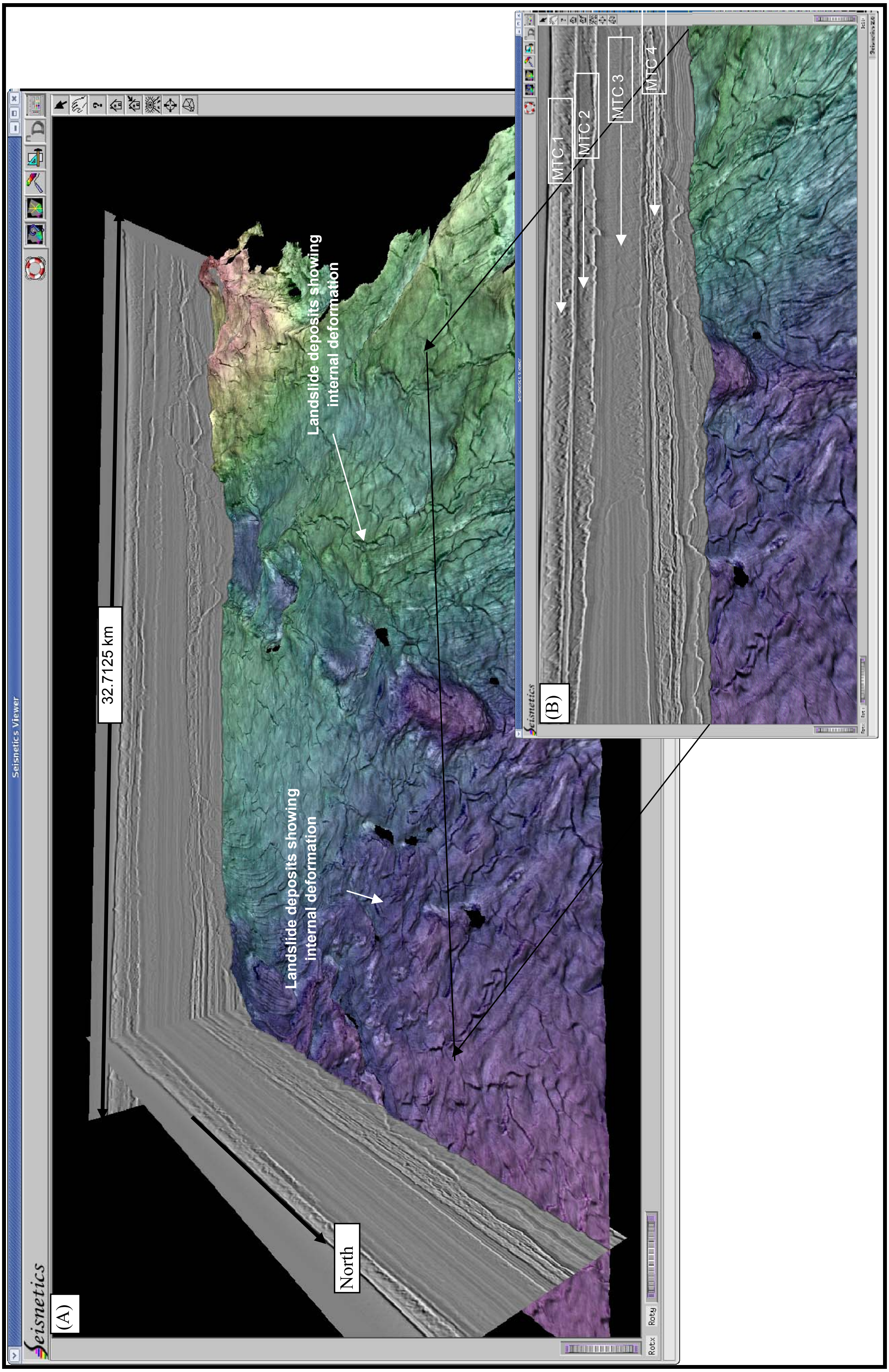


Figure 6. 3D perspective view to south across western end of Willem 3D seismic survey. The figure displays the combined Two-Way-Time and Amplitude attributes of GeoPopulation™ 130 from a subvolume of the Willem 3D survey in Seisnetics™. (A) The coloured horizon is a landslide deposit showing internal deformation.. (B) Arrows on inset image illustrate position of stacked submarine mass transport complexes (MTC).

debris flow chutes; and (d) a relatively smooth, sedimentary apron with little evidence of canyon formation or mass wasting. Fluid and gas expulsion features (pock marks) are common in the central and northern parts of the survey area and appear spatially associated with landslide failures; the expulsion features are absent in the areas where there is a smooth sedimentary apron.

The submarine canyon system in the southern part of the survey area has an average slope gradient of about 2–5 degrees. The individual canyons are about 5–8 km long and 1–2 km wide (Fig. 7[B]). Sedimentary fans are present at the base of the canyons and sediment waves have built up at the heads of the canyons. Relatively small (a few kilometres across) debris flows or translational failures are present at the base of the canyons and on the sedimentary fan, indicating static instability of the slope.

The landslide failure—labelled Slide 1 on Figure 7(A)—that occurred in the northern part of the Gorgon survey area extends from the upper slope in about 400 m of water to the lower continental slope in about 700 m of water; slope gradients range from 30–70 degrees and locally may be vertical (Fig. 8). The slide is roughly 30 km wide and has a minimum run out length of 75 km, from the head scarp to the base of the lower slope in the Kangaroo Syncline. The basal failure surface coincides with a stratigraphic horizon that can be followed in the 3D seismic volume beneath the scarp and into the un-failed portions of the upper continental slope suggesting stratigraphic control on the location of the basal failure plain and slide geometry. Extensive pock marks and expulsion features are recognised on sea-floor bathymetry maps (Fig. 8). These features occur both within the slide mass, within drape over the former slide plane, and locally outside of landslide related features (Fig. 8). Regional stratigraphic relationships suggest that the slide is of late Quaternary age. Localised debris fields lie beneath the landslide headscarp and may be related to small scale debris avalanche or topple failures from the oversteepened scarp.

