SUBMARINE LANDSLIDES ON THE SOUTH-EASTERN AUSTRALIAN MARGIN

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ABSTRACT

High-spatial resolution bathymetric data acquired during two recent RV Southern Surveyor voyages have identified several distinct large sediment slides varying in volume from <0.5 km^3 to 20 km^3 on the upper continental slope of the southeastern Australian margin. Gravity cores, up to 5 m long, have been obtained from areas within and outside the identified slide features, and are believed to intersect the slide planes in some cases at depths of between 85 cm and 220 cm below the present-day seabed.

The paper will provide a brief review of the factors believed responsible for submarine landslides, and discuss the relevance of these factors to the southeastern Australian margin. The paper will use the data from the recent ship surveys (SS2008/12 off the southern Queensland / northern New South Wales coastline and SS2006/10 off the mid New South Wales coastline) to show the size and magnitude of submarine landslides that have been identified, present results from soil characterisation studies of the recovered cores, and present the results of mechanical tests. These data will be used to consider the stability of the continental shelf sediments and to consider the tsunami risk that they pose.

1 INTRODUCTION

The consequences of submarine landslides include damage to seabed infrastructure (communications cables and buried pipelines), subsidence of coastal areas and the generation of tsunamis (Masson *et al*., 2009). Our failure to understand the causes of these phenomena means that submarine landslides present a significant risk to coastal and offshore development, and have on occasion resulted in the halting of offshore developments. It has been established that large submarine landslides can produce tsunamis, such as the earthquake triggered submarine slides in 1929 (Grand Banks, USA; Fine *et al*., 2005) and 1988 (Aitape, Papua New Guinea; Tappin *et al*., 2001) which both resulted in significant casualties. The large loss of life and damage to infrastructure from the Indian Ocean tsunami of 2004 (Lay *et al*., 2004) and the recent Japanese event have increased interest in the tsunamigenic potential of large submarine slides. Australia is vulnerable to tsunamis with 85% of the population living within 50 km of the coast and much of the critical infrastructure located close to the coast. It has been suggested (Dominy-Howes, 2008) that the maximum credible tsunami could cover Manly in 6 m of water, and while the possibility of such an event has major implications for risk assessment and siting of critical infrastructure, the likelihood cannot be sensibly determined.

The geological record contains many examples of submarine landslides, which can vary in scale from minor shallow slides to very large slides, such as the Storegga slides off the Norwegian coast which have a total volume of over 3000 km^3 (Haflidason *et al*., 2005). Statistics on known landslides on the eastern continental slope of North America, which has geological similarities to Australia's eastern margin, have been published by Masson *et al*. (2006). These show that between 30^{o}N and 45^{o}N there are 152 large landslides affecting an area of nearly 40000 km^2. Most failures occur on slopes of between 1^o and 7^o, with the greatest number of failures occurring on slopes of 3.5^o. The area affected by failures decreases as the slope increases, and the depth of water at the slide head ranges from 250 m to 2500 m, with the greatest number of failures occurring at water depths of around 1000 m. Despite extensive literature on the nature and causes of submarine landslides, their dynamics and triggering processes are not well understood (Locat and Lee, 2002; Bardet *et al*., 2003). One of the principal reasons for this is the limited data on the physical and mechanical properties of the sediments, particularly from the slide plane, as these materials have not traditionally been collected.

In Australia, studies of the southeastern (SE) Australian continental slope (Jenkins and Keene, 1992; Glenn *et al*., 2008; Boyd *et a*l., 2010) have been very limited until recently. Evidence of submarine landslides on the SE Australian margin was first reported by Jenkins and Keene (1992), but it was not until high resolution, multi-beam bathymetric data became available (Glenn *et al*., 2008; Boyd *et al*., 2010) that the true distribution of these slides could be established. The recent collection of high-resolution multibeam echo-sounding and sub-bottom profiling data has provided a detailed view of mass-transport features over a 900 km length of the margin. A wide range of slide features has been detected as well as a series of canyons which cut through the slope sediments. The submarine slides range in scale from hundreds of small slides with volumes of <0.5 km^3 up to the largest documented slide which has a volume of 20 km^3 (Boyd *et al*., 2010).

2 SUBMARINE LANDSLIDES

2.1 SOUTHEASTERN AUSTRALIAN MARGIN

The SE Australian continental margin stretches 1500 km north from Bass Strait to the Great Barrier Reef (Boyd et al., 2004). The margin which is by world standards narrow, deep and sediment deficient, was formed by rifting in the Cretaceous period between 90M and 65M years ago (Gaina *et al*., 1998). Since then, margin subsidence has been relatively minor. The continental shelf ranges between 14 and 78 km wide and is relatively flat with a thin sediment cover. The sediment reaches a peak thickness of about 500 m at the edge of the shelf, which occurs at depths ranging between 55 m and 180 m. The continental slope is the region from the shelf edge to the Tasman Abyssal Plain where the water depth is around 4500 m. The continental slope ranges from 28-90 km wide and has average slopes in the range from 2.8° to 8.5°. The sediment cover generally reduces from the shelf edge to the Abyssal plain, and is absent from the lower slope off southern NSW (Boyd *et al*., 2004).

Figure 1 shows the regions where detailed bathymetric studies have been conducted in the last 5 years and from which the sediments have been recovered that are discussed later. Two ship surveys have been conducted, one of the continental slope off Brisbane (SS2008-12), and the other off Sydney (SS2006/10). The surveys consisted of both sub-bottom profiles and echo-sounder records to provide a detailed picture of the seafloor and reveal the underlying geology. In addition 26 gravity cores were obtained from these regions from areas within and adjacent to several slide features, and further sediment was dredged from deeper water. An overview showing the bathymetry for both of the studied areas is given in Figure 2. At this scale it is possible to see that a number of canyons cut into the slope sediments and most of these are off the major rivers. Further details of some of the slides are shown in Figures 3 and 4.

