

# LANDSLIDE GEOMORPHOLOGY ALONG THE EXMOUTH PLATEAU CONTINENTAL MARGIN, 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 peak and trough surfaces in an unbiased and automated manner. The extracted surfaces were combined in a 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 six of the survey areas.

Geomorphic mapping shows the presence of slope failures ranging from small (<3 km across) to moderate (<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 mobilization 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 approximately 200 to 300m of water and run out to the Exmouth Plateau surface in approximately 1,100 to 1,400m 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 slides seem to occur more frequently than large slides and thus may pose a greater hazard to subsea infrastructure than large infrequent MTCs.

## 1. INTRODUCTION

As global energy demand continues to grow, numerous potential field developments are being identified in deep water along Australia's North West Shelf. A significant number of potential developments have been identified at depths of 500 to 1000 metres (m) or more, and several hundred kilometres 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 potentially could 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 amongst the largest earth movements in the world (Moore et al., 1989; Hampton et al., 1996; Masson et al., 2006) involving thousands of cubic kilometres 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 jeopardize system integrity.

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

## 1.1 GEOLOGICAL SETTING

The Exmouth Plateau encompasses part of the offshore Carnarvon Basin (Figure 1). This area is located on the northwestern margin of the Australian continent approximately 800 to 1000 km south of the tectonically active boundary between the Australian and Eurasian tectonic plates.

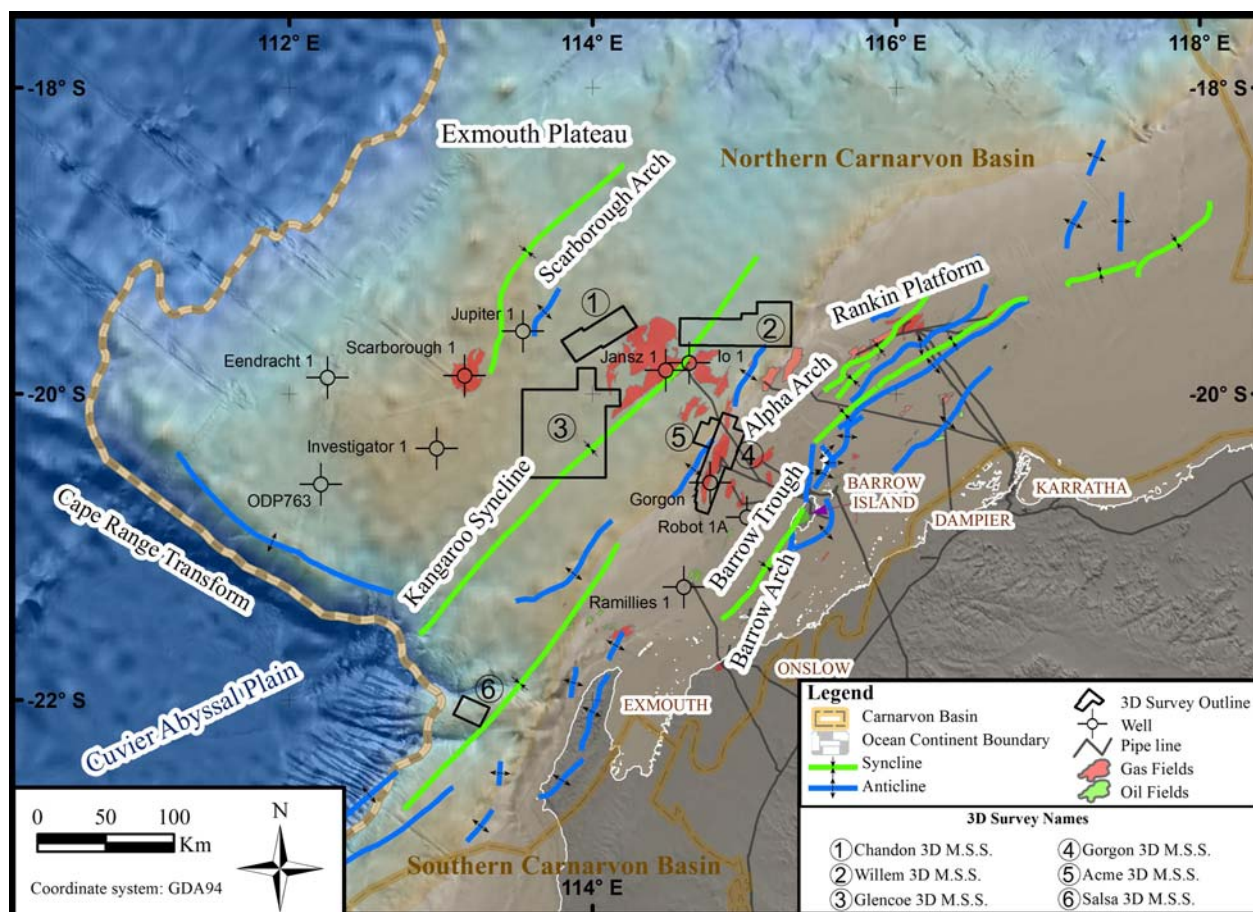


Figure 1: Regional tectonic and physiographic setting of the Exmouth Plateau. Grey polygons represent survey locations. Dark gray lines represent locations of sections shown on Figure 2. Coloured circles represent earthquake epicentre locations.

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 (modified from AGSO North West Shelf Study Group, 1994). The sedimentary sequences are each bound by erosional unconformities. There are three Palaeozoic 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).

Triassic to earliest Cretaceous sequences of the northern Carnarvon Basin (Figure 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 Cretaceous time (Hocking, 1990; Exon and Buffler, 1992; Exon et al., 1992; Baillie et al., 1994). The Late Cretaceous, Palaeocene 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; Burchette and Wright, 1992) and carbonate-dominated hemipelagic sedimentation (von Rad and Haq, 1992; Boyd et al., 1992).

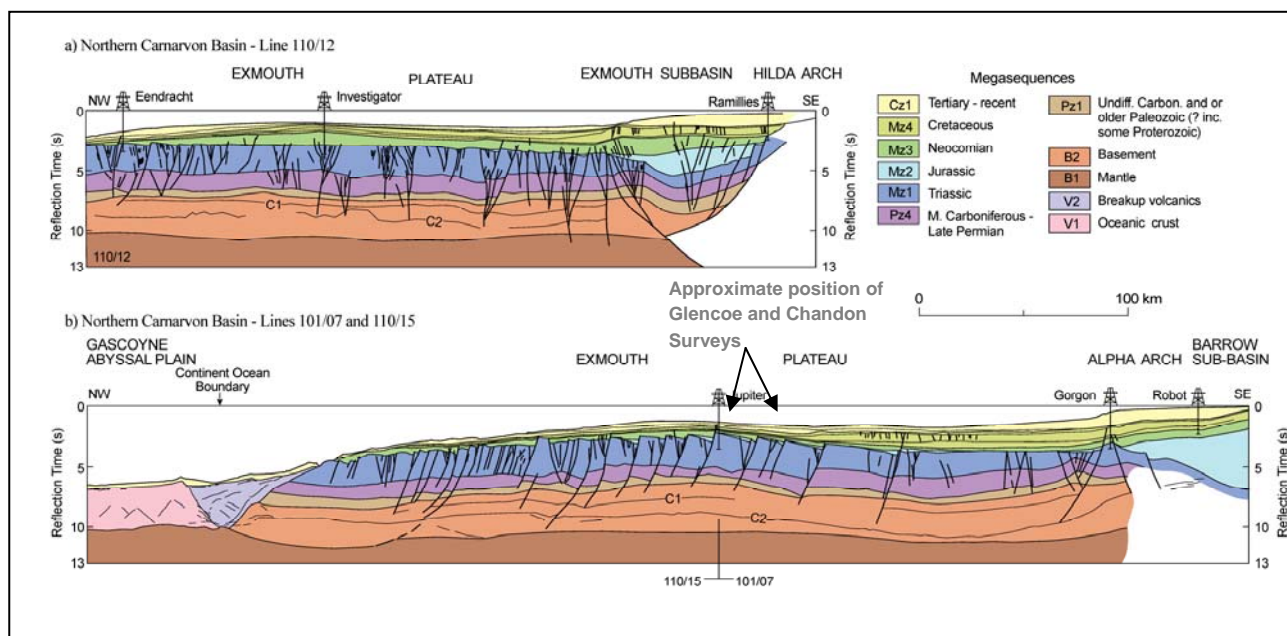


Figure 2: Regional geological sections showing major stratigraphic and structural relations across the Exmouth Plateau. Modified from AGSO North West Shelf Study Group (1994).

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. It is bound by rift-related normal faults at the craton margin (AGSO North West Shelf Study Group, 1994) and is bound by abyssal planes on the north, west, and south. 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 subarial lava flows at the ocean-continent boundary (Figure 1), fluvial/subarial depositional environments for pre-rift sedimentary sequences, as well as subsidence modelling (Kaiko and Tait, 2001) indicate that 1 to 4 km of subsidence has occurred (from east to west) across the Exmouth continental margin between late Jurassic and Pleistocene time. This subsidence is a combination of post-rift tectonic subsidence, thermal sagging, and sediment loading and is the driving mechanism 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 both transform and contractional reactivation leading to structural inversion of basin sequences both onshore and offshore. Reported relief across these structures varies from 300m to 900m (Hengesh et al., 2011a; Densley et al., 2000). This structural reactivation is widely attributed to the Neogene to Recent reorganization of the northern Australian plate boundary, but some structures may be as old as Cretaceous (Figure 3) (Boyd et al., 1992; Keep and Moss, 2000; Kaiko and Taite, 2001; Cathro and Karner, 2006; 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., 2011b).

## 1.2 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 approximately 200m 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 600m. Average slopes along the canyon systems are on the order of 3 to 7 degrees (following interflaves), while the average slopes across the landside complexes are much higher with common 30 to 70 degree slopes.