The submarine landslides observed within the Gorgon survey area are similar in scale to the large scale MTC deposits observed in the subsurface of the Willem survey area (Fig. 6). The slide geometry and MTC thicknesses suggest landslide volumes of about 100–500 km^3. Topple failures, debris avalanches, and debris flows sourced from the headscarp represent secondary retrogressive slope failures along the primary slide feature (Fig. 8). These secondary failures can be several kilometers across with run-outs of 5–15 km. Erosion of the seabed also is occurring at the base of submarine canyons either as a result of strong current scour, or scour during mass transport events.

Willem survey area

The Willem survey covers an area of about 75 km × 35 km along the Exmouth continental slope (Fig. 4) 50 km northeast of the Gorgon survey. In this area the continental slope extends from about 300–1,000 m depth (Fig. 9). The survey area only captures a part of the upper continental slope, but includes a large part of the lower slope (Fig. 9). The upper part of the continental slope has an average slope gradient of seven degrees, while the lower slope has an average gradient of one degree.

The seabed rendering illustrates the presence of large debris fields below the escarpment extending about 60 km from the slope to the eastern edge of Kangaroo Syncline (Fig. 9). These debris field deposits have been both draped by hemipalagic sedimentation and eroded by other younger debris flow deposits. Some of these debris flow deposits are observed extending more than 35 km across the debris fields on the lower slope (Figs. 9 and 10). These debris field deposits are associated with the nested large scale MTC deposits observed at depth in the seismic volume (Fig. 6).

A steep partially buried scarp is present at the base of the continental slope (Fig. 10). This is inferred to be a paleo-landslide headscarp. The headscarp is now partially buried by debris fans (Fig. 10). These fans have locally failed and produced debris flows that run down the lower continental slope. Several examples are shown on Fig. 10. The southernmost example is about 1–3 km wide and produced a scar about 7 km long. The debris field from this event extends about 6 km beyond the slide scar.

The large scale MTC deposits observed at depth (Fig. 6) are of about 80–100 m thick. The basal failure plane beneath these deposits shows linear striations that illustrate direction of transport of the landslide mass. The striations shown on the surface in Fig. 11 comprise three populations: those coming from the continental shelf to the east; those coming from the Scarborough Arch to the west; and those moving downslope along the axis of the Kangaroo Syncline. The curvilinear striations indicate some slides initially moved straight down slope, but then turned northward into the Kangaroo Syncline and likely continued down the axis of the syncline trough.

Chandon survey area

The Chandon survey covers an area of about 17 × 25 km on the eastern limb of Scarborough Arch (Fig. 4). The Chandon slide occurs on an east facing slope between the Scarborough Arch and Kangaroo Syncline and extends from a depth of about -1,180 m to at least -1,300 m (Fig. 12). The slide has a width of 20 km and a length of >30 km. The average slope gradient within the slide mass is less than 0.5 degree, however, steeper slopes of several degrees are present downslope (Fig. 4). The slide mass appears to be composed of rotational slide blocks (Fig. 12) that are mobilised above the gently dipping failure plane. A distinctive feature of the slide morphology is the lateral mote that follows the base of the head scarp (Fig. 12). The Chandon slide is transporting sediment from Scarborough Arch eastward into the Kangaroo Syncline.

Glencoe survey area

The Glencoe survey encompasses an area of about 60 × 65 km in the central trough of the Kangaroo syncline and part of the eastern limb of Scarborough Arch, about 20 km southwest of Chandon (Fig. 4). Slope gradients across the survey area are exceedingly low, generally less than 0.1 degrees. However, debris or earth flow lobes are observed in the southeastern corner of the survey area in water depths of 1,120–1,220 m (Fig. 13). These form the leading edge of landslide and lower continental slope deposits that originated 75 km to the east along the slope (Fig. 4). The sediment lobes shown on Figure 13 are each about 10–12 km wide and the easternmost lobe shows crevasse fields, internal shears, and prominent lateral shear margins (Fig. 14). Secondary flows are present on the edges of the lobes. The active earth flow lobes in the centre of the Kangaroo syncline could impose loads on seabed systems such as wells, infield flow lines and export pipelines that cross the syncline.

DISCUSSION

Seafloor digital terrain models (DTMs) were produced from five open-file, 3D seismic volumes located along the Exmouth Plateau continental slope and along the eastern limb of Scarborough Arch (Figs. 1, 4). The DTMs were produced to assess seafloor geomorphology and types of processes occurring across this 240 km long segment of the continental margin. Deep water projects such as Gorgon, Pluto, Scarborough, and Jansz-Io are all progressing along this part of the North West

