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An Analysis of the Morphology and Submarine Landslide Potential of the Upper and Middle Continental Slope Offshore Fraser Island, Queensland, Australia

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A thesis submitted in fulfillment of the requirements for the degree of Master of Science (by Research) within the Faculty of Science

June 2015
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Abstract

This study presents an investigation into the geomorphological, sedimentological and geotechnical properties of submarine landsliding along the eastern Australian seaboard of southern Queensland, with a particular focus offshore Fraser Island. High-resolution bathymetric data for this section of the margin, along with four gravity cores, were collected onboard RV *Southern Surveyor*. An extensive range of previously undiscovered features including marginal plateaus, linear rills, ridges and gullies, canyon systems, as well as slides and slumps, were identified.

Two potentially tsunamigenic submarine landslides were identified: the Upper Slope Slide within the Fraser Canyon Complex (25 km² and 200-300 m thick); and the Middle Slope Slide on the Wide Bay Plateau (11 km² and 100-150 m thick). Cores taken within the slides were relatively long (upper slope, GC2 = 565 cm; middle slope, GC3 = 364 cm) and dominantly comprised of Pleistocene to Recent hemipelagic muds; while the shorter gravity cores taken adjacent to both slides (upper slope, GC1 = 133 cm; middle slope, GC4 = 43 cm) terminated in stiff muds of upper Pliocene to lower Pleistocene (GC1), and upper Miocene to lower Pliocene age (GC4). This unique pattern shows that the sediment is being accumulated and protected inside the slide hollows, while being actively removed from the exposed adjacent slopes, most likely by abrasion. The core on the slope adjacent to the Upper Slope Slide (GC1) also presented a near surface layer of well sorted, coarse, bioclastic, shelly sand that is interpreted to be a grain flow or turbidite sand. This sand deposit, along with a large number of extensive linear rills evident in the bathymetry of the adjacent Fraser Canyon Complex, suggests that the continental slope offshore Fraser Island is a highly energetic and active system and has experienced top-down incision and slope failures during the recent geologic past (Pleistocene). Several hiatus surfaces within cores GC1, GC2 and GC3 were identified by sharp colour-change boundaries, small increases in sediment stiffness, and distinct AMS $^{14}$C age gaps of >30 ka. These surface boundaries indicate that a significant amount of sediment has been removed from the continental slope by sliding or scour events, and/or ‘turbidite-related’ abrasion, with events occurring at 8.4 ka BP for GC2, 14.6 ka BP for GC1, and ~71 ka BP for GC3.

A reliable average sedimentation rate for the middle slope on the Wide Bay Plateau of ~0.057 mka⁻¹ during Pleistocene to Recent times was determined from core GC3, inside the Middle
Slope Slide. Sedimentation rates for core GC4 on the slope adjacent to the Middle Slope Slide could not be calculated from GC3, as the sediment has not accumulated there recently. Instead, the exposure of upper Miocene sediment on the seafloor surface indicates that the smooth slope exposed at this mid-continental slope site is an erosional unconformity surface of significant antiquity. Due to a small sample size and termination into radiocarbon dead sediments, it is plausible that the sedimentation rates for the present day slope surface sediments (top 19 cm) adjacent to (GC1) and within (GC2) the Upper Slope Slide are slow, ~0.011 mka⁻¹ and 0.019 mka⁻¹ respectively. These results are inconsistent with penecontemporaneous long-term sediment accumulation, and are interpreted to indicate that erosion of the slope is ongoing and the slope is probably shedding sediment quasi-continuously.

Slope stability modeling using standard geotechnical methods shows both slopes to be comprised of relatively strong and inherently stable materials (FoS >4), yet a large number of failures have been identified along the entire east Australian continental margin (EACM). An increase in the effects of oceanic currents at various times during the Pleistocene is suggested to be a major contributing factor that has led to destabilising the EACM by causing widespread and further toe erosion that pre-conditions the slopes for failure.