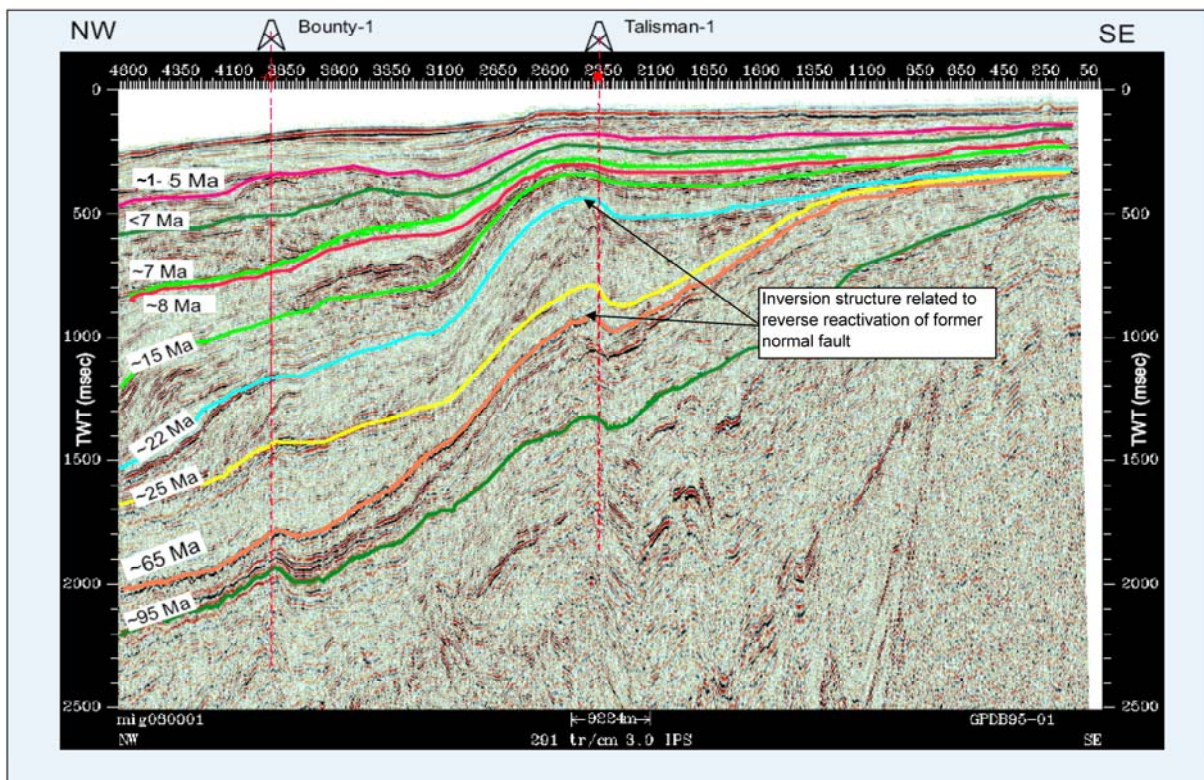


Figure 3: Example of late to post-Neogene inversion structure underlying the continental slope. Modified from Kaiko and Tait, 2001.

The continental slope extends from the shelf break to the Kangaroo Syncline at about 1,400m 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 (~1,400m depth), over the arch (~1100m depth), to the continent-ocean boundary at approximately (~5000m depth).

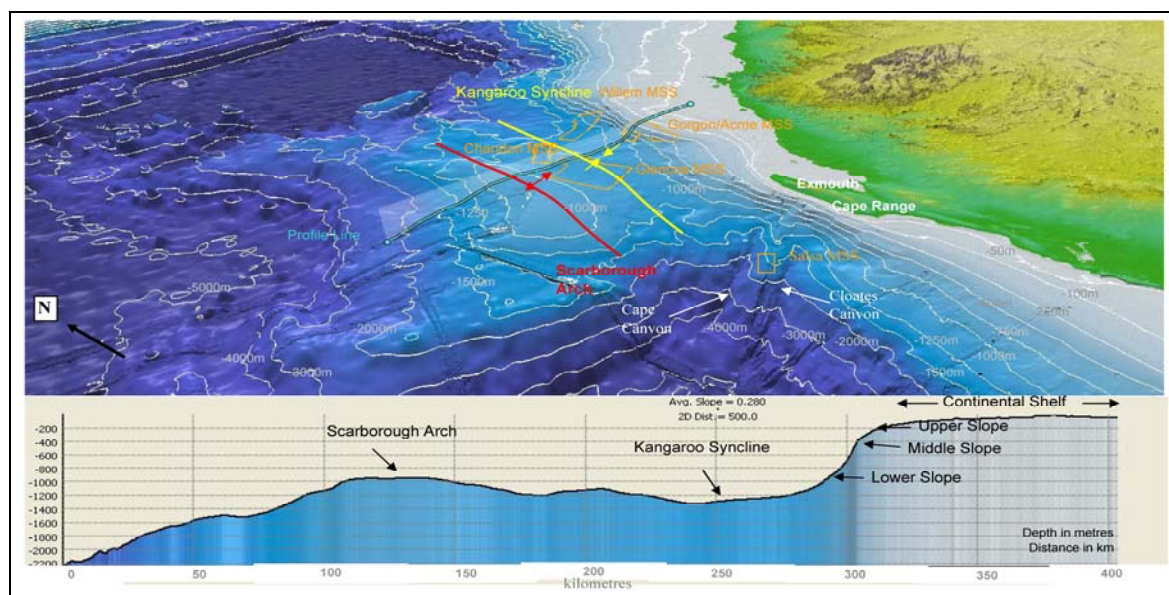


Figure 4: Oblique view to northeast across Exmouth Plateau showing major physiographic features and survey locations. Bathymetric data from Geoscience Australia. Vertical exaggeration 20 times.

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) hemipelagic 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 tens of metres of sediment.

## 2. 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 Late Triassic to earliest 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 (Figure 4).

late Miocene to Recent collision of the Banda Arc and Australian continental plate and tectonic re-organization of Australia's northern plate boundary (Audley-Charles, 1986a, 1986b, 2004; Keep and Haig, 2010) has resulted in the reactivation of some faults along the former rifted margin of Western Australia (Whitney and Hengesh, 2013). 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 sea-floor. Structures such as the Scarborough Arch and Kangaroo syncline (Figure 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 (Figure 5) (von Rad and Haq, 1992). Typical shear strength gradients in these shallow Quaternary age calcareous sediments are on the order of ~1 kiloPascal (kPa) per metre. These low shear strengths result in low residual stability of slopes and, given a triggering opportunity, a high slope hazard potential. The weak calcareous deposits overlie more competent Eocene and older sediments. Across parts of the Exmouth Plateau, the competent substrate includes polygonally faulted nanno-fossil chalk (von Rad and Haq, 1992). Figure 6 shows examples of the polygonally faulted substrate and a stacked series of large mass transport complexes (MTC) in the Willem survey area.

In other locations, such as the Bonaventure survey on the outer Exmouth Plateau (Dirstein et al., 2013), submarine landslides appear to be ancient features now draped by tens of metres to a few hundreds 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.

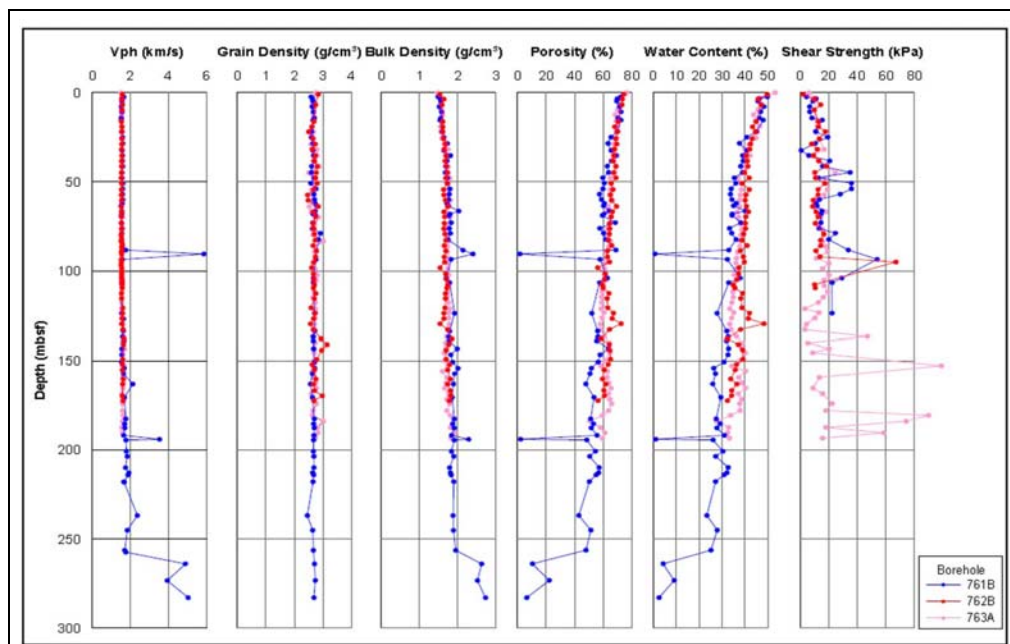


Figure 5: Sediment data from Ocean Drilling Project borings (ODP 761, 762, and 763) (von Rad and Haq, 1992).