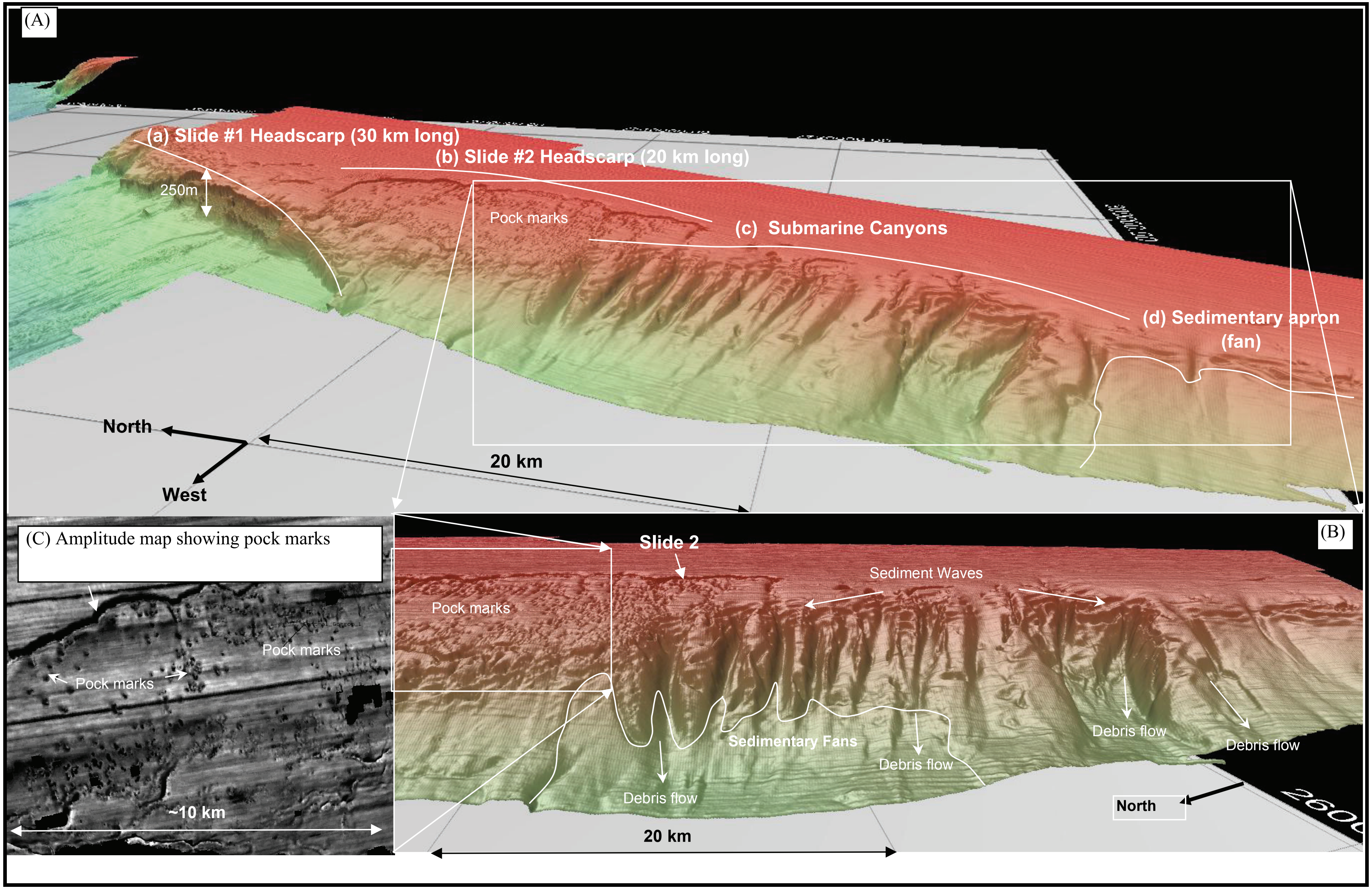


Figure 7. Perspective views of seafloor along Gorgon 3D survey area. (A) Shows four prominent morphological features along the Gorgon escarpment: (a) Slide #1 headscarp; (b) Slide #2 complex; (c) Submarine canyon system; and (d) Sedimentary apron or fan complex. Note also the extensive fields of pock marks in Slide #2 area. Inset image (B) shows the presence of sediment waves at top of submarine canyon complex and debris flow chutes. Inset (C) shows pock marks in Slide #2 complex. Some pock marks are up to 300 m across.

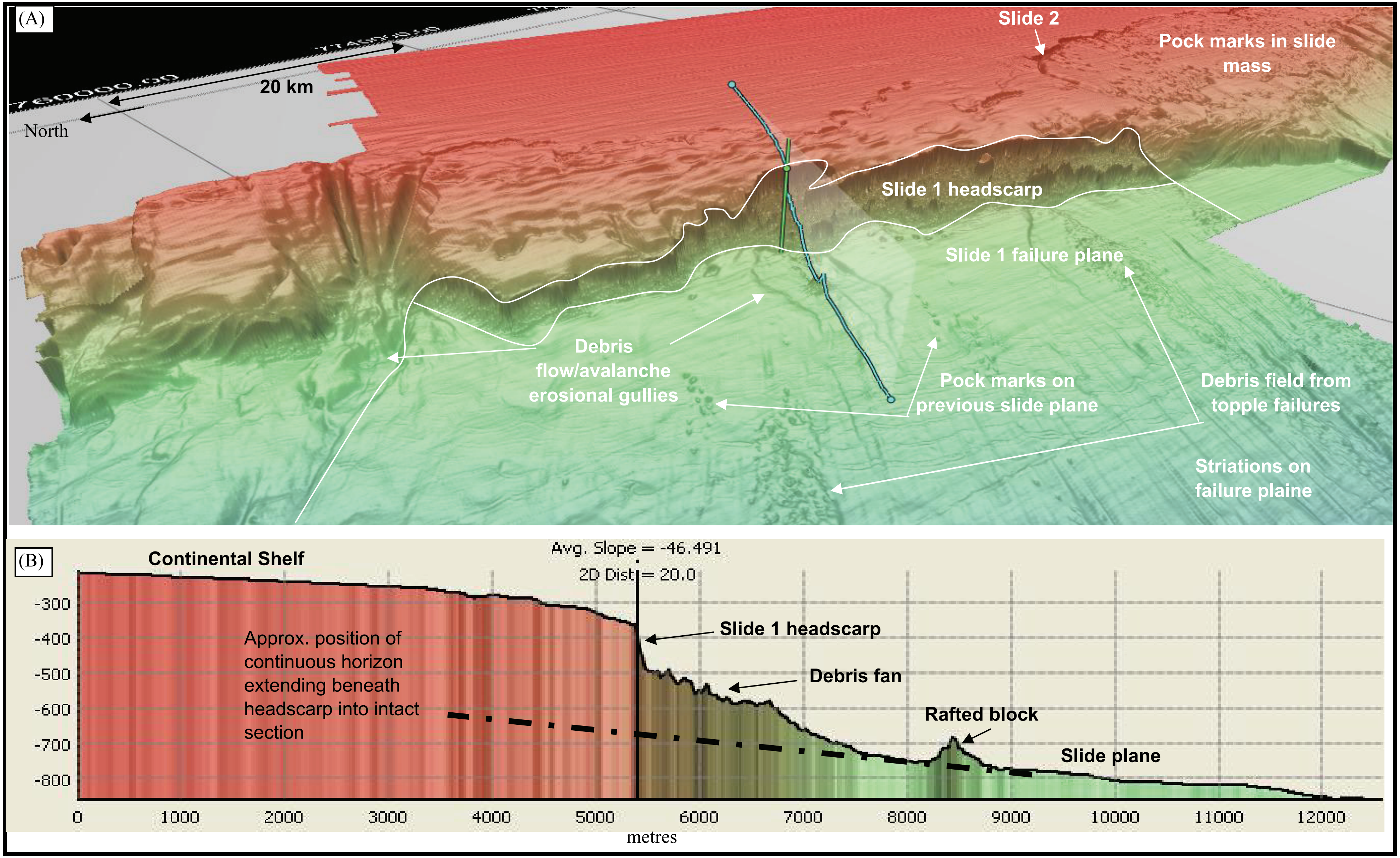


Figure 8. (a) Perspective view to east across Gorgon Slide #1 scarp. Note also the pock marks, debris fields from topple failures, and erosional channels near debris flow chutes. (b) Bathymetric profile across the scarp in the Gorgon survey area.