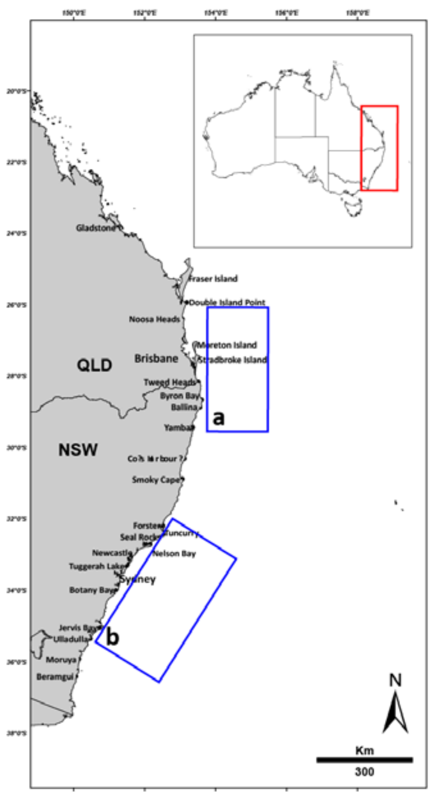

Figure 1: Location map of the two study areas along the southeastern Australian coastline. Blue insets a) and b) mark the location of the bathymetric maps presented in Figure 2.

Close inspection of the bathymetric data reveals several distinct large sediment slides varying in volume from <0.5 km^3 to 20 km^3 on the upper slope (water depths < 1200 m) of the SE Australian margin (Boyd *et al*., 2010). The large slides typically comprise a distinct U-shaped trough in cross-section (3-6 km wide and 20-250 m deep) backed by an amphitheatre shaped crestal zone. This slide morphology is similar to the classical circular failure profile described by Varnes (1978), but they are elongated in longitudinal profile. The sides and head walls of the scarps are relatively steep with slopes of up to 17^o. The largest slides are the Bulli (Figure 3c) and Shovel Slides, near Sydney, on slopes of around 4.5° that are up to 13 km long and 5 km wide with volumes of 20 km^3 (Glenn *et al*., 2008) and the Byron slide (Figure 3b), off Byron Bay, with a volume of 3 km^3 and slope of 6.5^o

(Clarke *et al*., 2011). Sub-bottom profiling data from multiple sections across the continental slope and in particular across the slides show the sediment is built up of well stratified beds (Glenn *et al*., 2008), which have been suggested to be evidence of past slide events. In most locations, sediments derived from the slides cannot be detected on the slope and it appears that the slide material has been transported to the abyssal plain. However, in a small number of locations (Figure 3a) where the slopes are less steep (< 2^{o}), the slide debris flow deposits have remained on the slope and contain blocks up to 350 m wide and 50 m high.

Figure 2 shows a large number of canyons that cut into the continental slope sediments. These have been categorised into large box canyons, and smaller narrow linear canyons. The 46 large box canyons are on average 14 km wide, 20 km long and over 600 m deep, they stretch from the middle slope to the abyssal plain, and have slopes up to 17° on the walls. Narrow linear canyons occur in the upper slope sediments, most located in central NSW off major river systems such as the Shoalhaven, Hunter and Tweed or off Fraser Island. Well developed examples are 800-1900 m wide, 120-320 m deep and extend downslope for 14-22 km. Canyon wall slopes are up to 34°, the steepest slopes found on this margin (Boyd *et al*., 2010).

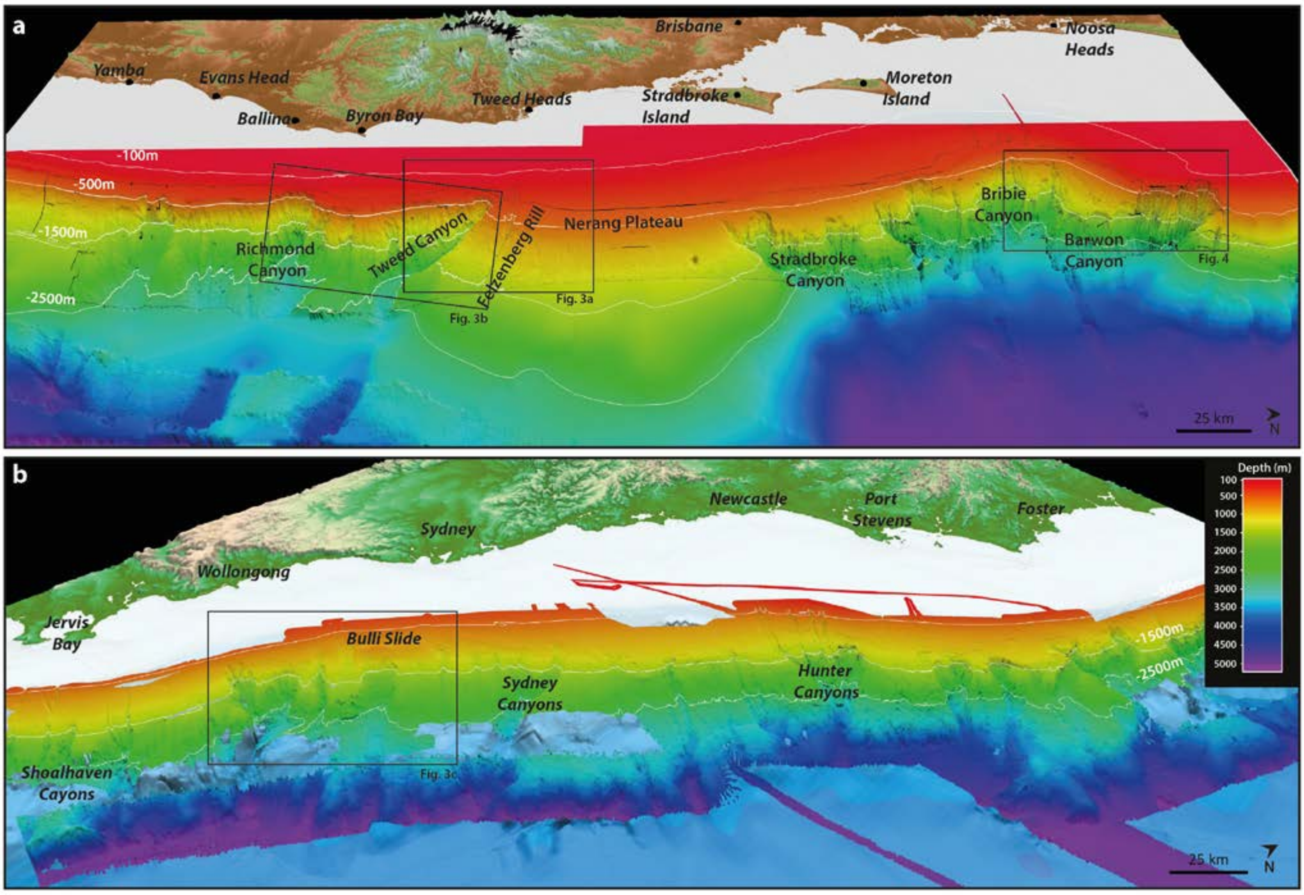

Figure 2: Bathymetric maps of the a) the southern Queensland / northern New South Wales continental slope and b) the mid New South Wales continental slope. Data for these maps were collected on two RV Southern Surveyor voyages: SS2008/12 off the southern Queensland / northern New South Wales coastline (Boyd *et al.,* 2010) and SS2006/10 off the mid New South Wales coastline (Glenn *et al.*, 2008). Insets mark the location of the close-up slopes images presented in Figure 3 and Figure 4.