Biostratigraphic ages determined for the basal material in GC1 and GC4 demonstrates that the seafloor surface of both slopes are effectively erosional unconformities and the maximum age at which these slopes formed can be determined. The basal, stiff sediments within GC1 (~127 cm) from the upper slope were dated at ~2-2.5 Ma BP, and this material was scoured and then buried 0.45 Ma BP indicating that this smooth, un-failed portion of the upper continental slope developed its current morphology by the late-mid Pleistocene and that the adjacent Upper Slope Slide occurred at some time after 0.45 Ma BP. Sediments within GC4 (~41 cm) on the middle slope are dated to ~6-8.5 Ma BP. This indicates that the morphology of the middle continental slope is a Post-Pliocene feature. It is thought that a series of geological events from the Pliocene-Pleistocene has caused significant changes in current intensity both relating to the southward East Australian Current and the northward Antarctic Circumpolar Current that has led to suppression of sediment delivery to the slope, or constant abrasion and erosion re-sculpting the slope morphology.
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List of Symbols

$C_v$  Coefficient of consolidation
$c'$  Cohesion
$C_c$  Compression index
$\sigma'$  Current effective stress
$z$  Depth to burial
$\phi$  Friction angle
$\text{LL}$  Liquid limit
$M_s$  Mass of solids
$M_w$  Mass of water
$\text{PI}$  Plasticity index
$\text{PL}$  Plastic limit
$u$  Pore water pressure
$\sigma'_{pc}$ or $pc'$  Preconsolidation stress
$^{14}\text{C}$  Radiocarbon age
$C_r$  Recompression index
$S_r$  Remoulded shear strength
$\gamma_{sat}$  Saturated unit weight
$S_t$  Sensitivity
$S_{ur}$  Shear strength
$\tau$  Shear stress
$\theta$  Slope angle
$G_s$  Specific gravity
$T_{90}$  Square root time at 90% consolidation
$\gamma$  Unit weight
$\gamma_{water}$  Unit weight of water
$e$  Void ratio
$w$  Water content
## List of Abbreviations

<table>
<thead>
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<th>Abbreviation</th>
<th>Description</th>
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<tbody>
<tr>
<td>AMS</td>
<td>Accelerator Mass Spectrometry</td>
</tr>
<tr>
<td>ASTM</td>
<td>American Society for Testing and Materials</td>
</tr>
<tr>
<td>ACC</td>
<td>Antarctic Circumpolar Current</td>
</tr>
<tr>
<td>AS</td>
<td>Australian Standard</td>
</tr>
<tr>
<td>BP</td>
<td>Before Present</td>
</tr>
<tr>
<td>EACM</td>
<td>East Australian Continental Margin</td>
</tr>
<tr>
<td>EAC</td>
<td>East Australian Current</td>
</tr>
<tr>
<td>FoS</td>
<td>Factor of Safety</td>
</tr>
<tr>
<td>GLORIA</td>
<td>Geological Long-Range Inclined Asdic</td>
</tr>
<tr>
<td>GC</td>
<td>Gravity Core</td>
</tr>
<tr>
<td>kPa</td>
<td>Kilopascals</td>
</tr>
<tr>
<td>MTD</td>
<td>Mass Transport Deposit</td>
</tr>
<tr>
<td>Ma</td>
<td>Million Years</td>
</tr>
<tr>
<td>NSW</td>
<td>New South Wales</td>
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<tr>
<td>OCR</td>
<td>Over-Consolidation Ratio</td>
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<tr>
<td>QLD</td>
<td>Queensland</td>
</tr>
<tr>
<td>RCD</td>
<td>Radiocarbon Dead</td>
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<tr>
<td>RV</td>
<td>Research Vessel</td>
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<tr>
<td>SEM</td>
<td>Scanning Electron Microscope</td>
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<tr>
<td>SS</td>
<td>Southern Surveyor</td>
</tr>
<tr>
<td>ka</td>
<td>Thousand Years</td>
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<tr>
<td>USCS</td>
<td>Universal Soil Classification System</td>
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<td>VE</td>
<td>Vertical Exaggeration</td>
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<td>XRD</td>
<td>X-Ray Diffraction</td>
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CHAPTER 1

Global Overview of Submarine Landslides

1.1 Introduction

The study of offshore geohazards such as submarine landslides is of vital importance for
government organisations, risk managers, the insurance industry, engineers, scientists and,
ultimately the general public (Solheim et al. 2005; Smolka 2006; Nadim 2006; 2012).
Understanding the geomorphology, stability and sedimentology, as well as the triggering
mechanisms involved in initiating submarine landslides, is a necessary requirement for
evaluating their potential to damage or destroy seabed infrastructure or generate
potentially lethal and property threatening tsunamis. With over half of the world’s
population living on or near coasts, it is critical to determine the frequency of submarine
landslide occurrence (Masson et al. 2006; Geist and Parsons 2010; Yamada et al. 2012;
Urlaub et al. 2013).