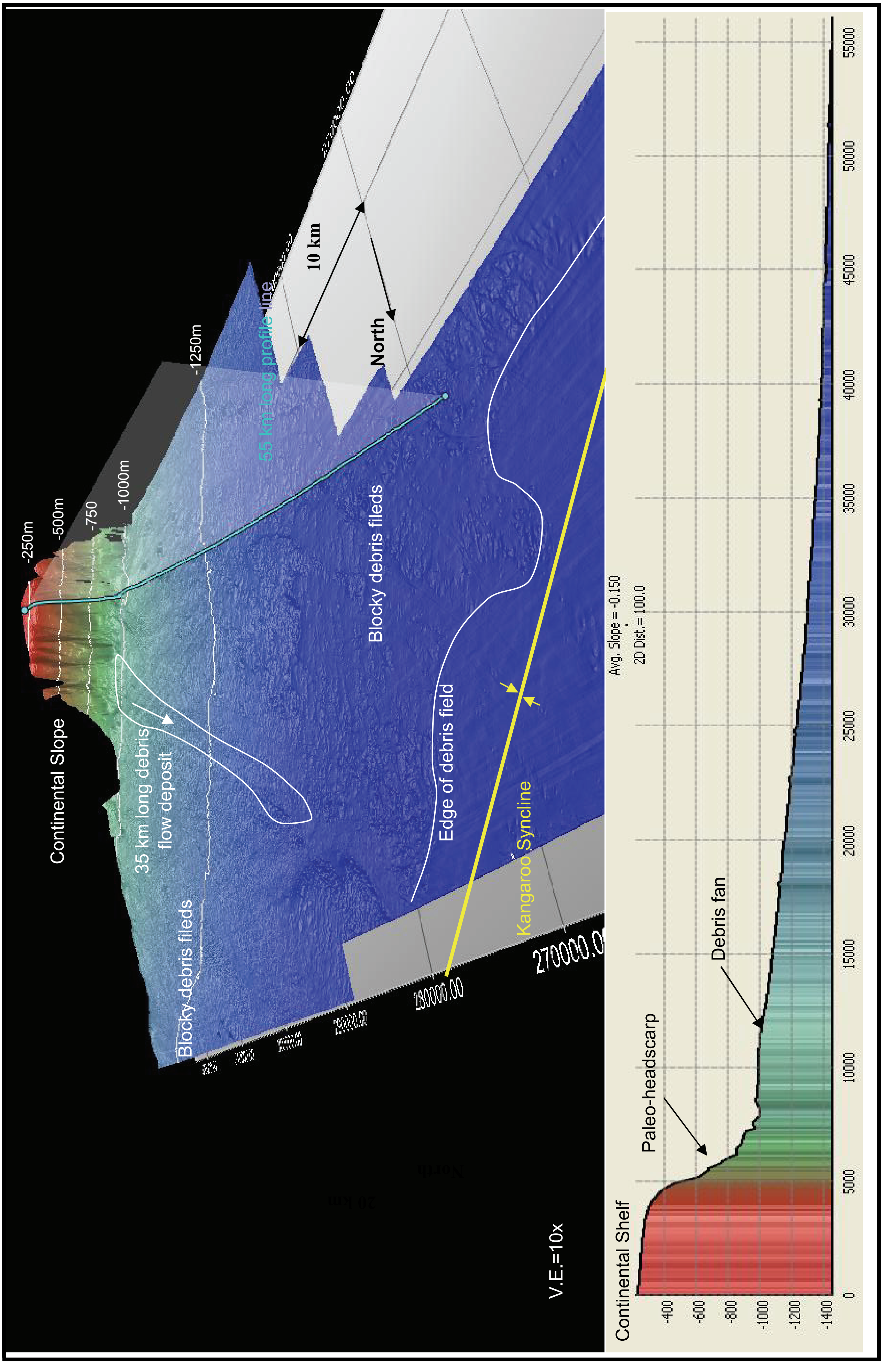


Figure 9. Seabed rendering of Willem survey area showing Kangaroo Syncline, continental slope in distance, MTC debris field along lower slope, and other debris flow deposits overlying MTC debris field.