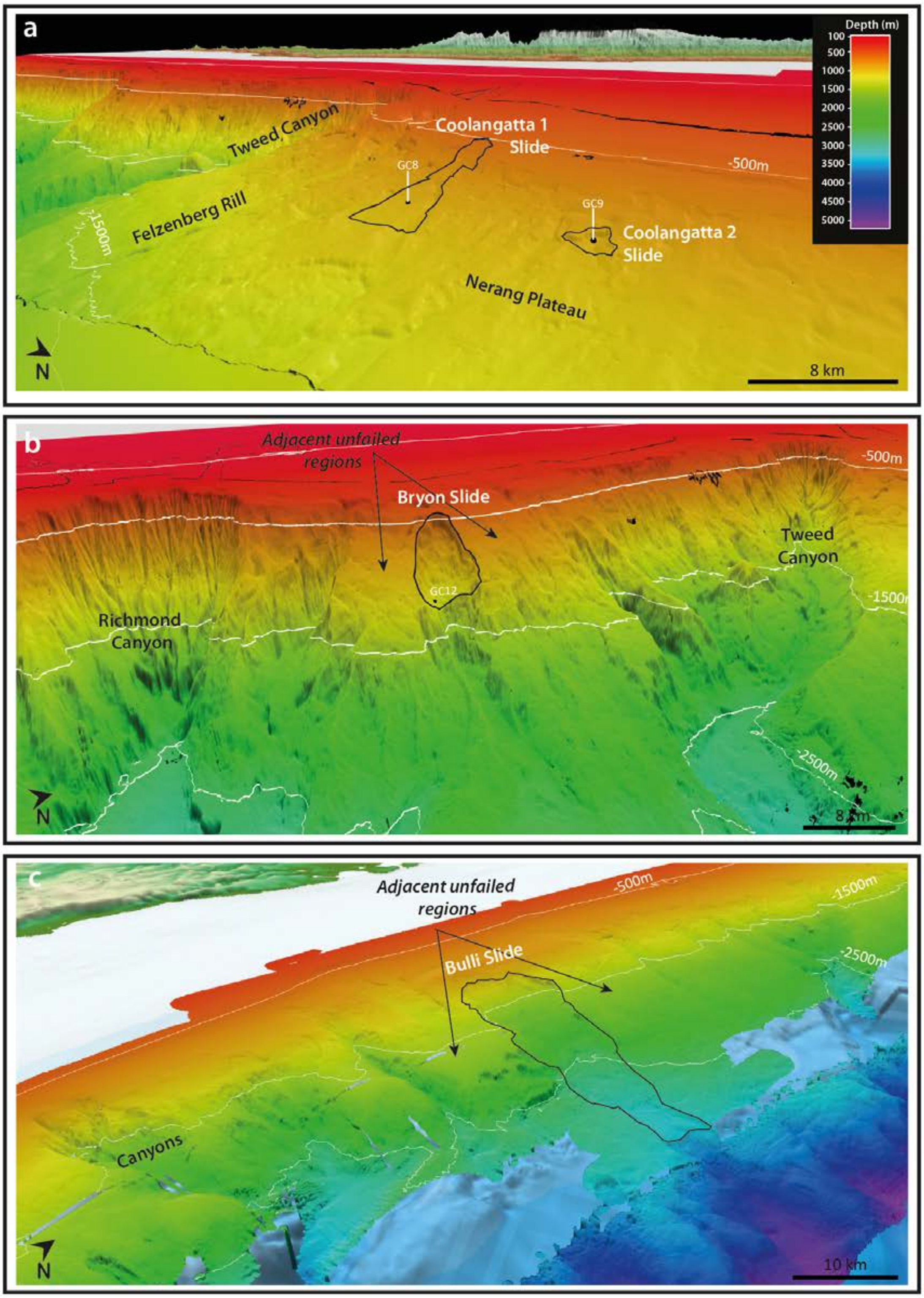

Figure 3: Digital elevation model (DEM) of the slope geometry for four slide sites (outlines denoted by black line): (a) Coolangatta 1 and Coolangatta 2 Slides, (b) Byron Slide, (c) Bulli Slide. Also shown are locations of the three gravity cores (GC8, GC9, GC12) referenced in this study, collected on the RV Southern Surveyor SS2008/12 voyage.