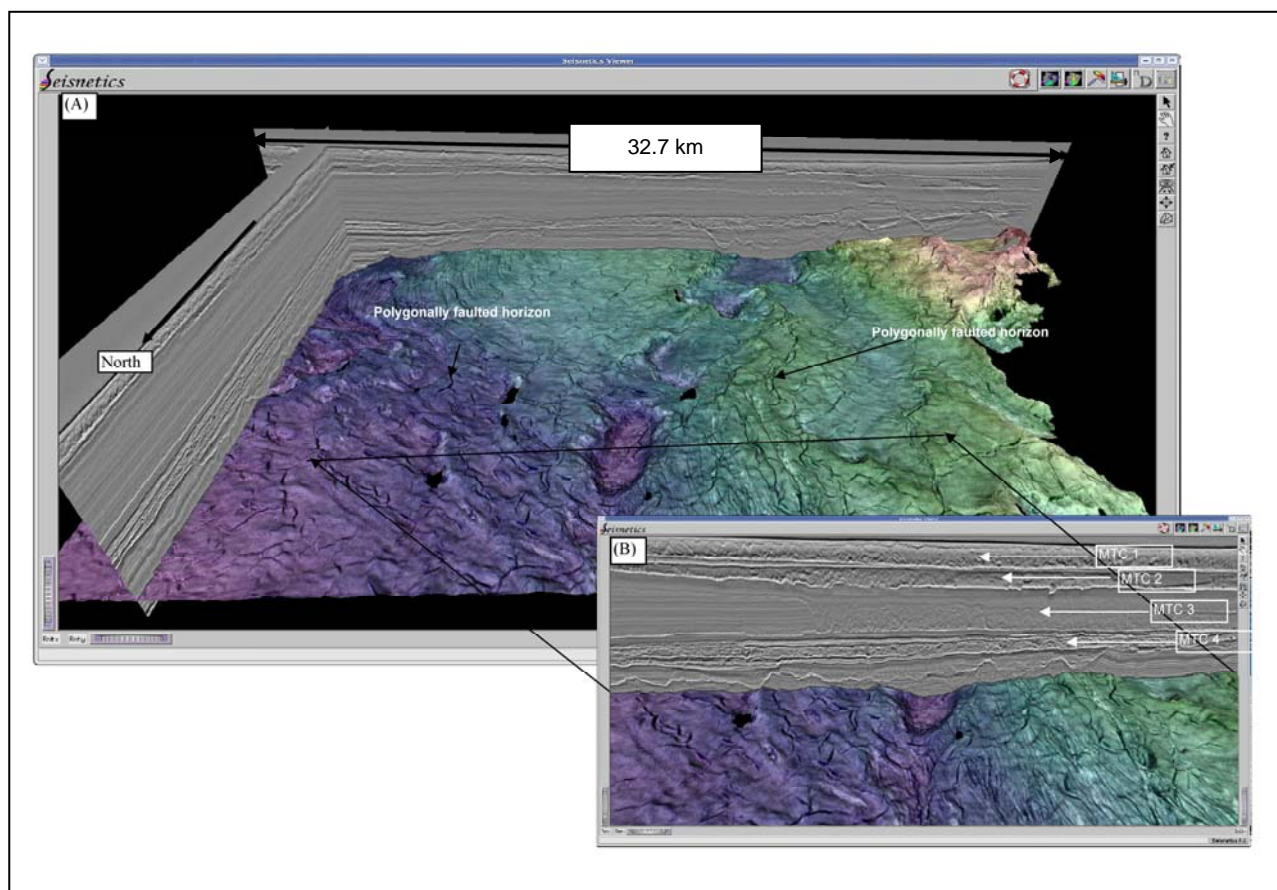


Figure 6: 3D perspective view to south across western end of Willem 3D seismic survey. The figure displays the combined Two-Way-Time and Amplitude attributes of GeoPopulation™ 130 from a subvolume of the Willem 3D survey in Seisnetics™. (A) The coloured horizon is a polygonally faulted chalk near the base of the nanno fossil ooze mobile section. (B) Arrows on inset image illustrate position of stacked submarine mass transport complexes (MTC) above the polygonally faulted chalk.

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 coordinate data were imported to Fledermaus to develop the seafloor DTMs. The exploration 3D seismic data typically have bin spacing of 12.5 to 25m 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, seismic geomorphology, and characteristics of submarine landsides. Examples are shown for the Gorgon/Acme, Willem, Chandon, Glencoe, and Salsa surveys.

## 2.1 GORGON/ACME SURVEY AREAS

The Gorgon survey covers an approximately 75-by-17 km area along the Exmouth continental slope (Figures 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 approximately 200 to 700m water depth and includes four distinct morphologies including (from north to south): (a) the 35-km long 250m high Slide 1 landslide headscarp; (b) the 20 km-long Slide 2 area of incipient slope failure lying above both submarine canyons and the Slide 1 headscarp; (c) a system of submarine canyons and debris flow chutes (referred to as Southern Canyons); and (d) a relatively smooth, sedimentary apron (fan) with little evidence of canyon formation or mass wasting. Concentrated fluid and gas expulsion features (pock marks) are common in the northern and central parts of the survey area and appear spatially associated with the Slide 1 and Slide 2 landslide failures; the expulsion features are less common in the Southern Canyons area, and are uncommon in the areas where there is a smooth sedimentary apron.

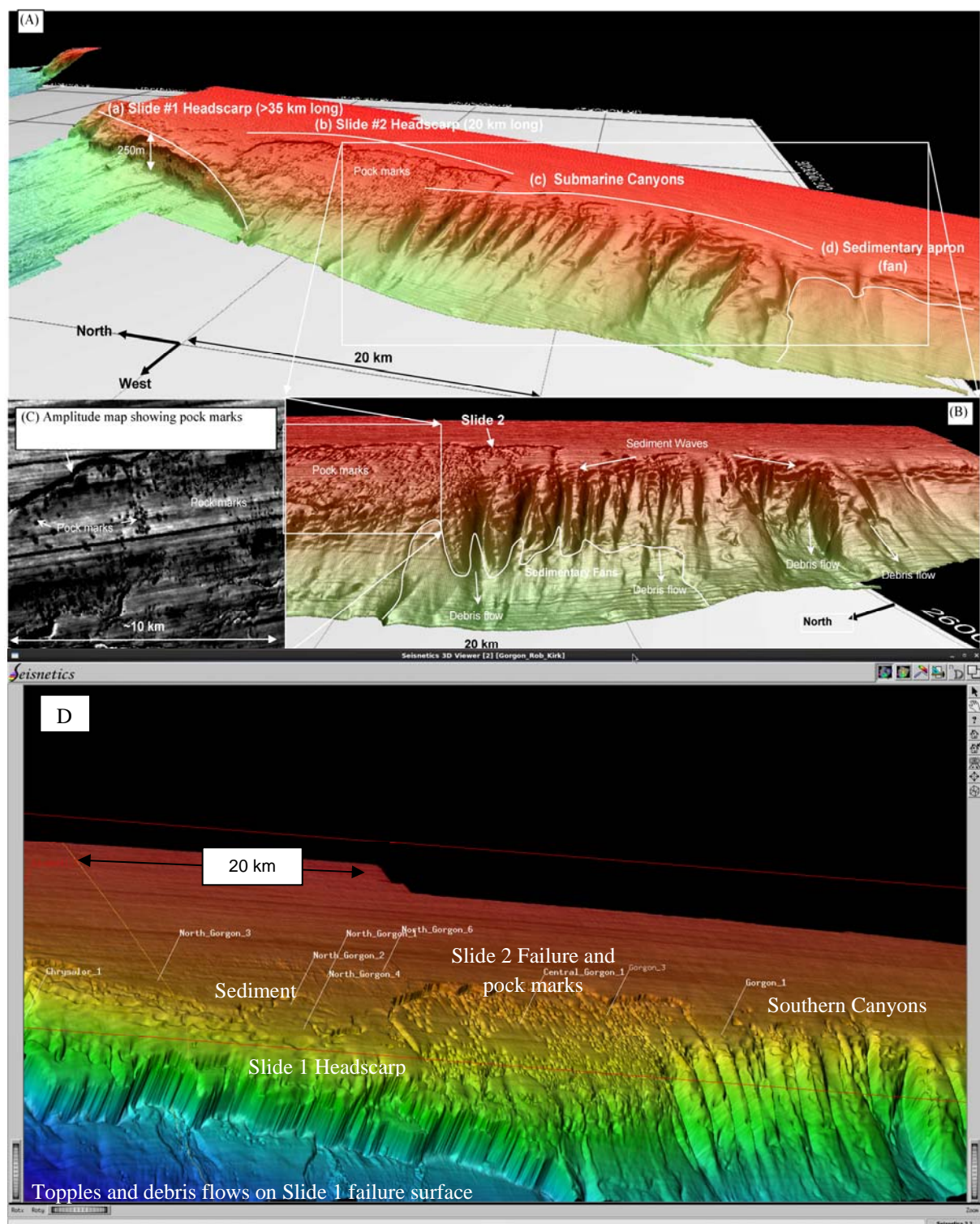


Figure 7: Perspective views of seafloor along Gorgon 3D survey area. (A) Shows four prominent morphological features along the Gorgon escarpment: (a) Slide #1 headscarp; (b) Slide #2 complex; (c) Submarine canyon system; and (d) Sedimentary apron or fan complex. Note also the extensive fields of pock 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 300m across. Inset (D) shows perspective view of Gorgon Scarp including significant wells and Slide 1, Slide 2, and Southern Canyons (from Seisnetics 3D viewer).

The submarine canyon system in the southern part of the survey area has an average slope gradient of about 2 to 5 degrees: 4 to 8° in the upper canyons; 2 to 4° in the middle part of the canyons; and 1 to 3° along the lower canyon and fan complexes. The individual canyons are approximately 5 to 8 km long and generally 0.8 to 1.6 km wide, though one



canyon is 4.5 km wide (Figure 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 instability of these slopes under static conditions. Sediment waves have formed near the top of the slope along the shelf break and provide sediment sources for down slope transport through the canyon systems and down the continental 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 350m of water to the lower continental slope in approximately 700m of water. The slope gradient is 30 to 70 degrees and locally may be vertical (Figure 8). The slide is a minimum of 35 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 (Table 1). 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 (Figures 8 and 9). The slide thickness was about 300m. Note also the near vertical fault that projects from approximately 5.2 seconds two-way time (TWT) in the underlying inversion structure to the base of the landslide failure (Figure 9). This is a deep structure and if seismically active could be the source of the earthquake that triggered the Slide 1 and Slide 2 failures. A secondary kink band located several hundred metres west of the main fault extends to the near sub-bottom which implies recent structural deformation along the fault zone. The stratigraphy along the fault shows subtle drag folding. This folding increases the dip along east block of the fault (along the continental slope), creating a dip slope condition that reduces stability along the slope.

Extensive pock marks and expulsion features are recognized on sea-floor terrane models (Figures 7D and 8). These features occur both within the slide mass, within drape over the former slide plane, and locally outside of landslide related features (Figure 8). Offset shallow stratigraphy and the thin layer of drape 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 (Figure 8).

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 (Figure 6). The slide geometry and MTC thicknesses suggest landslide volumes  $>50 \text{ km}^3$ , but most likely between 50 and  $100 \text{ km}^3$ . Topple failures, debris avalanches, and debris flows sourced from the headscarp represent secondary retrogressive slope failures along the primary slide feature

(Figure 8). These secondary failures can be several kilometres across with run-outs of 5 to 15 km. Erosion of the seabed also is occurring at the base of submarine canyons; these failures tend to be thin translational failures.

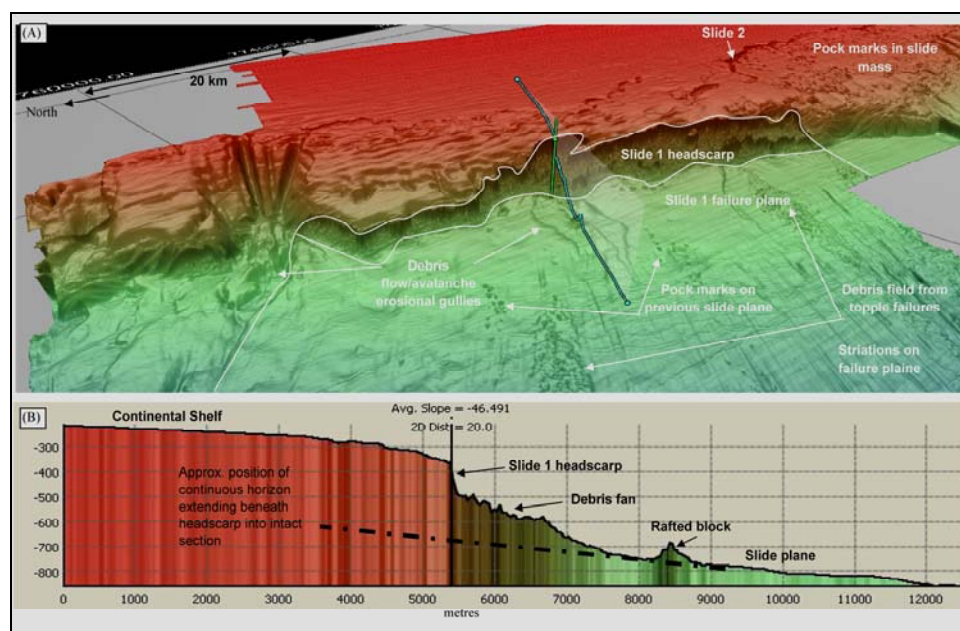


Figure 8: (a) Perspective view to east across Gorgon Slide #1 scarp. Note also the pock marks, debris fields from topple failures, and erosional channels near debris flow chutes. (b) Bathymetric profile across the scarp in the Gorgon survey area.