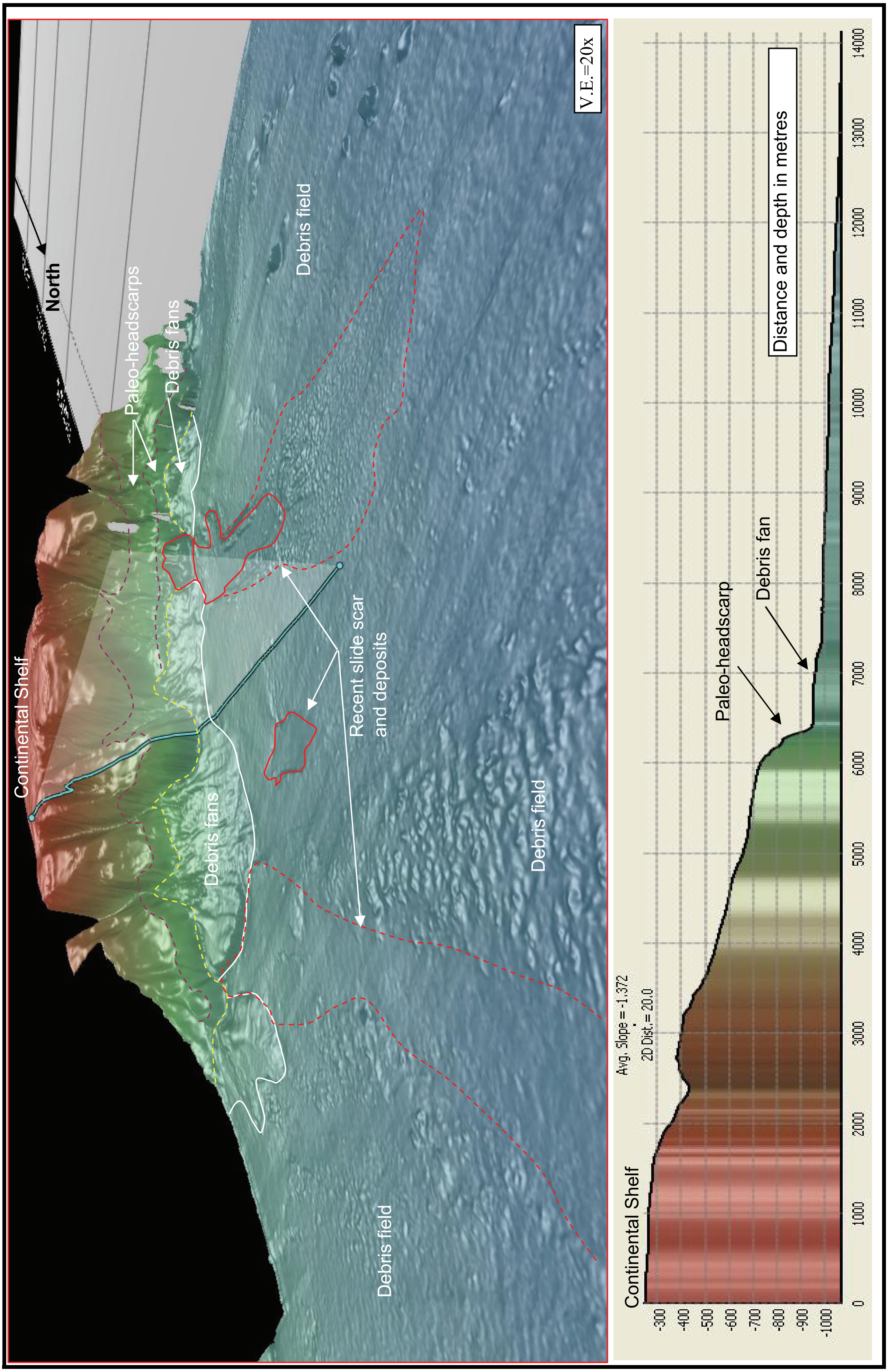


Figure 10. Paleo landslide headscarp at base of Willem slope. Note also sedimentary fan development, and debris flow failure of fan complexes. Profile line is 14 km long and average slope gradient is 1.3 degrees.

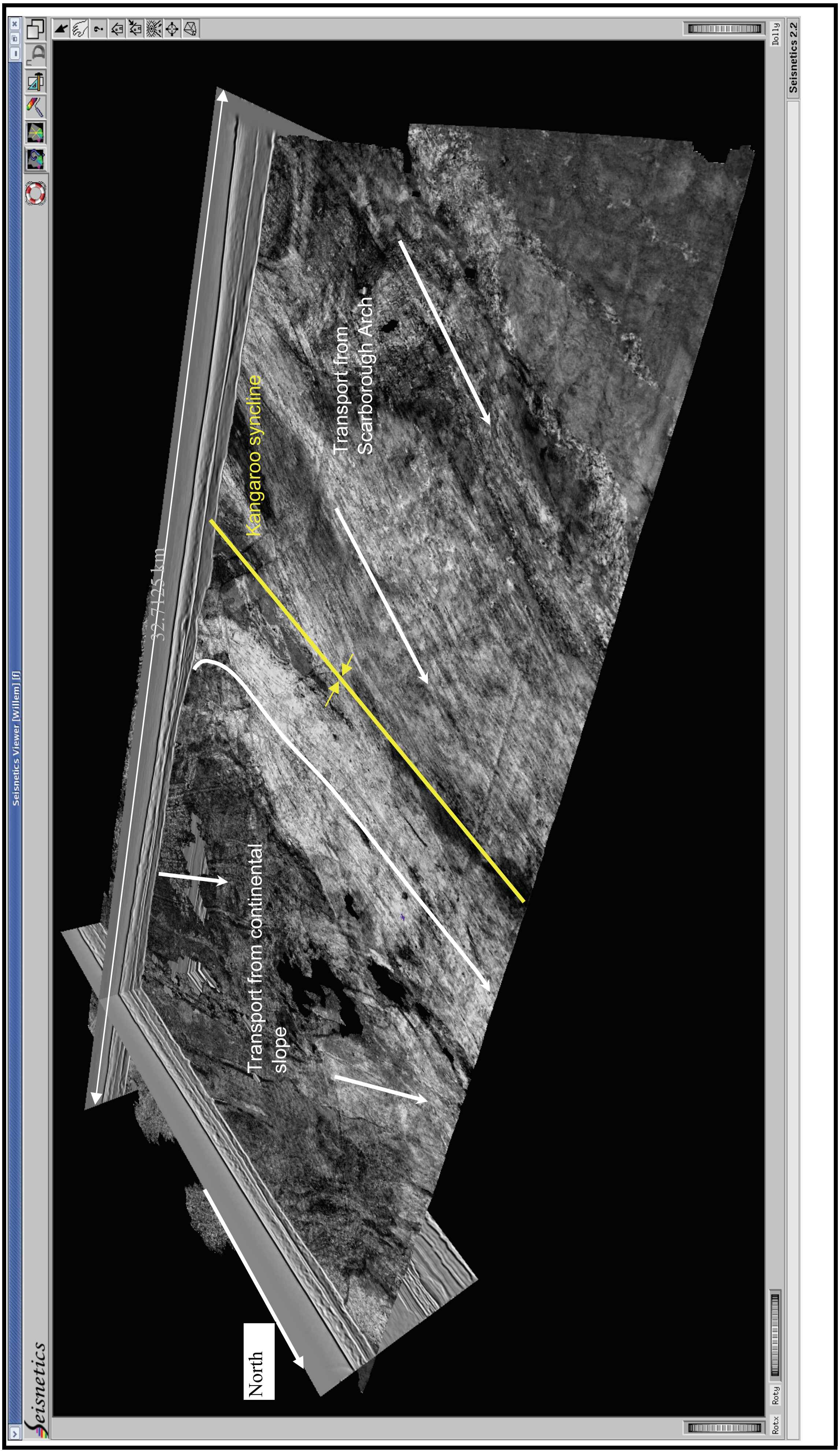


Figure 11. Striations on basal failure plane of MTC deposit, Willem 3D marine seismic survey.