Submarine landslides are gravity-driven mass movements of marine sediments downslope
and are commonly the initial transport stage of continental slope material to the abyssal
plain. They can take the form of rotational or translational slides, slumps and debris
avalanches, and generate a variety of depositional products (Mass Transport Deposits,
MTD’s) includingolistostromic blocks, debris flows (debrites), grain flows, mud flows, and
turbidites (massive graded sands) (Coleman and Prior 1988; Mulder and Cochonat 1996;
Masson et al. 2006; Lee et al. 2007). Slope failure occurs when the driving downslope forces
acting on a segment of the slope are greater than the resisting forces which results in shear
failure along one or more surfaces bounding the block (Hampton et al. 1996; Wright and
Rathje 2003). Alternatively, external factors cause a loss of shear strength or liquefaction in
a particular layer (Lewis 1971; Papatheodorou and Ferentinos 1997; L’Heureux et al. 2012;
Locat et al. 2014). In both of these cases some form of external triggering mechanism is
required to initiate failure (Wright and Rathje 2003; Sultan et al. 2004; Masson et al. 2006;
see Section 1.5).
This study will investigate submarine landslides along the east Australian continental margin (EACM) located offshore Fraser Island in southern Queensland. This research will help us to further understand the underlying processes that have caused failure both in this region and elsewhere; and to assess the likelihood of slide reoccurrence and the related potential tsunami hazard. Not only will this study benefit science in creating a wider understanding on the processes involved in this region, it will enhance our understanding in tsunami hazard research to help ensure the safety of Australians living on the eastern seaboard and to protect their social and economic well-being.

This chapter provides a review of previous work at a global scale to contextualise the current investigations presented in Chapters 2-6. The specific aims and objectives for this study are presented in Chapter 2, along with a summary of earlier studies specifically focussing on submarine landslides along the EACM.

1.2 Distribution of Submarine Landslides

Submarine landslides have been identified on nearly all of the Earth’s continental margins, which are the transition zones between the high standing continents and the deep ocean basins (Mienert et al. 2003; Harris et al. 2014). The continental margins are commonly divided into the shelf, slope and rise, and account for around 20% of the areal extent of the world’s marine system (Wefer et al. 2000; Garrison 2010; Harris et al. 2014; see Figure 1.1). Prior to 1990, single-beam echo sounder records were used to map ocean bathymetry and these enabled the production of accurate but low-resolution underwater maps. The development of high-resolution, depth-sounding multi-beam techniques, and differential global positioning systems during the 1990’s enabled the production of better-detailed bathymetry of the continental margins. In the case of identifying their complex erosional and depositional features, including submarine landslides, clarification was provided by aerial photographs of terrestrial features (Locat and Lee 2002). This led to suggest that the absence of identified slides in a particular region was more often likely to be a consequence of poor data coverage than the absence of these features themselves (Mienert et al. 2003). Lee et al. (2007) also stated that it was the development in side-scan sonar from the GLORIA
The advent of side scan sonar and GLORIA in the mid-1980’s was developed specifically to map the morphology of seafloor features in the deep ocean. These investigations identified numerous slides along the United States (US) continental slope (McAdoo et al. 2000; USGS 2013) and the Hawaiian Ridge (Moore et al. 1989). Subsequent advances in multibeam technology have enabled the identification of large slides globally. The Bulli Slide in southern New South Wales, Australia (Jenkins and Keene 1992), the Saharan Slide in northwest (NW) Africa (Georgiopoulou et al. 2010), the Storegga Slide in Norway (Kvalstad et al. 2005), and the Grand Banks Slide in Newfoundland, Canada (Fine et al. 2005), are examples of the slides identified since the 1980’s. Figure 1.2 shows the location of some of the better-studied submarine landslides that have been described in the academic literature (c.f. Harris et al. 2014). Furthermore, the European, US Atlantic, and NW African continental margins have been studied extensively through various projects such as GLORIA (Schwab et al. 2014).
1991), STRATAFORM (Nittrouer and Kravitz 1996), COSTA (Sultan et al. 2004), ENAM II, STEAM and ADFEX (Locat and Lee 2002). In comparison, little is known about the slides of Australia’s continental margin, a country that has an estimated 16 million people living within 50 km of the coastline (Australian Bureau of Statistics 2006).