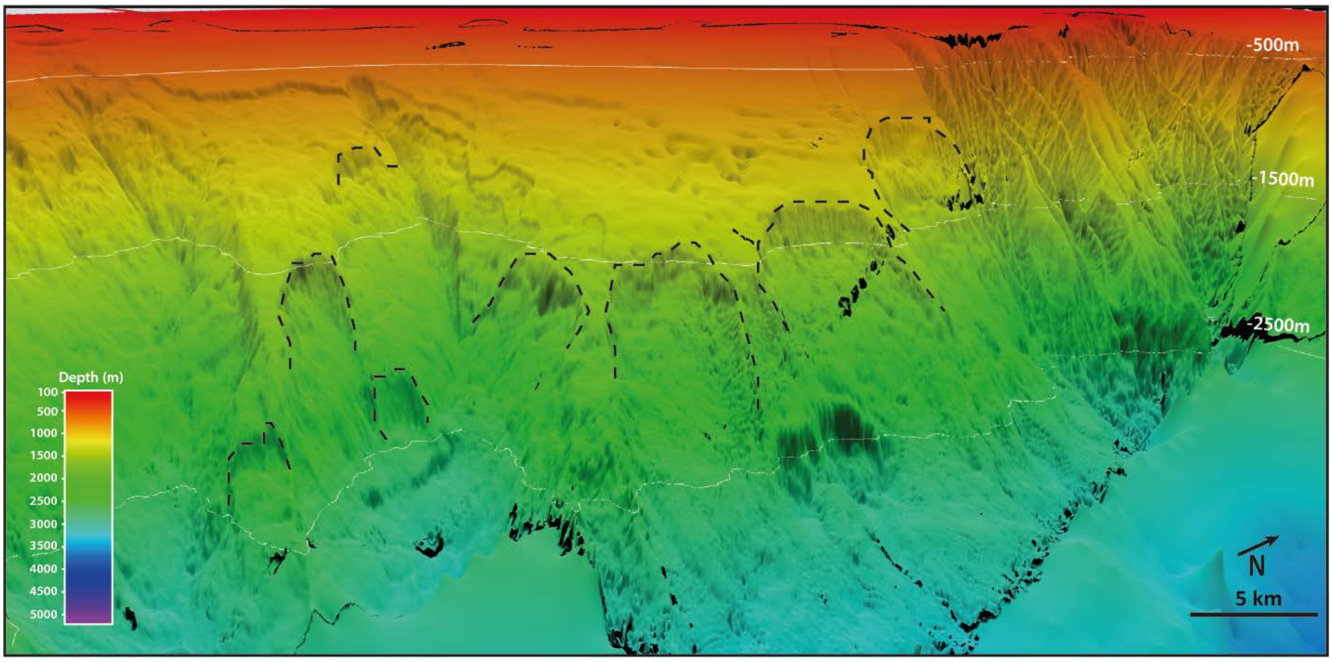

Figure 4: Digital elevation model (DEM) of a section of the mid-slope within the study area. Note the abundance of slump/slide scars presenting arcuate crests (crest outlines denoted by black dashed lines). Modified from Hubble, 2011.

Further observations from the bathymetry include the widespread slope failures on the mid-slope, shown in Figure 4, which demonstrates an average slope of around 8^o and the widespread relatively shallow failures observed on the Nerang plateau shown in Figure 3a, where the average slope is $< 2^o$. There are also circular depressions, referred to as pock marks, off Newcastle which are believed to be associated with gas leakage from the underlying Permian coal measures (Glenn *et al*., 2008).

The figures reveal evidence of widespread erosional features on the SE Australian continental slope. This is different from other margins of similar age, for example the US Atlantic and Gulf Coasts, where sediment deposition is the more dominant process. However, both margins exhibit extensive slides and other erosional features. The 500 m thickness of the sediments on the SE Australian margin has been taken as evidence of a previous period of deposition (Davies 1979, Boyd *et al*., 2004), but the sediment thickness is substantially less than other margins. This can in part be explained by the dryness of the Australian continent, the relatively subdued highlands and its small rivers. When the resulting low sedimentation is combined with ongoing subsidence of the abyssal plain caused by initial crustal thinning and later thermal cooling, which has caused the gradients on the margin to slowly increase, the result has been a retrogressive gravity failure over all of the lower slope and much of the upper slope. Thus it is considered that the present state of sediment instability, where the overlying sediment wedge is continually undercut by slope failure over geological time, is the cause for modern episodes of failure (Glenn *et al*., 2008).

2.2 TRIGGERS

The literature on submarine landslides summarised by Masson *et al.* (2009) and Locat and Lee (2002) lists a variety of causes for their initiation. These include: earthquakes, storm wave loading, erosion and in particular slope over-steepening, rapid sedimentation leading to under-consolidation, the presence of weak layers, gas hydrate dissociation, sea-level changes, glaciations/isostatic uplift, volcanic activity and diapirs. It is also widely accepted that a combination of these factors is required to initiate a landslide, especially where these occur on very shallow slopes. There is data indicating that several large landslides have coincided with earthquakes, (e.g. Tappin *et al*., 2001; Bardet *et al*., 2003; Masson *et al.*, 2006; Synolakis *et al*., 2002). The role of weak layers, oriented parallel to the sedimentary bedding, has long been used to explain the scale of some large slides, but more recently the importance of weak layers in controlling sliding at all scales has been noted (Masson *et al.*, 2009). Despite this Masson *et al*. (2009) also commented that “we know very little about the nature and characteristics of these weak layers, since they have rarely been sampled and very little geotechnical work has been done on sediments recovered from them”. An important consideration is the brittleness of the sediments. Weak layers need to lose strength rapidly and pore pressure needs to rise for effective stresses to reduce. Masson *et al*. (2009) suggest that clay rich sediments with high water content and high plasticity are required for this to occur.

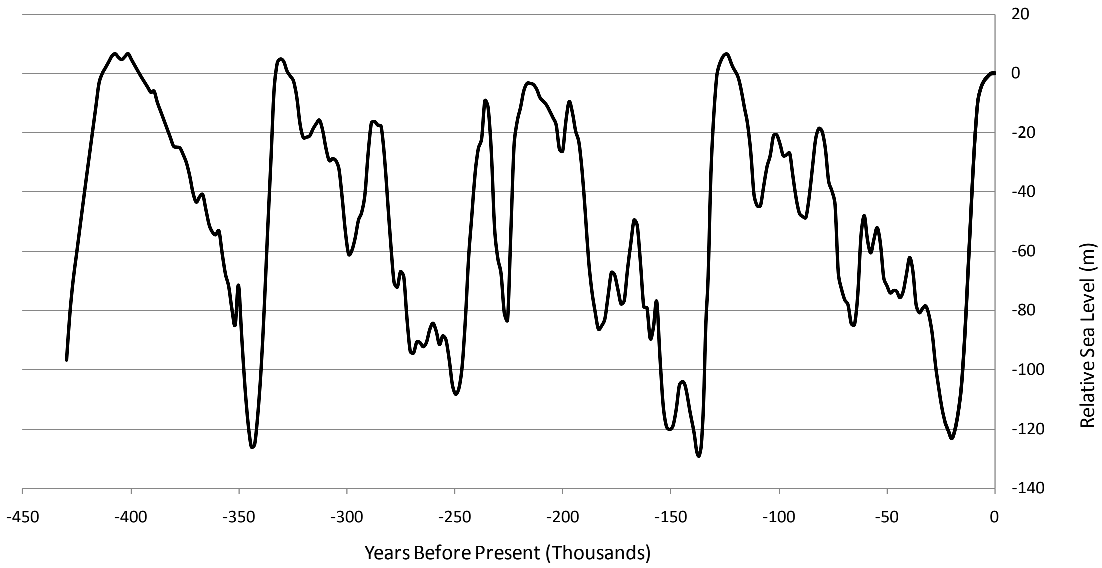

Figure 5: Relative sea level history (after Waelbroeck *et al*., 2002)