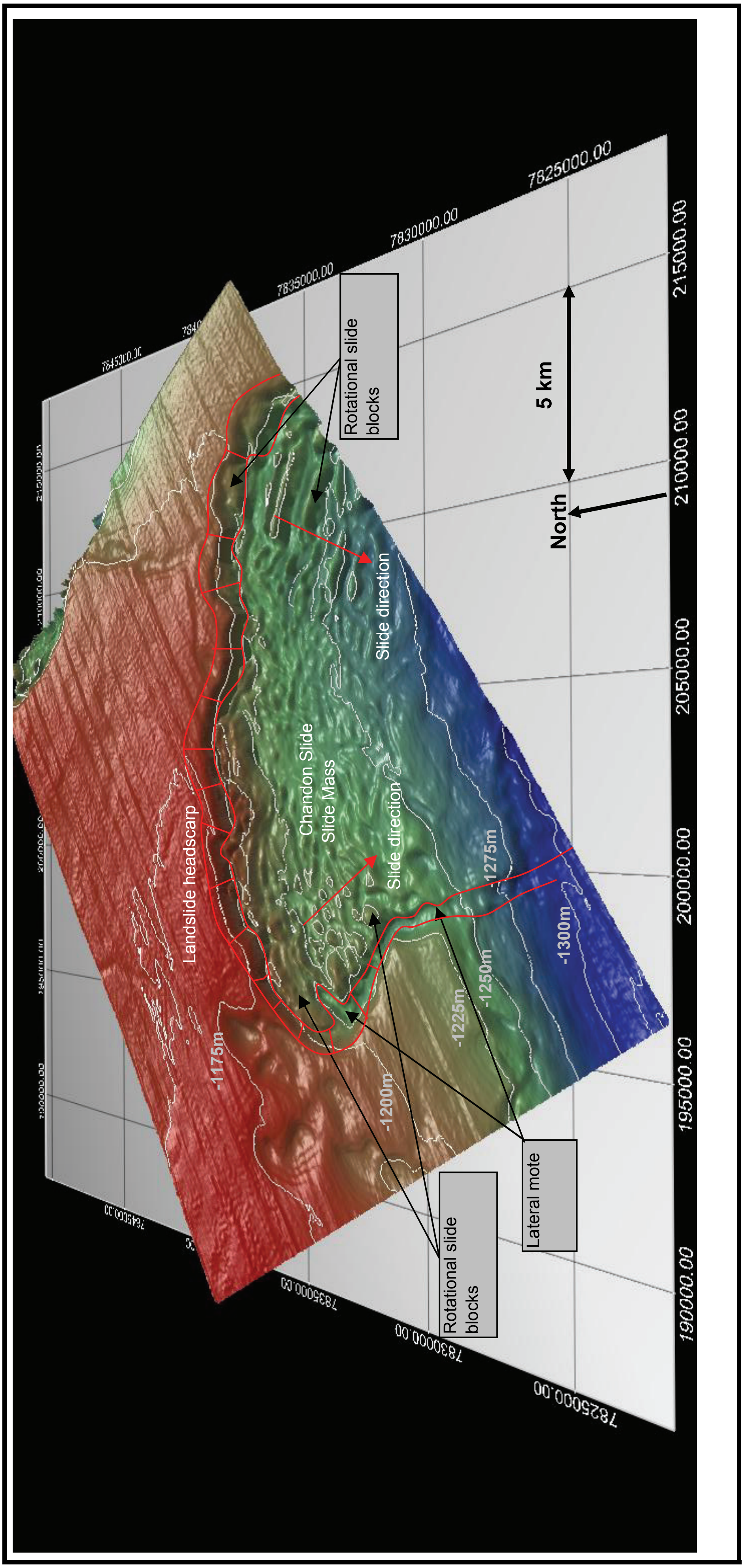


Figure 12. Seafloor rendering of the Chandon slide, northeastern Scarborough Arch. Regional relations suggest the slide should connect to a larger slide downslope and extend about 35 km to the trough axis. The slide mass shown is 17 km wide and 10 km long (to the limit of survey).