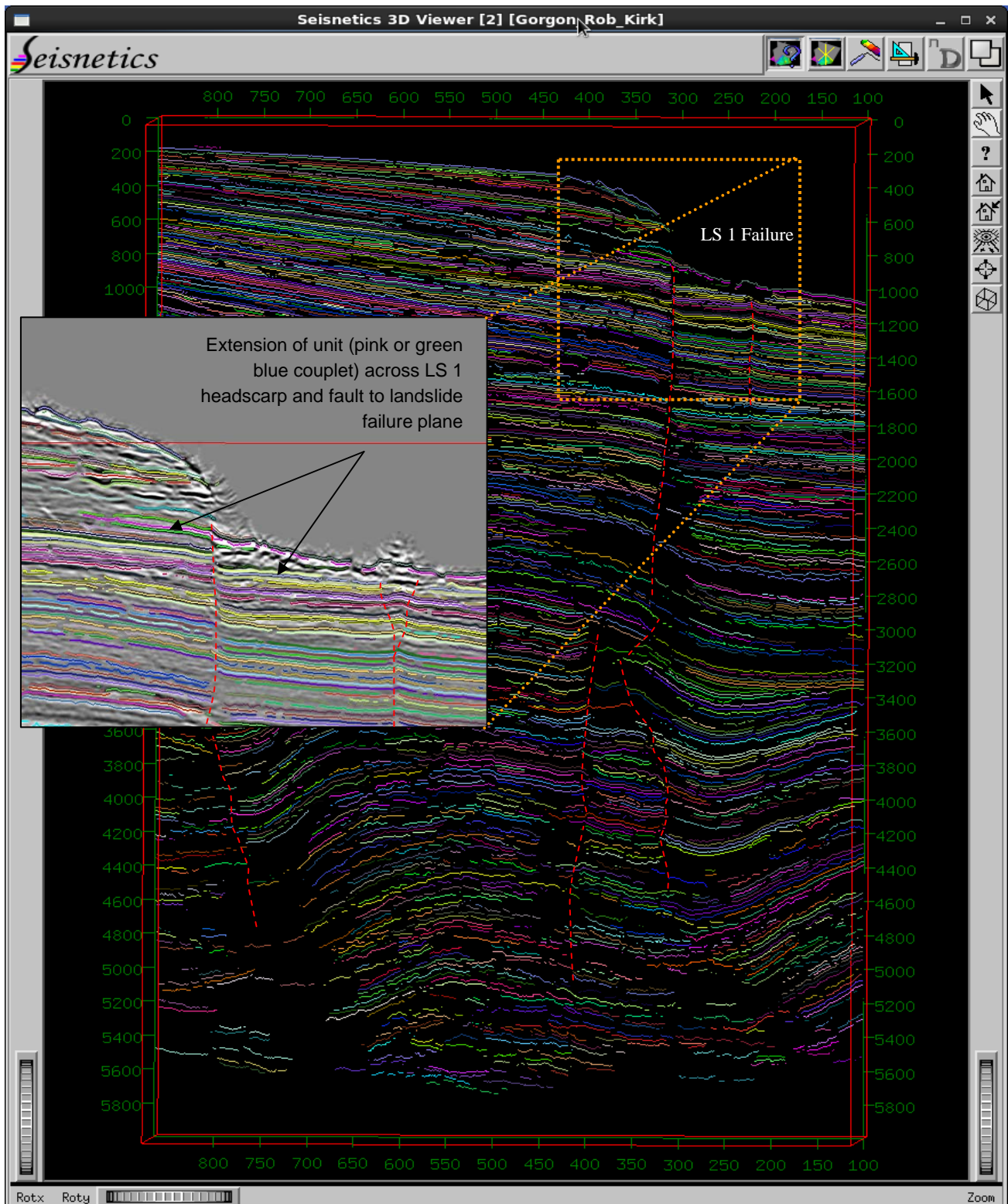


Figure 9: Cross line profiles of Gorgon 3D seismic survey showing Geopopulations<sup>TM</sup> associated with every mappable horizon. The pink horizon or the green blue couplet shown by arrows on inset diagram illustrate position of possible stratigraphic units that controlled the basal failure plain of the Gorgon Slide #1 failure. Note also the control of the headscarp position by the underlying fault.

## 2.2 WILLEM SURVEY

The Willem survey covers an area approximately 75 km long by 35 km wide along the Exmouth continental slope (Figure 4) 50 km northeast of the Gorgon survey. In this area the continental slope extends from approximately 250 to 1000m depth (Figure 10). The survey area only captures a part of the upper continental slope, but includes a large part of the lower slope (Figure 10). The upper part of the continental slope has an average slope gradient of 7 degrees, while the lower slope has an average gradient of 1 degree.

The seabed rendering illustrates the presence of large debris fields below the escarpment extending approximately 55 km from the slope to the eastern edge of Kangaroo syncline (Figure 10). The debris field includes large (20 to 60m above seabed) landslide blocks located up to 13 km from the continental slope, and smaller debris blocks that extend to the Kangaroo syncline. These debris field deposits have been draped by hemipelagic sedimentation and sediment transported down slope, and have been eroded and incised by other younger debris flow deposits. Some of these younger debris flow deposits are observed extending over 35 km across the underlying debris fields on the lower slope (Figures 10 and 11). These underlying, older debris field deposits are associated with the nested large scale MTC deposits observed at depth in the seismic volume (Figure 6).

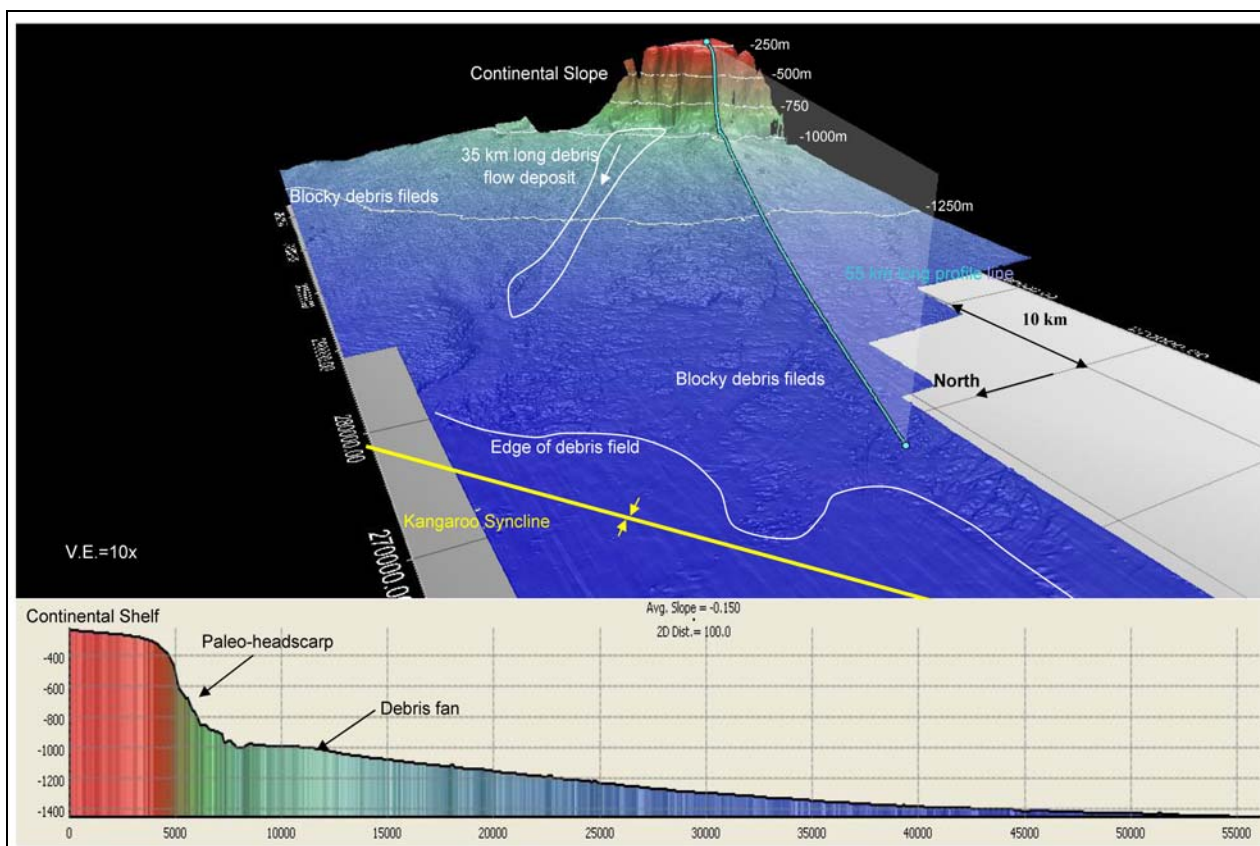


Figure 10: Seabed rendering of Willem survey area showing Kangaroo Syncline, continental slope in distance, MTC debris field along lower slope, and other debris flow deposits overlying MTC debris field.