Lee (2009) has shown that landslides were more frequent during and just after the last period of glaciation than they are today. One of the suggested reasons for this is that glacial periods coincide with periods of low relative sea level. Figure 5 shows the relative sea level curve for Australia for the last 0.5 million years, which indicates that the sea level has been over 100 m below its present level on several occasions, and the times of these minima are associated with glacial periods. The lowered sea level can increase the likelihood of sliding because it results in the shoreline migrating closer to the shelf edge, leading to increased erosion and higher rates of sedimentation offshore, which now occurs directly on the slope. The lower water pressures (and possibly changed temperatures) can lead to release of gas from gas hydrates increasing pore pressures and reducing strength, and related changes to stress levels in the crust can increase seismic activity. Increased groundwater flows from underlying rocks can occur also contributing to reduced strength. It has also been suggested that changes to deep ocean currents are associated with glaciations and erosion from these currents can contribute to slope steepening (Hubble *et al*., 2011).

Another mechanism that has been postulated to explain submarine slides is that of creep, slow down slope movements due to gravity stresses that may lead to failure of the sediment mass or to failure on a weak layer at depth. It has been demonstrated that thick deposits on steep slopes can fail by this process (Silva and Booth, 1984). However, as noted by Hampton *et al.* (1996) proof that creep is significant on continental slopes is elusive.

Observations of the widespread occurrence of submarine slides suggests that weak clay layers cannot be a major cause, and tend to favour earthquakes as the triggering mechanism. Nevertheless, it is widely accepted that neither the submarine sliding process nor the slide triggering mechanisms are very well understood (e.g. Locat and Lee, 2002; Mosher *et al.,* 2009), and this is particularly so in the cases of submarine mass failures that do not appear to be linked to seismic activity.

2.3 SEDIMENT PROPERTIES

From the recent ship cruises 26 gravity core samples have been obtained, 14 from the region off Sydney and 12 from the region off Brisbane. For most of the gravity cores the soil has been logged and basic properties, particle size distribution, mineralogy and densities have been obtained. The results from the Sydney region have been reported in detail by Glenn *et al*. (2008) and only typical results are reported here. The basic classification tests have been supplemented by a limited number of triaxial, oedometer, shear box and vane shear tests to investigate the mechanical behaviour of the sediments. The mechanical tests have been performed to investigate the landslide triggering processes and in particular to determine the collapse potential of the sediment and the influence of composition and stress level on this behaviour.

A summary of the classification data, which is limited to material from the upper 5.3 m of the sediments as this was the maximum depth of penetration of the gravity corer, is included in Table 1. This shows that the continental slope sediments are predominantly comprised of silt sized material, with about 15% clay, variable amounts of sand sized particles and significant organic content. The sediments contain a significant amount of carbonate grains derived from the remains of living organisms and also significant amounts of terrigeneous material, believed to be transported by the wind from the interior of the continent. Although there is some variability in the composition from core to core there is a broad similarity in the particle distributions all along the margin.

Table 1: Summary of available classification data

	Clay (%)	Silt (%)	Sand (%)	Carbonate (%)	Organic (%)	LL	Ip	Moisture content (%)
Brisbane	10-20	50-65	15-40	20	8	46.5	9	50-100
Sydney	8-25	30-80	10-60	35	?	44	18	55-85

Several of the gravity cores were obtained from within detected landslide features in an attempt to penetrate through the base of the slides to assist in constraining the slide depths and dates. In most locations this was unsuccessful as the recent sediment drape overlying the slide surface was thicker than the gravity corer could penetrate. However, in three locations off SE Queensland a distinct boundary in the sediments could be detected at depths between 87 cm and 220 cm. The sedimentalogical and geotechnical properties of the sediments and their variation with depth from one of these cores (GC12; see Figure 3b for core location) are shown in Figure 6. It can be seen from the figure that there is a distinct change in density and moisture content, as well as appearance of the material at a depth of 87 cm. It is also noticeable that this change in density is not associated with any significant change in the grading, carbonate content or organic content of the material.