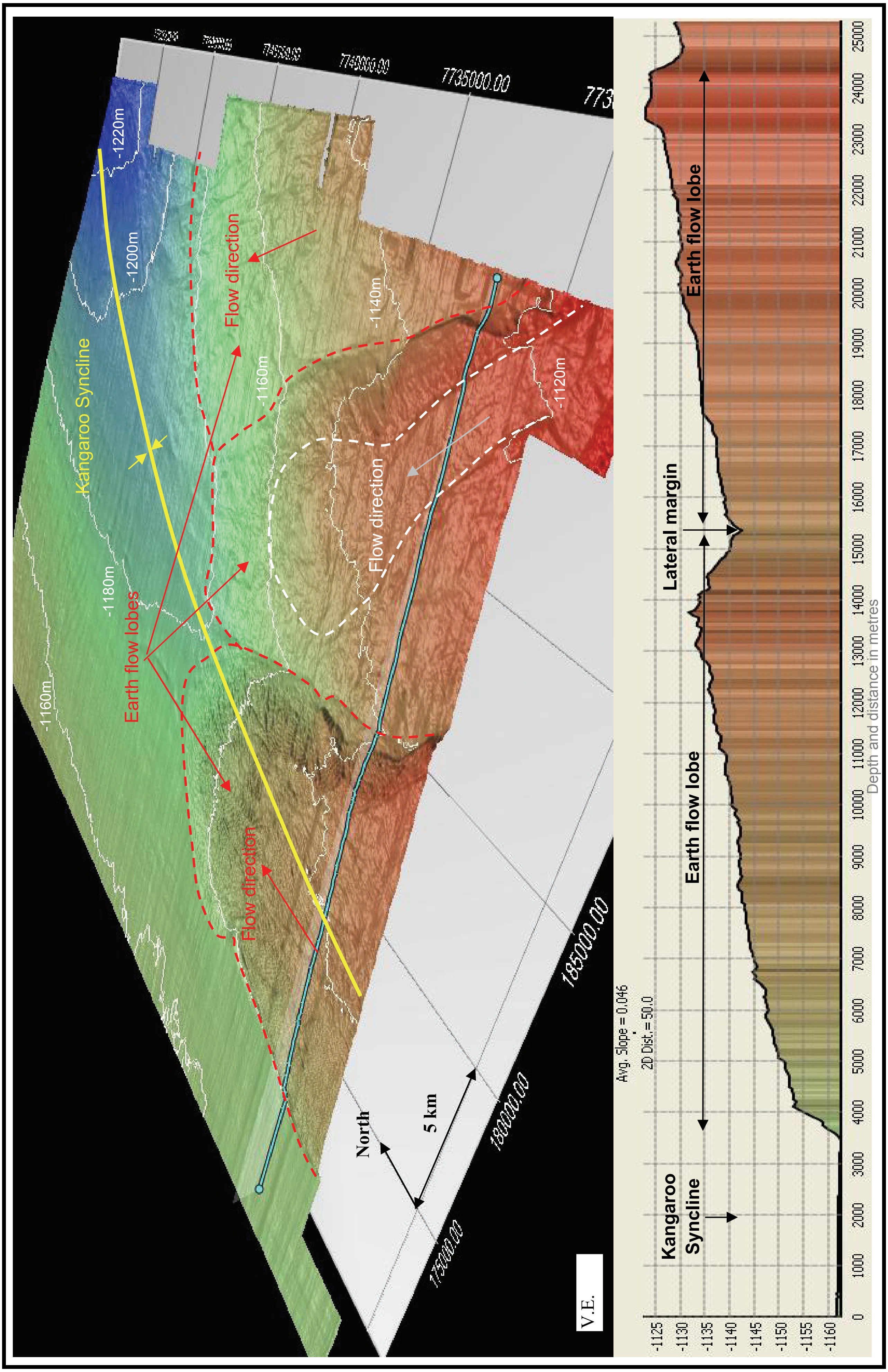


Figure 13. (a) Ten kilometer wide debris flow lobes within the Glencoe survey area in the centre of Kangaroo Syncline, 75 km from the continental slope. (b) Bathymetric profile across debris lobe in the Kangaroo Syncline.

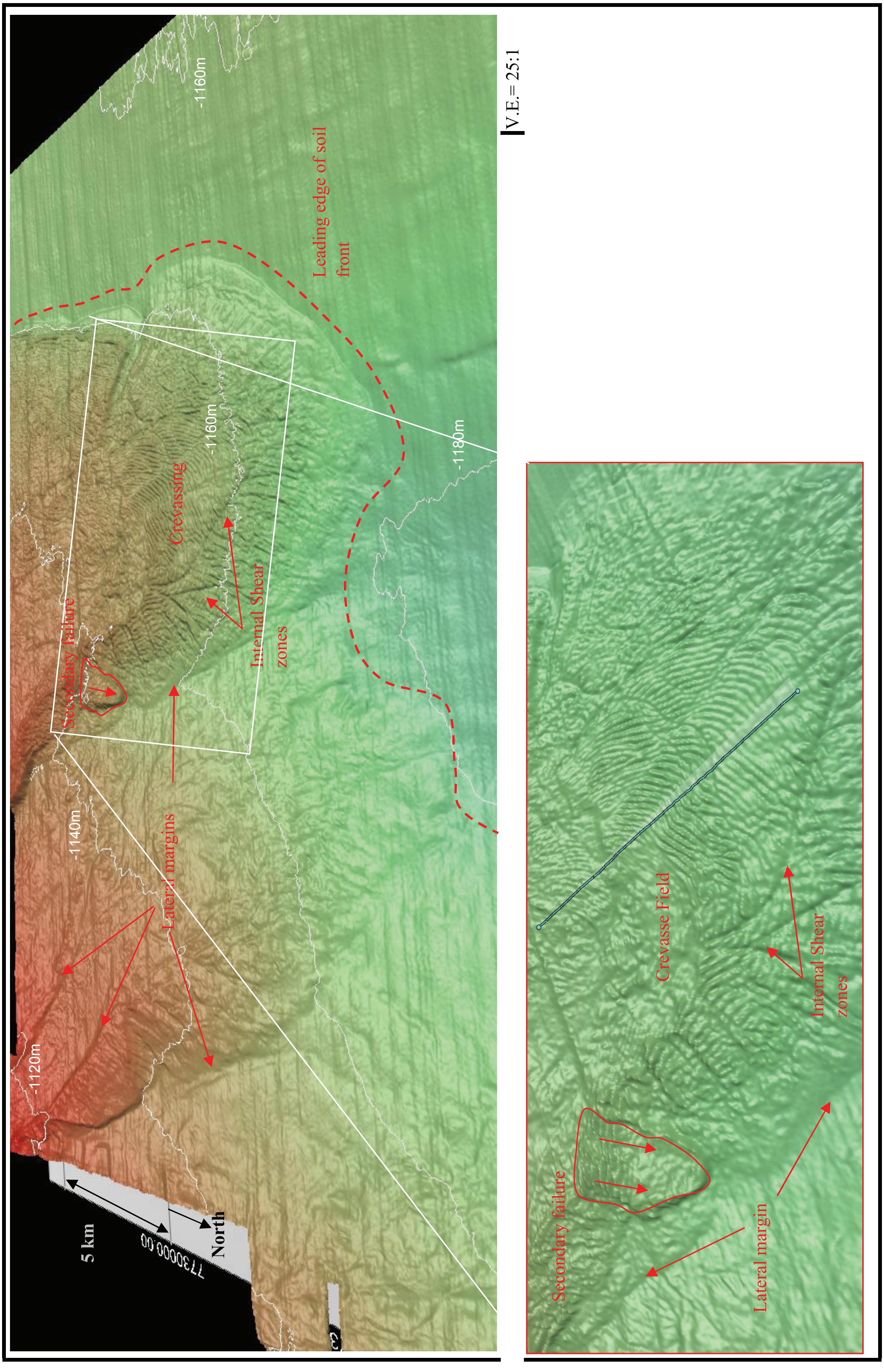


Figure 14. Close up views of debris flow lobes shown in Figure 13. Close up view illustrates the presence of crevasse fields, internal shears, and lateral shear margins.