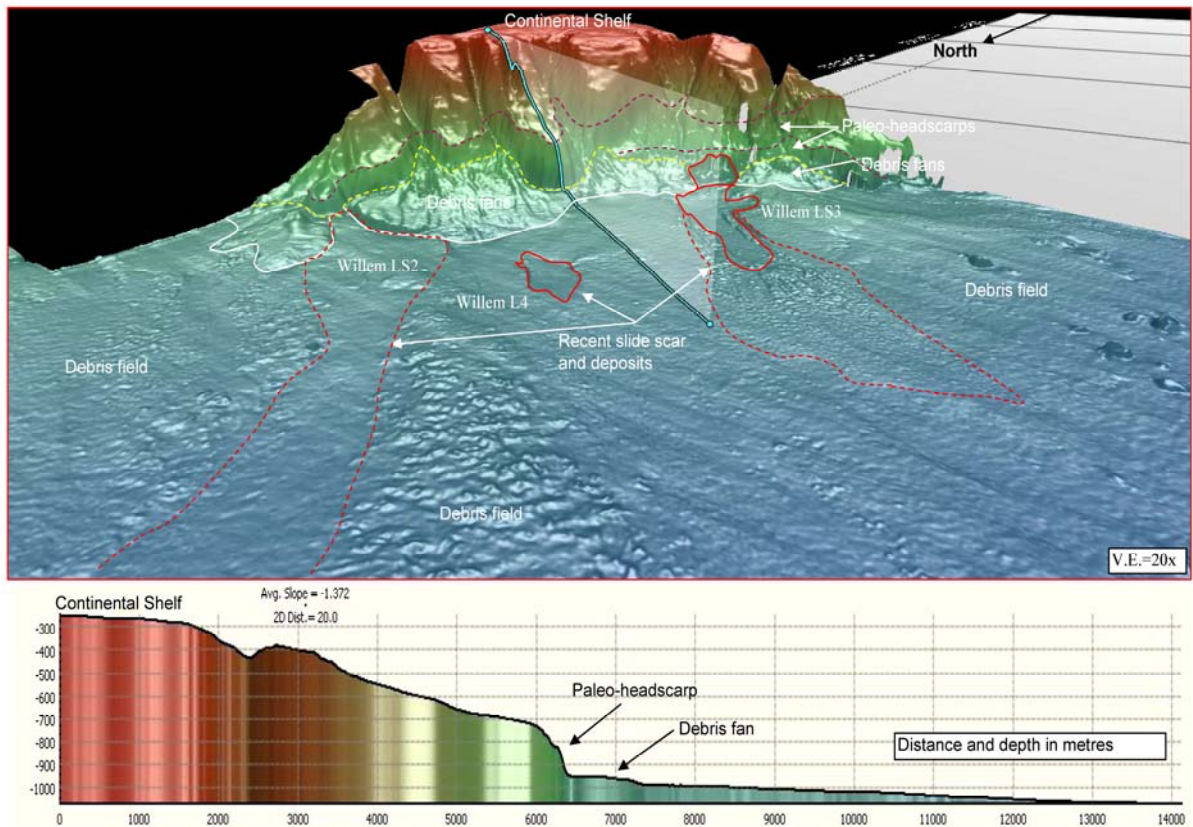


Figure 11: Palaeo landslide headscarp at base of Willem slope. Note also sedimentary fan development, and debris flow failure of fan complexes. Profile line is 14 km long and average slope gradient is 1.3 degrees.

In the Willem survey area the continental slope is oversteepened at its base. A partially buried scarp with slopes between  $20$  and  $66^\circ$  is present at the base of the continental slope (Figure 11). This is inferred to be a palaeo-landslide headscarp. The headscarp is now partially buried by debris fans (Figure 11) shed from the slope. The debris fans dominantly form at the base of submarine canyons and coalesce into a complex of individual fans along the base of the palaeo-landslide headscarp. These fans have failed in two ways: (a) global failures of the entire fan complex leading to Mass Transport Complexes (Figure 6) and slide volumes of tens of cubic kilometres, and (b) local failures of individual fans at the base of canyons that have produced either rotational/debris flow events or translational slides that run down the lower continental slope. Several examples are shown on Figure 11. The southernmost example (Willem LS3) is about 1.7 to 3 km wide and produced a scar approximately 7 km long. This failure is approximately 20 to 30m deep and occurred on a failure plane with a slope of  $0.37$  to  $0.95^\circ$  (Table 1). The debris field from this event extends approximately 5 km beyond the slide scar. A retrogressive failure has expanded the landslide upslope into the debris fan complex (which has steeper seabed slopes of  $5$  to  $15^\circ$ ). The headscarp of the retrogressive failure is 60 to 80m high. The slope on the headscarp is up to  $72^\circ$ .

The large scale MTC deposits observed at depth (Figure 6) are on the order of 80 to 100m thick. The basal failure planes beneath these deposits show linear striations that illustrate direction of transport of the landslide mass. The striations shown on the horizon surface in Figure 12 comprise three populations: those coming from the continental shelf to the east; those coming from the Scarborough Arch to the west; and those moving down slope through 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 toward the Argo abyssal plain. A summary of slide parameters from the survey areas is included in Table 1.

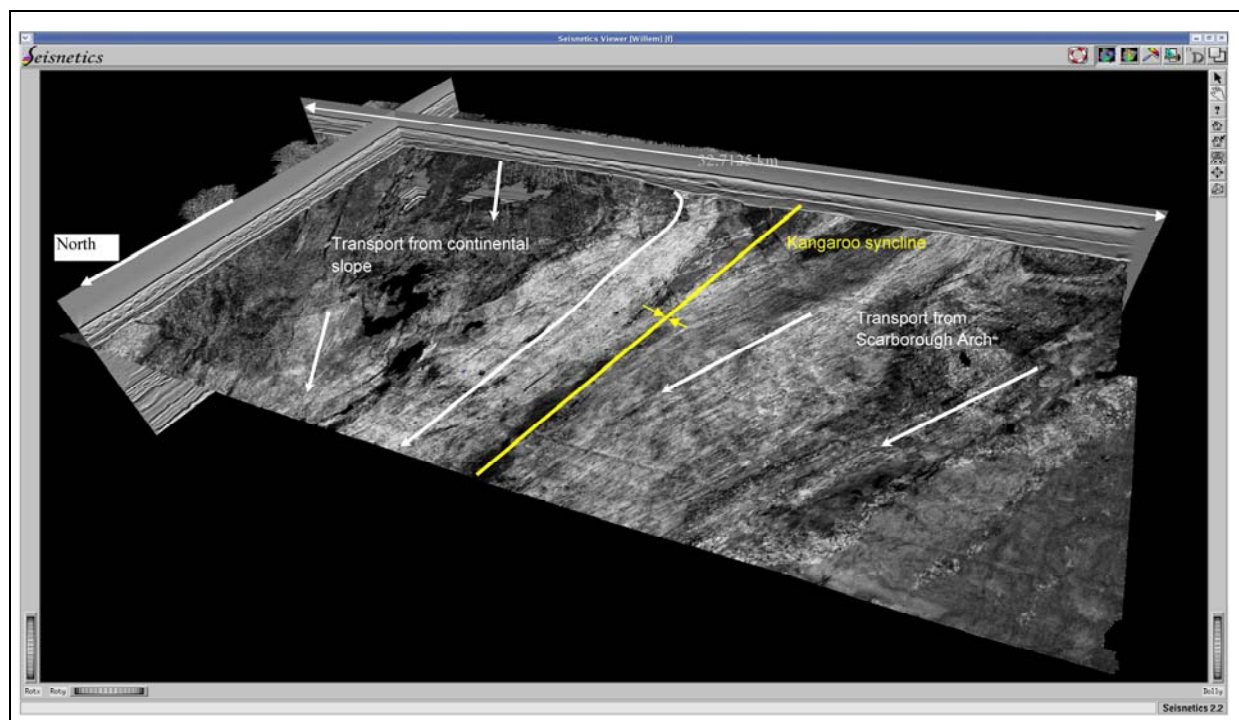


Figure 12: Striations on basal failure plane of MTC deposit, Willem survey.



Table 1: Summary of landslide parametres

Slide	Fairway Length (LS scar) (m)	Runout Length (Debris Field) (m)	Width (min) (m)	Width (max) (m)	Thick-ness (m)	Height Drop Failure zone (m)	Total Drop of Failure and Runout (m)	~Area (km <sup>2</sup> )	~Vol. (km <sup>3</sup> )	Ave Dip Failure Plane angle (degrees)/ distance (m)	Ave Stable Slope angle (degrees)/ distance (m)	Headscarp Ave Slope angle (degrees)/ distance (m)	Failure Mechanism	Velocity of down slope failure (qualitative)
<b>Gorgon LS 1</b>	8000	75000	35000	65000	300	500	800	540.0	162.00	2.0/7000	3.5/5000	21/270	Rotational/ debris flow	Rapid
<b>Willem LS 1</b>	16000	>40000	16000	22000	40	200	550	432.0	17.28	0.71/17000	0.9/1600	45/25	Translational	Moderate
<b>Willem LS 2</b>	7500	>40000	950	1400	55	110	550	12.38	0.68	0.8/7000	1.5/500	10/200	Rotational/ debris flow	Rapid
<b>Willem LS 3</b>	6000	5000	1700	3000	25	60	150	19.20	0.48	0.95/1110; 0.37/3500	0.67/5200	10.7/200	Translational	Rapid
<b>Willem LS 4</b>	2600	2600	1200	1200	8	35	65	4.68	0.04	0.5/2000	0.72/1800	2.3/166	Translational	Rapid
<b>Chandon LS 1</b>	11000	?	15000	17000	50	120	??	258.5	12.93	0.28/780	1.38/2780; 0.31/7460	10.8/450	Rotational	Slow
<b>Glencoe LS 1</b>	60000	?	30000	70000	25	80	80	3900	97.50	0.03/30000	0.16/10000	2.2/400	Translational	Slow
<b>Salsa LS 1</b>	15000	?	12000	16000	60	600	?	300	18.00	0.83/4940; 2.3/6000	1.3 to 2.4	5.5/520	Translational	Slow

### 2.3 CHANDON SURVEY AREA

The Chandon survey covers an area of approximately 17-by-25 km on the eastern limb of Scarborough Arch (Figure 4). The Chandon slide occurs on an east facing slope between the Scarborough Arch and Kangaroo Syncline and extends from a depth of approximately -1180m to at least -1300m (Figure 13), and likely extends to a depth 1550m in Scarborough trough. The Chandon slide is transporting sediment from Scarborough Arch eastward into the Kangaroo syncline. The slide has a width of 15-20 km and a visible length of 11 km, but a likely total length of >30 km. The average slope gradient within the slide mass is less than 0.28 degree, however, steeper slopes of 1.4° and possibly up to several degrees are present down slope (out of the survey area (Figure 4). The slide has a rotational failure mechanism and the mass is composed of rotational slide blocks (Figure 13) that are mobilized above the extremely low angle failure plane. At the point of initial detachment from the headscarp, the rotational blocks are up to 40m high and 1.5 km across and 6 km long. The low angle of the failure plane and internal coherence are evidence that this is a “slow” failure. A distinctive feature of the slide morphology is the lateral mote that follows the base of the head scarp (Figure 14). Large gas/fluid expulsion features are present above the headscarp on the south side of the landslide complex. These gas/fluid vents are 650 to 2000m across and form a field of pockmarks that is at least 8 km across. The association the gas expulsion features with the landslide suggests gas/fluid expulsion may have been the triggering mechanism for this event. The process of gas/fluid expulsion may localize future slope failures in this area.