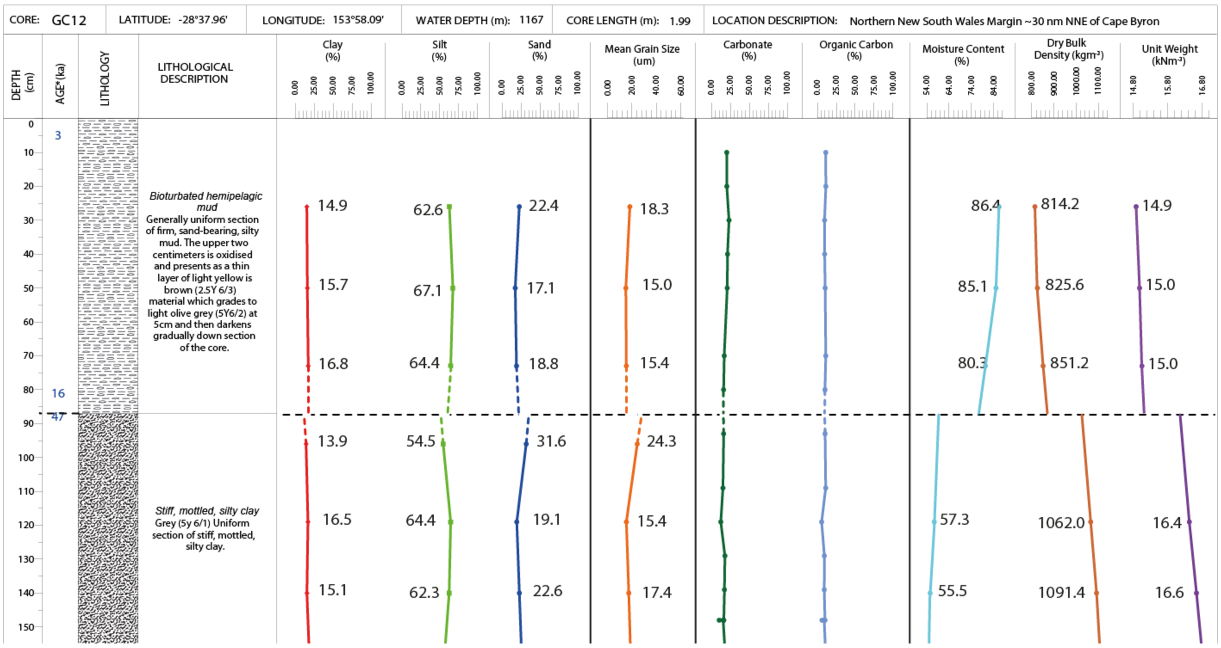

Figure 6: Characterisation of sediment from core GC12, showing physical properties with depth below seabed. Bulk radiocarbon dates are also shown. The presumed slide plane is indicated with a dashed black line at 87 cm depth below seabed (Modified from Clarke *et al*., 2011)

Additionally, a bulk radiocarbon (14C) age was determined for sediment sampled directly above the slide plane for this core, returning a date of 15.8 ka for the recent material just above the inferred slide surface (Clarke *et al.*, 2011). This date is consistent with sliding occurring around the time of the most recent sea level low shown in Figure 5. Dating for the deeper sediment could not be determined because its age exceeded that for which 14C dating is reliable. The dating has also enabled the rate of sedimentation to be determined, providing values between 0.3 and 1.2 m/10,000 years. As the rate of deposition is expected to have been higher in the past, these rates of sedimentation suggest that sliding must have been a geologically common event since the formation of the margin 60 million years ago as the current sediment deposit is less than 500 m thick.

Using the values of Cc given below, the change in moisture content at the inferred slide plane can be interpreted as representing a slide depth of anywhere between 10 m and 200 m. The depth reconstructed at the GC12 site by replacing the material apparently missing from the U-shaped trough, i.e. by maintaining the continuity and shape of the adjacent slope and projecting it above the GC12 site, is approximately 250 m. Thus while it is possible to date a possible slide at approximately 16,000 years there is insufficient information to determine whether this is the date of the main slide at this location and further mechanical and dating studies are in progress to further constrain the result.

2.4 GEOMECHANICAL BEHAVIOUR

Limited geomechanical data are available from the vicinity of the slides close to Sydney and from the region off Byron Bay. This has consisted primarily of one-dimensionally consolidated undrained triaxial tests, with some additional shear box tests to evaluate residual strength properties for the Sydney sediments.

Figure 7 shows typical compression plots from 1-D compression tests on undisturbed specimens. Results of three specimens from one of the cores (GC9; see Fig 3a for location), from SE Queensland are shown together with a typical specimen from a core off Sydney. Although there is some variability in the responses the similarity of the response of the specimen from Sydney and SE Queensland is remarkable. Based on these very limited data it appears that the grading, mineralogy and compressibility of specimens on the continental slope are similar along most of the 1500 km of the SE Australian margin. The specimens show high compressibility with Cc values ranging from 0.3 to 0.65. This is considerably higher than would be expected from their remoulded index test results, as the correlation Cc = IpGs/2 would suggest Cc values of 0.13 to 0.26 for plasticity indices of 10% to 20%. It can also be noted that the moisture contents in the upper 5 m are significantly higher than the liquid limit and vane shear tests have indicated that the specimens have significant sensitivities (>2). These data indicate that the slope sediments are structured and, while the cause of the sensitivity has not been established, it could be related to the relatively high organic content of up to 8%, which is known to be a factor in sensitivity in other soils.

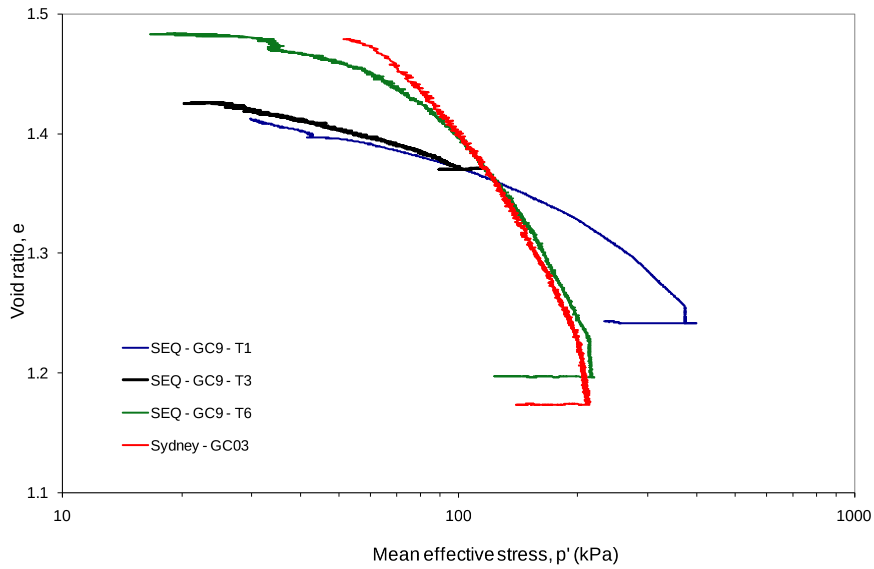

Figure 7: Response of core specimens to 1-D compression

The responses of 3 specimens to undrained shearing in triaxial compression are shown in Figure 8, and the associated effective stress paths are shown in Figure 9. To enable comparison of the tests the deviator stress and excess pore pressures have been normalised by the vertical effective stress at the start of shearing. Specimens GC9-T1 and GC9-T3 were adjacent specimens and have similar compressibilities, as seen from Figure 7, but they responded differently to shearing. Specimen GC9-T1 at the higher stress level ($\sigma'v$ = 620 kPa) shows a more brittle response with the peak deviator stress attained at a very small strain, after which the resistance rapidly decreases to its ultimate value. In contrast, specimen GC9-T3 at the lower stress ($\sigma'v$ = 167kPa) does not reach a maximum until relatively large strain. From the pore pressure responses and the effective stress paths it can be seen that this difference is a consequence of a transition from dilative to compressive behaviour as the stress level increases. The more compressible (Sydney) specimen shows a response similar to the higher stress GC9-T1 even though the stress level ($\sigma'v$ = 220kPa) is similar to GC9-T3. The shear response of GC9-T6, which has similar compressibility to the Sydney specimen also shows the tendency for increasing brittleness with increasing stress level, however, this result is not considered reliable due to non-uniform deformation during shearing. This pattern of reducing dilation and increasing brittleness with stress level can explain why deeper failure surfaces develop.