Shelf and therefore improving our understanding of seabed processes will help to reduce the risk to these and future projects in the area.

The Gorgon/Acme and Willem surveys are located along the continental slope and the Willem survey extends across the lower slope to the Kangaroo Syncline (Fig. 4). The large scale morphology of this part of the continental slope is characterised both by undisturbed sedimentary fans, submarine canyon systems, and submarine landslide complexes (Fig. 7).

A range of geomorphic features on the seabed indicate that surficial geomorphic processes play an important role in the evolution of the continental slope and landslides are probably the dominant mechanism by which sediment is transported down the slope. This process has likely persisted since formation of the continental slope following continental rifting and landslide complexes may be an important part of the sedimentary section preserved along the base of the slope.

The landslides observed during this study provide analogies to the types of post-rift landslide deposits that are present at depth along the continental margin of the Exmouth Plateau. The types of landslides observed along these parts of the continental slope include: small translational failures and slumps (<1 km across); moderate scale debris flows, debris avalanches, and topple failures (5–10 km across); and large scale mass transport complexes (~20–30 km across). The small failures and slumps have the greatest likelihood of occurrence on steeper slopes with unstable sediment accumulations, such as the sedimentary fans at the base of canyons, near sediment waves at the tops of the canyons, or along sedimentary aprons such as the one that blankets the slope in the southern part of the Gorgon survey area (Fig. 7). The moderate scale failures appear most likely to occur along the sedimentary fan complex that has accumulated at the base of submarine canyons, or at the base of paleo-headscarps from past mass failure events (i.e. the Gorgon and Willem scarps). The debris fields from topple failures beneath the Gorgon scarp (Fig. 8), and the recent slide scars and deposits shown on Fig. 10 provide examples of these types of moderate scale failures. We infer that these types of failures are primarily driven by gravitational instability related to oversteepened scarps, or areas with rapid sediment accumulation (fans).

Large scale mass transport events such as those that formed the Gorgon Slide 1 failure (Figs 7 and 8), or the buried series of MTCs shown on Fig. 6 from the Willem survey area, involve deep seated translational failures that may be up to 200 or 300 m thick, 20–30 km wide, and 50–75 km long. The volumes for these events therefore can be of the order of several hundred km^3. We speculate that deep seated failures of these magnitudes likely require a triggering mechanism such as an earthquake and/or gas expulsion event. The association of reactivated faults (Fig. 3), inversion structures, gas reservoirs and seafloor expulsion features (pock marks: Fig. 7) suggests there may be a tectonic control on seafloor stability (Hengesh et al, 2011). Large scale mass transport events may occur near areas where fault reactivation has inverted former basin structures along the rifted margin. The structural inversions can locally increase slope gradient (driving force) and can provide a source for gas/fluid release (venting) that reduces soil effective stress. A magnitude-frequency relationship from the historical seismicity at Exmouth Plateau (Fig. 1) indicates that one earthquake of M~7 can occur within the area about every 1,000–1,500 years. Earthquakes of this magnitude generate earthquake strong ground shaking that increases lateral loads and reduces effective stresses through pore pressure changes. Consideration should also be given to the impact long term production would have upon the structural stress tensors found in the overlying section. Due to the unusually weak calcareous soils on the North West Shelf any of these factors may be sufficient to trigger a large scale mass wasting event.

The Chandon slope failure on the flanks of the Scarborough Arch has a different character to the debris flows and mass transport complexes along the continental slope. The Chandon slide appears to be a large translational failure with rotated soil blocks within the slide mass (Fig. 12). The failure is interpreted to be a slow moving translation of large soil blocks on a very low angle failure plane. The slide appears to be the upper retrogressive failure of a larger landslide complex that exists downslope.

Submarine landslides from both the continental slope and Scarborough arch are creating metastable deposits that are moving downslope and into the Kangaroo Syncline. Striations on failure planes from buried MTCs indicate movement into the syncline from both directions and the continued northward downslope movement within the syncline axis (Fig. 10). Figures 13 and 14 show examples of soil lobes on the seafloor that have mobilised from the continental slope more than 75 km away. Although the driving process for these soil lobes is probably slow moving soil creep, the soil lobes will pose unusual geotechnical conditions and could impose strains on subsea infrastructure systems, especially in the areas where crevasses have formed or along the lateral margins. Although the Kangaroo Syncline appears flat on many bathymetric maps, a careful understanding of the seafloor conditions and route options is important to minimise risks.

Together all of these landslide types form elements of a slope process model. Within a slope process model the types and frequency of landslide occurrence tends to follow a power law (ten Brink et al, 2006), meaning that like many natural processes there is a relationship between the magnitude of an event and its frequency of occurrence. Specifically, there are many more small slope failures than large ones. Though the large failures are the most impressive, even smaller failures can jeopardise pressure integrity of a field development or export system. As such, it is very important that the data acquisition programs carried out in support of site investigations and engineering design be fit-for-purpose. Although regional 3D exploration seismic data are suitable for general screening purposes, these data are not suitable for detailed mapping and characterisation of the sea-bed to support detailed design and engineering. The 3D exploration data are useful for identifying the types of failures from infrequent moderate to large events, such as the landslide complexes along the Gorgon scarp and Scarborough arch (Fig. 4), but these data are not suitable for identifying small failures (e.g. 10s of metres) that still could impose unacceptable loads on sea-bed developments. It is recommended that additional high resolution swath bathymetry or AUV datasets be collected for future slope process risk assessments in this area and other deep water, far shore areas of the North West Shelf.

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