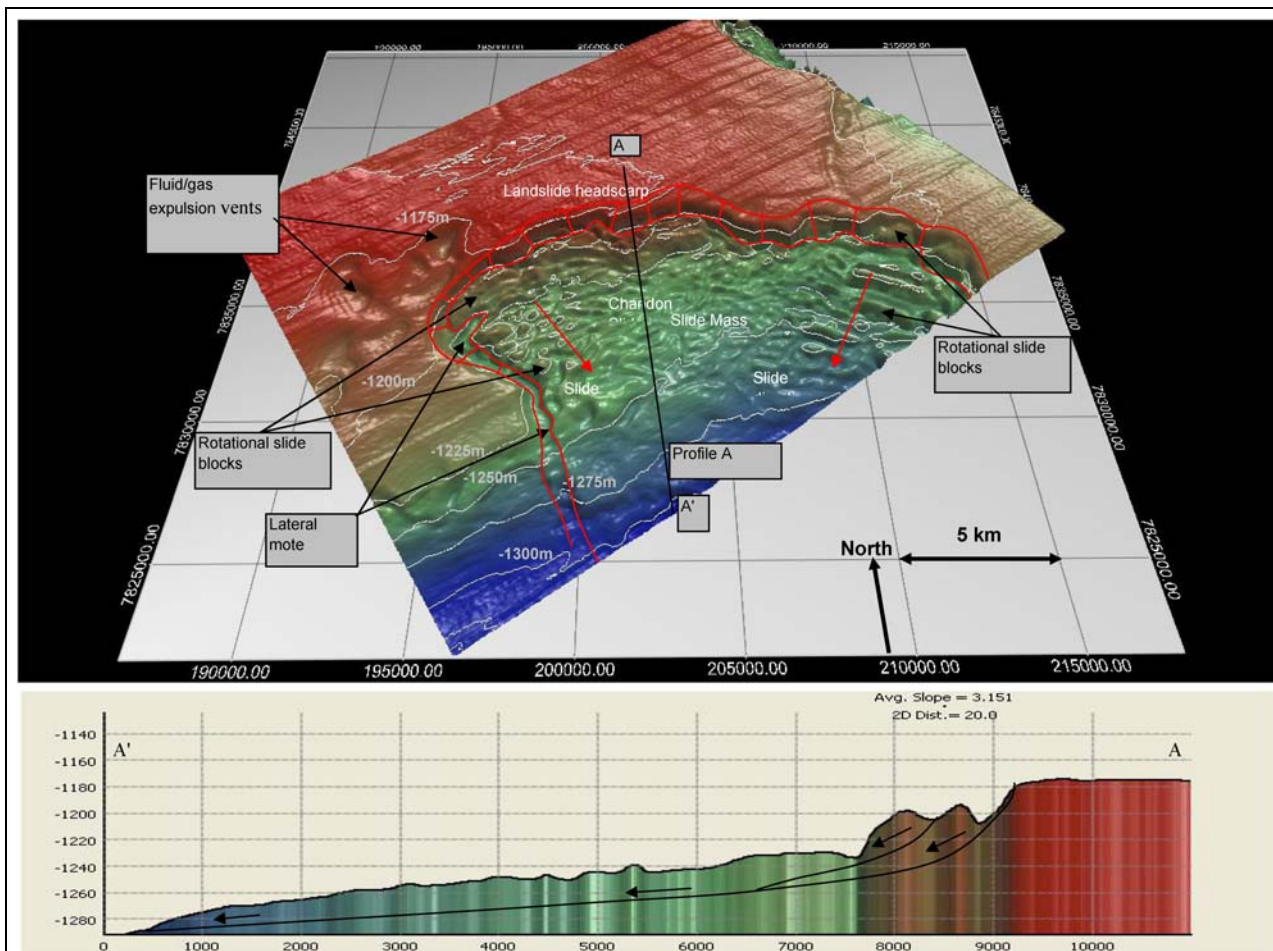


Figure 13: Seafloor rendering of the Chandon slide, northeastern Scarborough Arch. Regional relations suggest the slide should connect to a larger slide down slope and extend approximately 35 km to the trough axis. The slide mass shown is 17 km wide and 10 km long (to the limit of survey).



## 2.4 GLENCOE SURVEY AREA

The Glencoe survey encompasses an area of approximately 60-by-65 km in the central trough of the Kangaroo syncline and part of the eastern limb of Scarborough Arch, about 20 km southwest of the Chandon survey area (Figure 4). The axis of the Kangaroo syncline in the survey area is characterized by very gentle slopes. The seabed along the syncline axis slopes from south to north between  $0.08^\circ$  and  $1.5^\circ$ . The western part of the survey area is characterized by a greater than 65 km long topographically sharp 10 to 20m high curvilinear scarp with a down to the east sense of displacement (Figure 14). The slope leading from the axis of the Kangaroo syncline up to the scarp is characterized by a rhythmic ripple type structure (Figure 14 and 15). The ripples have amplitudes of up to 2m, but the amplitude is highest near the scarp and diminishes down slope toward the axis of the Kangaroo syncline. The ripples (Figures 15A and B) are formed by drape that overlies or mantles blocks of displaced sediment (Fig 15C) that lies above a low angle failure plane. The blocks of displaced sediment appear to be rafted along the low angle detachment and the edges of the failure are defined by distinct lateral margins seen in the seismic horizon (Figure 15A). The white ovals on Figure 15C also show areas of gas migration associated with the displaced blocks. The average gradient of the slope, over the 20 km distance leading up to the scarp, is  $0.032^\circ$ ; this also approximates the dip of the failure plane (Table 1). The coherent displaced blocks that characterize the Glencoe slide are likely a form of mega-flow failure. The presence of gas suggests this might be a triggering mechanism; however, pock marks are not common on the surface. Therefore, another mechanism, such as earthquake loading, may have triggered this failure. The low angle of the failure plane and internal coherence are evidence that this is a “slow” failure.

Slope gradients across the southeastern corner of the survey area, on the extreme lowermost part of the continental rise are generally less than 0.2 degrees. However, debris or earth flow lobes are observed in this part of the survey area in water depths of 1120 to 1220m (Figures 14 and 16). These form the leading edge of a landslide complex and lower continental slope deposits that originated 75 km to the east along the slope (Figure 4). The sediment lobes shown on Figure 16 are each about 10 to 12 km wide and the easternmost lobe shows crevasse fields, internal shears, and prominent lateral shear margins (Figure 17). Secondary flows are present on the edges of the lobes. The lobes are interpreted to be the front of a landslide complex that has moved down the lower continental slope and into the Kangaroo Syncline. The lobes are likely moving slowly, perhaps analogous to a glacier.

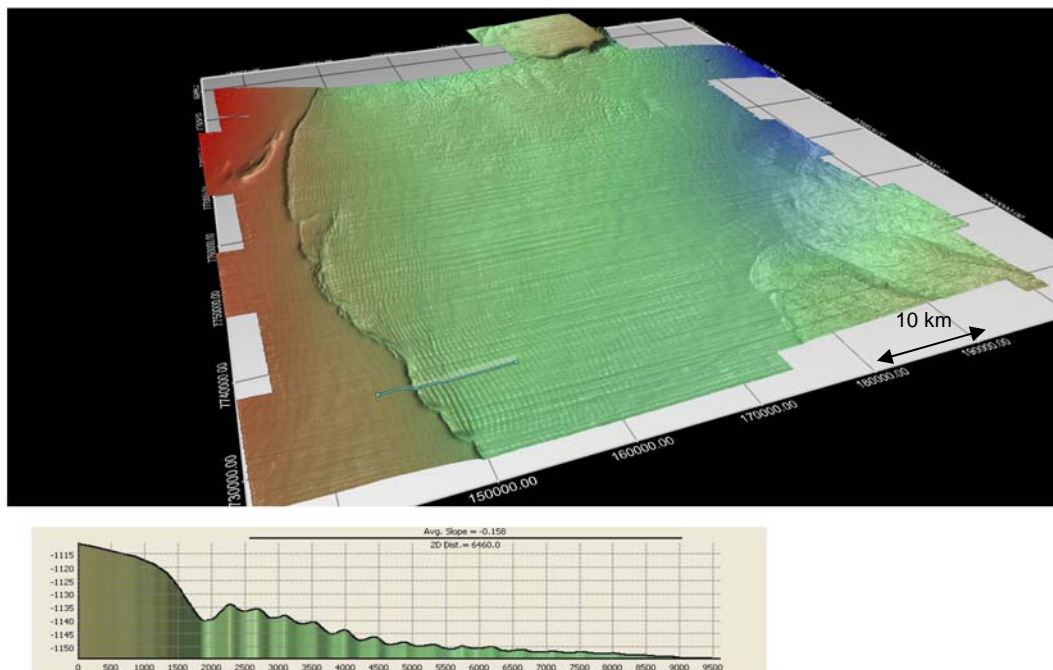


Figure 14: Seafloor rendering of the Glencoe survey area, eastern flank of Scarborough Arch. Arcuate scarp is the headscarp of a >65 km long landslide complex. Seafloor ripples are drape over landslide blocks at depth.