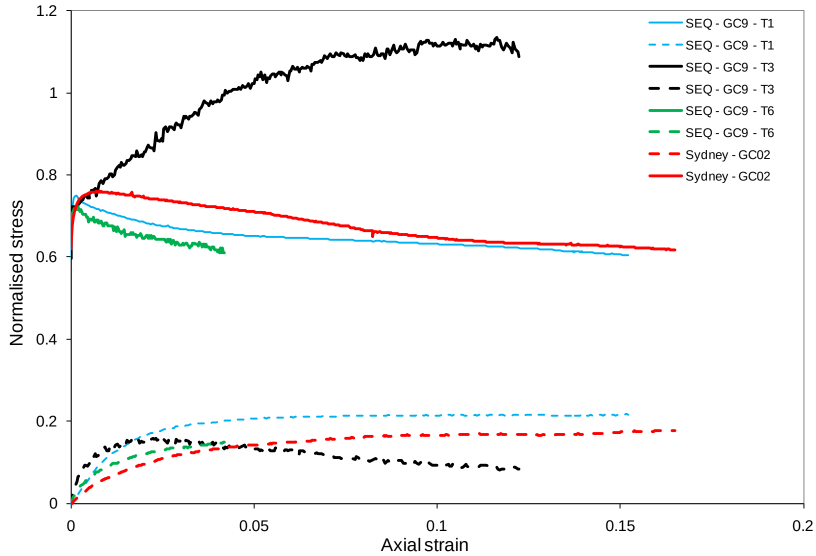

Figure 8: Normalised deviator stress and pore pressure responses from 1-D compressed specimens.

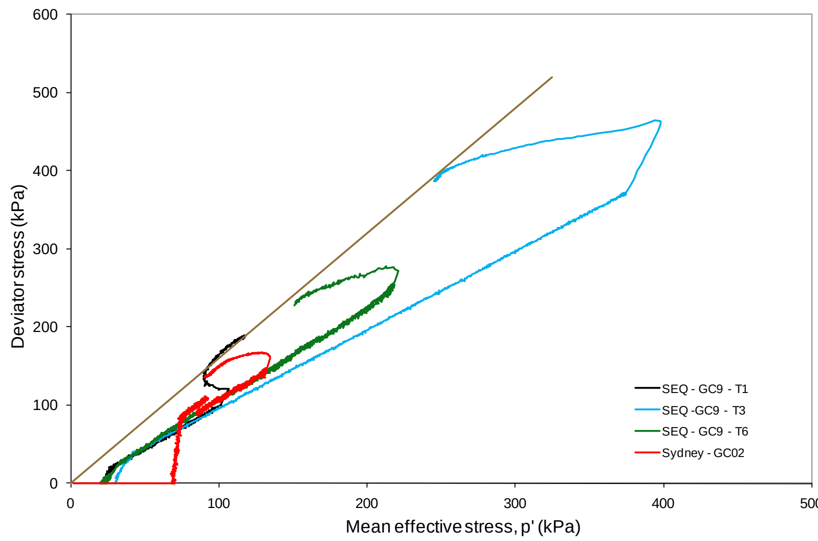

Figure 9: Effective stress paths from triaxial tests

From Figure 9 it can be seen that all specimens approach a similar ultimate frictional resistance, which for the specimens shown ranged from 37^o to 40^o. Cyclic shear box tests showed no evidence of any lower residual frictional strength (Glenn *et al*., 2008).

3 ANALYSIS

3.1 LANDSLIDE INITIATION

Geomechanical modeling of three of the submarine landslides has been undertaken using the slope stability program GEO-SLOPE/W (2007) to examine the influence of cohesion, friction angle and slope geometry on the stability (Clarke *et al*, 2011). As the friction angle is around 40^o and the slopes are from 3^o to 6^o static analyses predict very high factors of safety. Analyses have also been conducted to investigate the effects of earthquake loading by including a factor for seismic accelerations in the standard pseudo-static limit-equilibrium calculations. Selecting an appropriate value for the seismic coefficient acting on the failure mass can be especially difficult (Seed and Martin 1966). A very crude investigation of seismic loading on the slopes indicates that lateral and vertical accelerations of 0.3 g (a_h = 0.3 g, a_v = -0.3 g), the upper limit of those used to investigate the stability of earth dams during earthquakes (Seed and Martin, 1966; Ozkan, 1998), would be sufficient to destabilise the slopes of the seafloor in the present study. While this approach has been widely used to assess the stability of submarine slides to earthquake events, its applicability to such large volumes of soil is questionable and the approach is of limited value in understanding the mechanisms leading to failure.

Puzrin *et al.* (2004) have argued that it is unlikely that a failure can develop over distances of several kilometres instantaneously, and that a progressive failure mechanism must be considered. On land progressive failures are often observed to result from oversteepening of the toe of a slope, where failure at the toe leads to a retrogressive failure that migrates upslope. This mechanism is also considered to be responsible for the large Storrega submarine slide. Puzrin *et al*. (2004) have suggested an alternative progressive failure mechanism that involves a weakened zone propagating down slope. The basis of the analysis can be explained by considering Figure 10. The starting point is that a zone of elevated pore pressures develop (Figure 10a), possibly owing to an earthquake, where the soil reaches a state of failure for which the mobilisable soil resistance is lower than the stresses at equilibrium from the weight of the overlying soil ($\tau_r < \tau_g$ Figure 10b). If the length of this failed zone is sufficient a global and catastrophic failure will occur. However, if the zone of failure is more limited the soil will tend to move downslope into the currently unfailed region. If the failure plane can propagate because the energy released is greater than that needed to progress the failure then the shear plane can grow, and if conditions are unfavourable, it may continue to advance until it reaches a length where global failure results. For significant energy release to occur the ultimate resistance of the soil needs to be lower than that required to resist the gravitational stresses, and the soil needs to respond in a brittle manner. The triaxial test data shown above display the type of brittle behaviour that can potentially lead to this type of mechanism.