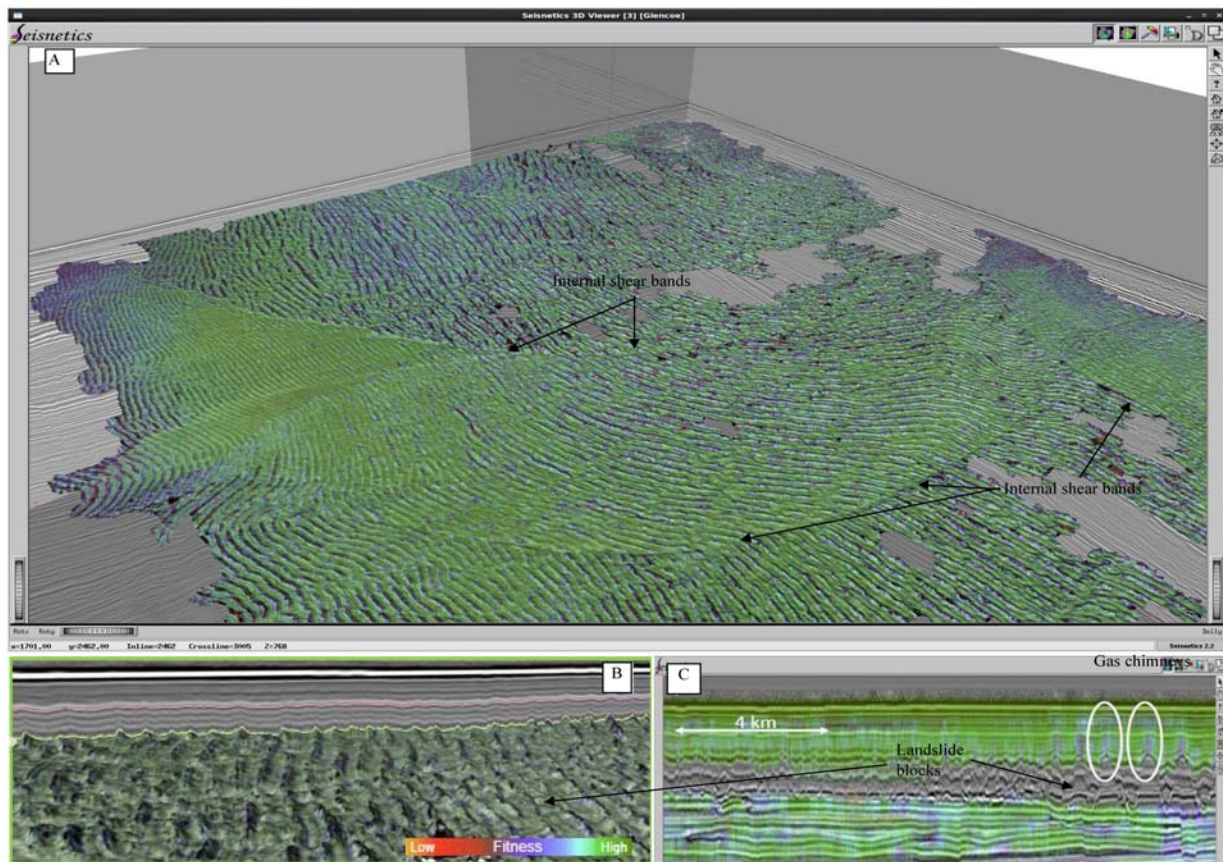


Figure 15: Seismic horizon from Glencoe Survey showing internal deformation of slide complex. (A) shows displaced landslide blocks and internal shear bands. (B) shows close up of landslide blocks; and (C) shows further close up of blocks and associated gas chimneys. Images are “fitness” plots where green colours suggest coherent wave properties, while blue and purple colours suggest some alteration of the soil properties. The alteration may be related to gas or fluid expulsion.



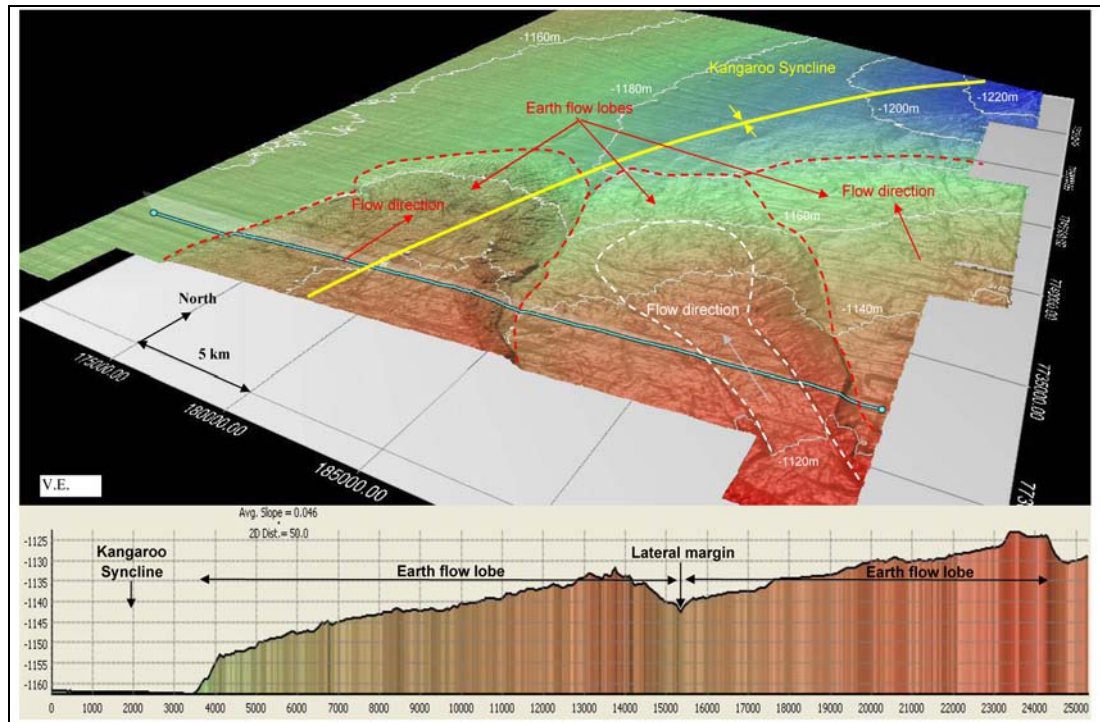


Figure 16: (a) Ten kilometre wide debris flow lobes within the Glencoe survey area in the centre of Kangaroo Syncline, 75 km from the continental slope. (b) Bathymetric profile across debris lobe in the Kangaroo Syncline.

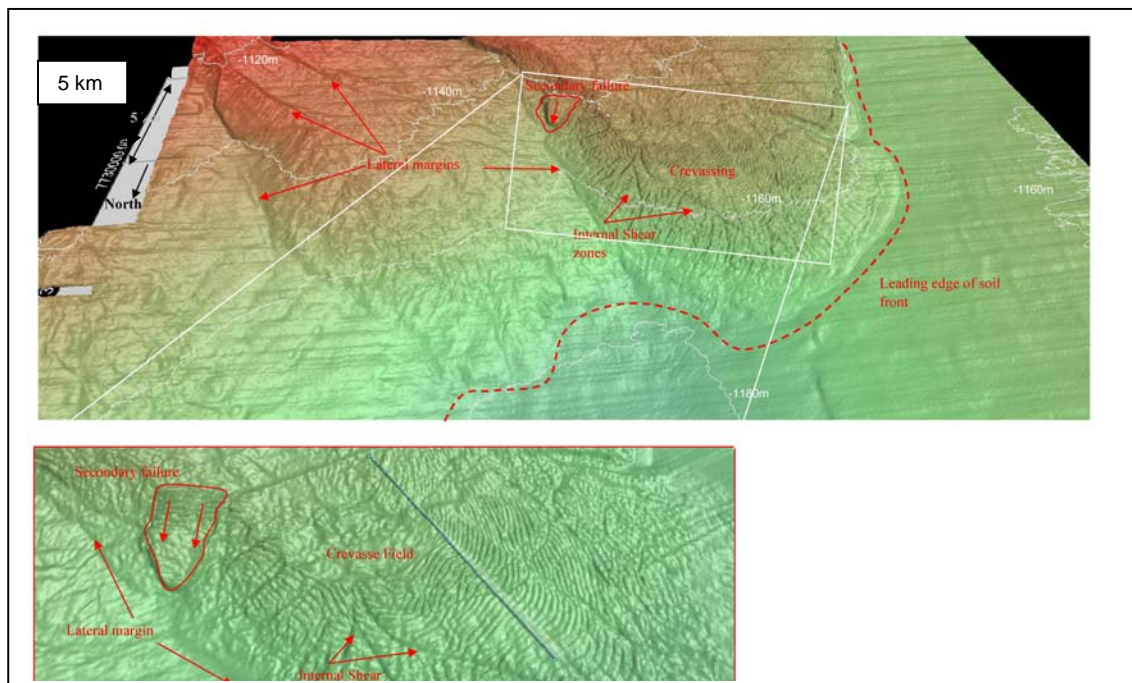


Figure 17: Close up views of debris flow lobes shown in Figure 16. Close up view illustrates the presence of crevasse fields, internal shears, and lateral shear margins.



## 2.5 SALSAL SURVEY AREA

The location and general physiography of the Salsa Survey area is shown on Figures 1 and 4. The area is located on a ridge spur between two major canyons on the middle part of the continental slope; these are the Cape Range and Cloates submarine canyons. The continental slope typically extends from the shelf break to the abyssal plain, but in the Cuvier region of Western Australia the continental slope includes three distinct steps: (a) between 200 and 1000m depths the slope dips seaward 2 to 3 (locally 5) degrees; (b) at approximately 1000m the slope encounters an 80 km-wide plateau surface that dips ~1 degree toward the west and continues to a depth of approximately 2000m; and (c) between 2000m and 4000m the slope dip increases again to 3 to 4 degrees and the slope descends to the Cuvier abyssal plain. The plateau between 1000 and 2000m depth represents the southern offshore continuation of the Northern Carnarvon Basin and is analogous to the Exmouth Plateau.

The Salsa Survey lies in approximately 1,250 to 1,875m water depth (Figure 18). The axis of the ridge spur plunges approximately  $0.4^{\circ}$  to the west, and the dips on the north and south facing slopes of the ridge spur vary from 1 to  $2.5^{\circ}$ . The survey partially captures two large landslide complexes, which occur on the north and south slopes of the ridge spur (Figure 19). The landslide on the north slope (Salsa LS 1) is a minimum of 15 km long and 12 km wide (Table 1). The headscarp of the landslide is approximately 60m high and the overall elevation drop, from the top of the slide to the bottom is about 600m. The average slope gradient of the slide mass varies from  $0.83^{\circ}$  on the upper flat part of the slide complex to  $2.3^{\circ}$  on the lower steepened part of the complex (Table 1). The gradient of the nearby unfailed slope varies from  $1.3$  to  $2.4^{\circ}$ . However, the base of the slope near the canyon is up to  $15^{\circ}$ . The slide mass is complex and composed of numerous nested slope failures. The main features include failures at the slope break near the base of the slide, a main slide mass, and a series of retrogressive slope failures near the upper part of the slide (Figure 19).

The top of the Salsa LS1 slide complex is characterized by a longitudinal mote (Figure 19), much like the Chandon slide and Glencoe slides. This is a channel like feature that connects a series of pock marks, or expulsion vents. The pock marks are 500 to 1000m across and can be up to 50m deep. The pock marks, or vents, coincide quite closely with the position of the landslide headscarp and may indicate an association between fluid expulsion and landslide triggering.

The Salsa Slide is a large complex failure with multiple retrogressive failures along the top and sides of the slide. It is less coherent than either the Chandon or Glencoe slides and therefore is inferred to have been a somewhat more rapid failure. However, a section of drape (landslide deposits from the upper slope) over the slide deposits suggests that at least in the upper part the slide is not currently active, however, the lower part of the slide complex on the steep slope near the canyon may still be active.