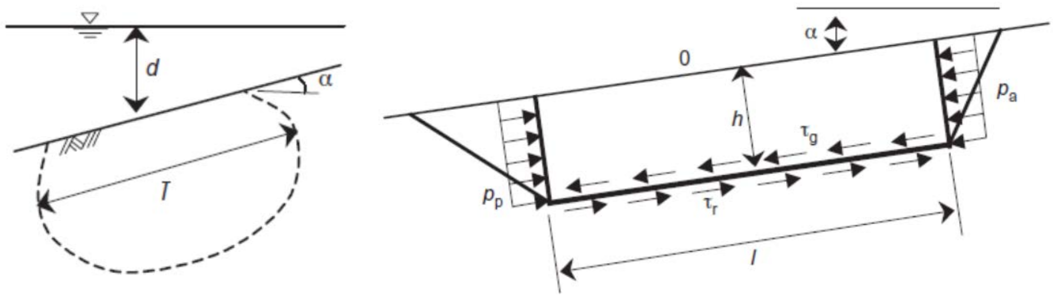

Figure 10: (a) Zone of elevated pore pressures, (b) Slope failure mechanism (after Puzrin *et al*., 2004)

The analysis of Puzrin *et al*. (2004) suggests that failure begins upslope, but depending on the soil type and behaviour progressive failure may be limited or not occur and it is possible that the resulting length of the failure surface may be less than the critical value required for a catastrophic failure. There is some evidence for this from a number of head scarps present on the SE Australian margin where the soil below has not moved significantly. Glenn *et al.* (2008) suggest that these features represent the sites most likely to fail in the future. However, if the analysis of Puzrin *et al*. (2004) is correct, the soil movements make these sites less likely rather than more likely to lead to failure.

3.2 TSUNAMI GENERATION

The viscous drag on the overlying ocean due to the movement of the slide block is responsible for the tsunami generation. Many studies have been conducted into tsunami generation and propagation, but only the work of Ward (2001) will be mentioned here. Ward (2001) presents results of tsunami generation and propagation based on classical tsunami theory and assuming linear wave theory. This theory uses a rigid seafloor overlain by an incompressible, homogeneous and non-viscous ocean subjected to a constant gravitational field. Figure 11 provides an indication of the size of the tsunami from analysis of a rectangular block of length L (km) and width W (km) sliding down an inclined plane for a water depth of 1000 m. The tsunami velocity is given by $\sqrt{(gh)}$ where h is the water depth, and in 1000 m of water this is 99 m/s. There are no reliable data on the speed of submarine slides, although turbidity currents from the 1929 Grand Banks slide travelled at 25 m/s, and based on travel distances of slide debris speeds of up to 80 m/s have been inferred for some large slides (Masson *et al.*, 2006). The fracture mechanics approach proposed by Puzrin *et al.* (2010) enables an estimate of the initial velocity to be determined and values of around 10 m/s were estimated for some reported slide geometries. For the largest slides on the SE Australian margin the water depth is around 1000 m, the maximum slide thickness is 200 m, and assuming a maximum velocity of 20 m/s a peak tsunami wave height of around 20 m can be estimated from Figure 11. As the maximum dimensions of the sliding blocks on the SE Australian margin are 20 km x 5 km some reduction to this height may be appropriate. Further reductions in wave height will occur as any waves approach the coast.

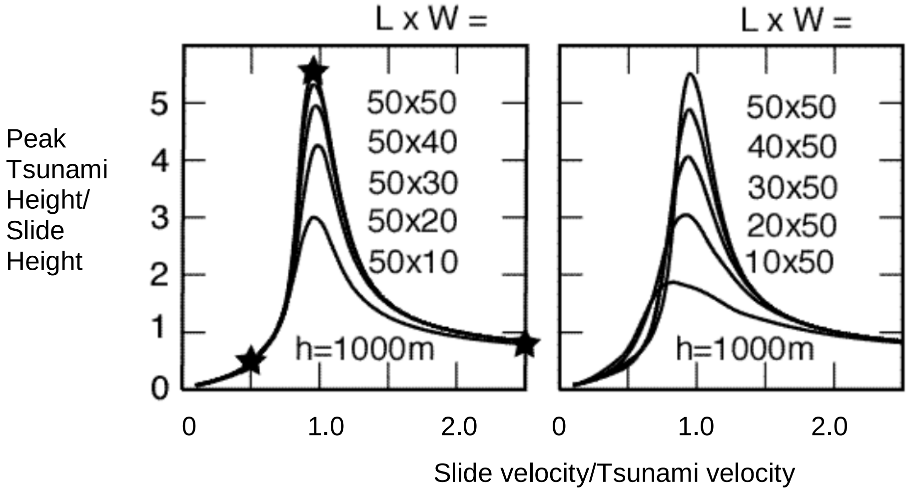

Figure 11: Effects of slide velocity and slide dimensions on peak tsunami height (after Ward, 2001).

4 SUMMARY

The paper has shown evidence of large scale mass wasting phenomena on the SE Australian continental slope, including the existence of many landslide features. Slides are evident all along the margin from Shoalhaven to the Sunshine Coast, and on slopes ranging from 1^o to 9^o. The soil properties of the upper sediments are similar along the margin and show no evidence of weak clay layers, although they do contain significant amounts of clay. The friction angles of the sediments are in the range of 37^o - 40^o, so that conventional soil mechanics would suggest the slopes have high factors of safety. However this is clearly not the case, as slope failures are widespread. Triaxial tests have indicated a significant increase in the brittleness of the shear response with stress level, and this is thought to be significant in explaining why the slides have thicknessess of 50 m to 200 m. The largest slope failures have a volume of 20 km^3 and have the potential to generate significant tsunami waves.

The dating of the slides suggests that the most recent failures occurred at the time when the sea level was at its minimum during the last glaciation. There are several reasons why the likelihood of slides should increase at these times, however the cause of the slides on the SE Australian margin is not well understood. While the likelihood of slides appears to be lower in inter-glacial periods there are examples of earthquake caused submarine slides that have occurred recently and the possibility that a large submarine slide could occur any day cannot be discounted.

5 ACKNOWLEDGEMENTS

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