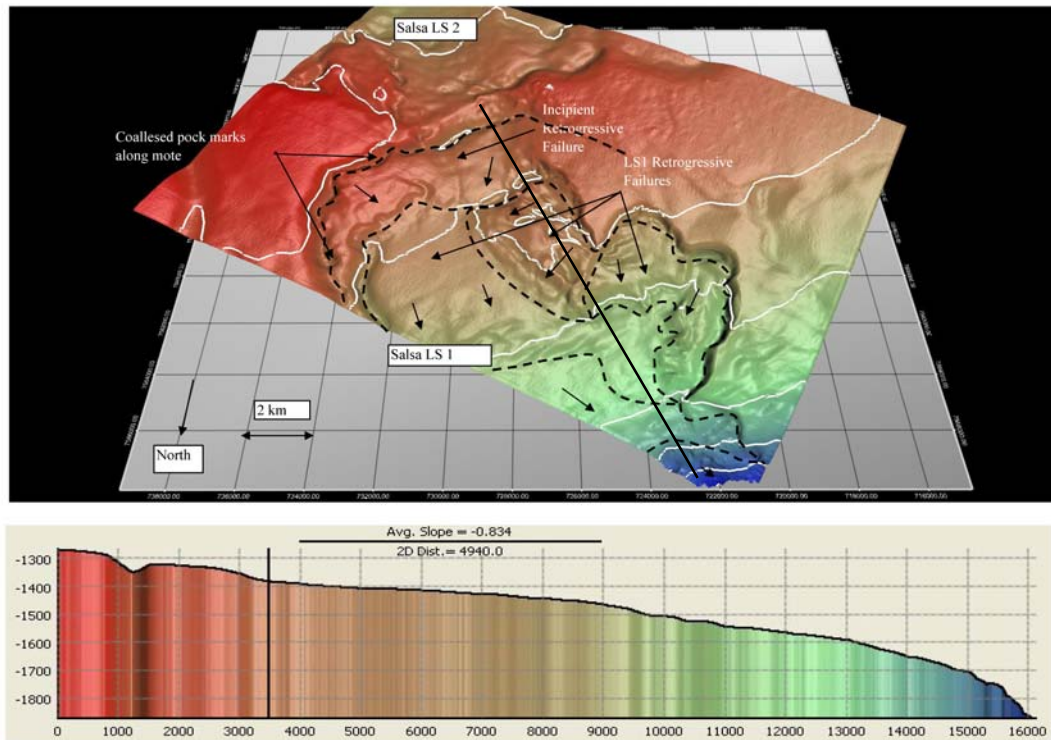


Figure 18: Overview of landslide complex from the Salsa survey area and associated bathymetric profile.

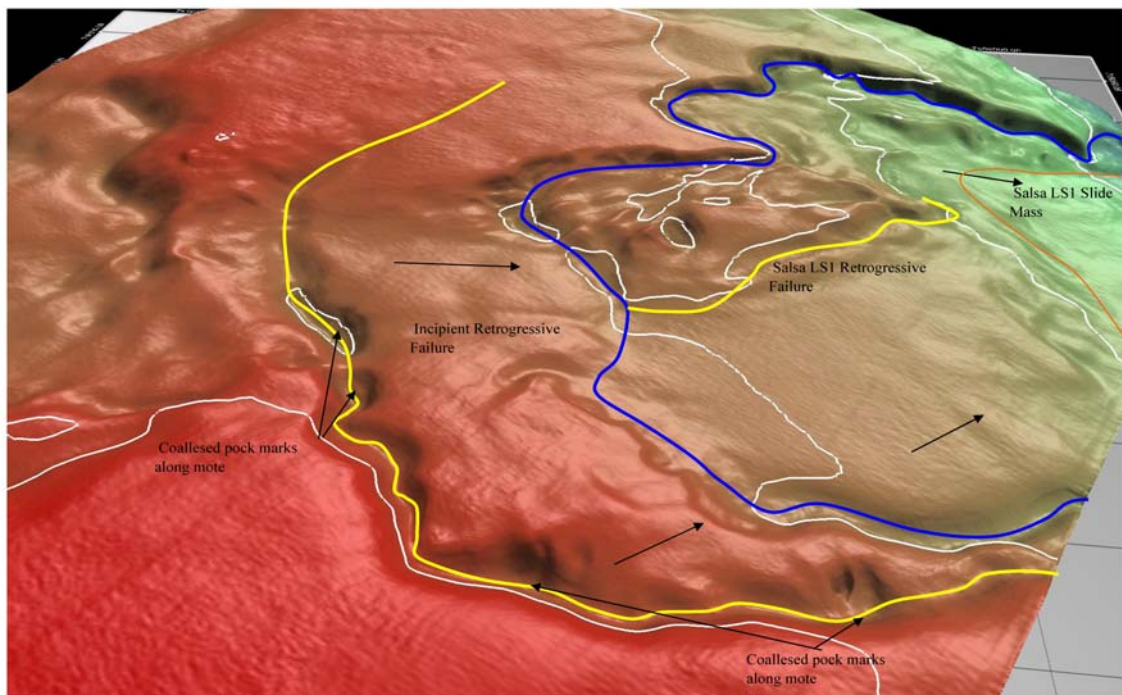


Figure 19: Close up of Salsa landslide complex showing association with gas/fluid expulsion features and retrogressive failures. Grid lines are 2 km.

### 3. DISCUSSION

Seafloor digital terrain models (DTMs) were produced from six 3D seismic volumes located along the Exmouth Plateau continental slope, along the eastern limb of Scarborough Arch, and along the Cape and Cloates Canyons (Figures 1 and 4). The DTMs were produced to assess seafloor geomorphology and types of processes occurring across this approximately 240 km long segment of the continental margin. Deep water projects such as Gorgon, Pluto, Scarborough, and Jansz-10 are all progressing along this part of the North West 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 (Figure 4). The large scale morphology of this part of the continental slope is characterized both by undisturbed sedimentary fans, submarine canyon systems, and submarine landslide complexes (Figure 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. The types of landslides observed along these parts of the continental slope include: small translational failures and slumps (<3 km across); moderate scale debris flows, debris avalanches, and topple failures (<10 km across); and large scale mass transport complexes (>20 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 and Willem survey areas (Figures 7 and 10). 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 palaeo-headscarps from past mass failure events (i.e. the Gorgon and Willem scarps). The debris fields from topple failures beneath the Gorgon scarp (Figure 8), and the recent slide scars and deposits shown on Figure 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 over-steepened scarps, or areas with rapid sediment accumulation (fans). Evidence of pock marks in the canyons and on the sedimentary fans indicate that fluid over-pressures also might play a role in triggering the moderate scale failures.

Large scale mass transport events such as those that formed the Gorgon Slide 1 failure (Figures 7 and 8), or the buried series of MTCs shown on Figure 6 from the Willem survey area, involve deep seated translational failures that may be up to 200 or 300m thick, 20->30 km wide, and 50 to 75 km long. The volumes for these events therefore can be on the order of a hundred cubic kilometres, or more. 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 (Figures 3 and 9), inversion structures, gas reservoirs and seafloor expulsion features (pock marks: Figure 7D) suggests there may be a tectonic control on seafloor stability (Hengesh et al., 2011b). 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), provide a source for gas/fluid release (venting) that reduces soil effective stress, and can generate localized earthquake strong ground shaking that increases lateral loads and reduces effective stresses through pore pressure changes. 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, Glencoe and Salsa slope failures have a different character to the debris flows and mass transport complexes along the continental slope. The Chandon slide appears to be both a rotational failure near the headscarp and a translational failure within the slide mass. The translational part of the slide mobilizes the rotated soil blocks within the slide mass and transports them down slope (Figure 13). 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 down slope. The very low angle slopes in these areas likely prevent the failures from gaining significant speed or energy. The failures appear to be slow and thus the soil mass can stay relatively in tact compared to failures on steeper slopes.

Submarine landslides from both the continental slope and Scarborough arch are creating metastable deposits that are moving down slope and into the Kangaroo Syncline, or down Cape Range and Cloates Canyons. Striations on failure planes from buried MTCs indicate movement into the syncline from both directions and the continued northward down slope movement within the syncline axis (Figure 10). Figures 16 and 17 show examples of soil lobes on the seafloor that have mobilized 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 minimize 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 jeopardize pressure integrity of a field development or export system. As such, it is very important that the data acquisition programmes 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 characterization 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 (Figure 4), but these data are not suitable for identifying small failures (e.g. tens of metres) that still could impose unacceptable loads on sea-bed developments. It is recommended that additional high resolution swath bathymetry datasets be collected using Autonomous Underwater Vehicles (AUV) for future slope process risk assessments in this area and other deep water, far shore areas of the North West Shelf.

#### 4. CONCLUSIONS

Our analysis of Open File exploration seismic data has identified several types of slope failures along submarine slopes on Exmouth Plateau. The landslides range in size from less than a kilometre to greater than 30 kilometres across and show a range of failure mechanisms from small debris flows and topple failures to large scale Mass Transport Complexes (MTC). Some of the observed characteristics of these slides are summarized below:

- Slide lengths vary from 2.6 to 60 km in length;
- Slide widths vary from <1km to 70 km in width;
- Slide thicknesses varies from 8 to 300m;
- Slide volumes range from 40m<sup>3</sup> to over 100 km<sup>3</sup>; and,
- All slides occur on slopes less than 2 degrees, and most slides occur on slopes less than 1 degree.

The characteristics of the landslide deposits suggest different velocities of failure events. For example the relatively intact soil blocks observed in the Chandon and Glencoe slides are used to infer that these events were relatively slow failures, while the large dispersed debris fields observed at the Gorgon LS 1 and Willem LS 2, 3, and 4 sites are used to infer that these were relatively rapid failures. The velocity of landslide failure is an important consideration for performance analysis of subsea infrastructure that may lie in the path of these events.

Although a quantitative analysis of slope failures and triggering mechanisms has not yet been carried out, the geomorphic observations provide indications of the types of mechanisms that might be controlling slope processes along the Exmouth slope. Small to moderate failures such as debris flows in canyons and on fans, and translational failures on the lower slope may be occurring under sediment loading and gravitational instabilities; in other words these are likely to be static slope failures. However, the large MTC's such as observed at Gorgon and in the Willem subsurface appear to be related to observed factors including increased stratigraphic dips above inversion structures, fluid and gas expulsion, and near surface faulting. We recognize a frequent association of fluid expulsion features and slope failures (e.g. Gorgon Slide #2) and so this may be a common triggering mechanism. Seismic loading also is a likely triggering mechanism and the association of slides with potential seismic sources will be a topic of ongoing research.

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