Figure 1.2. Location of large ancient submarine mass movements and tsunamigenic failures of the slope along active and passive continental margins (modified from Harris et al. 2014). Details of each slide are provided in Table 1.

There are two types of continental margins, those facing active or fossil mid-ocean ridges are called ‘passive margins,’ and those facing or located adjacent to subduction zone trenches at converging plate boundaries are called ‘active margins’ because of their related frequent large earthquakes and ongoing volcanism (Garrison 2010; see Figure 1.3). Passive margin morphology is commonly dominated by burial of the rifted continental edge by material eroded from the adjacent landmass, while tectonic and volcanic processes control active margin terrains constructed of imbricated sheets of oceanic crust (Harris and Whiteway 2011). Both types of margin are apparently able to generate enormous
submarine landslides. Examples of slides on the passive margin include the Storegga Slide located offshore western Norway, one of largest known reported slides generating a volume of 3000 km$^3$ (Evans et al. 1996; slide 2 in Figure 1.2) and the Currituck Landslide (150-165 km$^3$) off North Carolina (Locat et al. 2009; slide 11 in Figure 1.2). Slides along active margins include the ‘BIG’95’ slide along the Ebro continental slope in the Mediterranean (26 km$^3$; Lastras et al. 2004; slide 15 in Figure 1.2), and the Kidnappers Slide Complex in New Zealand (33 km$^3$; Barnes et al. 1991; slide 7 in Figure 1.2). A third setting that generates large slides are oceanic islands such as the Hawaiian Group and the Canary Islands. The Nuuanu Landslide (5000 km$^3$, oceanic volcano; Moore et al. 1989), Palos Verge debris avalanche (Bohannnon and Gardner 2004), and the El Golfo Avalanche (Longpre et al. 2011) are all examples of oceanic island slides (slides 10, 9, and 16 respectively in Figure 1.2). There are differences between the types of mass movements recorded for the two margin types. Active margins tend to shed blocky avalanches as a result of frequently large earthquake shaking removing material frequently steeper, whereas passive margins tend to accumulate thick deposits that are shed less frequently (Nelson et al. 2011). As a result, passive margins are more likely to produce debris flows and have longer run out distances, whereas active margins are more inclined to slide as discrete large blocks or avalanches (Harris and Whiteway 2011; Nelson et al. 2011). Submarine mass movements can vary greatly in their size and extent with some volumes as large as 5000 km$^3$ and run-out distances well over 200 km (Lee et al. 2007). At the other end of the scale submarine landslides as small as 0.5 km$^3$ are often identified and are suspected to have the potential to cause damage to seabed infrastructure (Boyd et al. 2010). Table 1.1 provides examples of well-studied submarine landslides that indicate the range of sizes and physical properties involved (see Figure 1.2 for their location).

1.3 Recurrence Intervals and Offshore Effects

Recurrence intervals for submarine landslides are poorly constrained with the average frequency for submarine landslides suspected to range between 2-150 thousand years (ka) (Talling 2014). Some submarine landslide recurrence intervals are thought to be similar
Figure 1.3. Cross-sectional profiles of a) a typical ocean basin bordered by passive continental margins, and b) a typical continental margin bordering both active and passive edges of a continent (from Garrison 2010).

to those of large intraplate earthquakes and large volume mega-eruptions that are commonly 10 ka to 1 million years, and as a consequence, commonly excluded from risk analyses (Clare et al. 2014; Talling et al. 2014). Numerous studies have been undertaken on terrestrial landslides (Shang et al. 2003; Schuster et al. 2004; Owen et al. 2008; Runqiu 2009). Nevertheless, submarine landslides have the potential to generate both near and far-field tsunamis. In 1998, a magnitude 7.0 earthquake struck off the north coast of Papua New Guinea triggering a landslide (Sisano Aitape Slide) followed by a series of three large waves with the first arriving 20 minutes after the earthquake. Many villages were destroyed and over 2200 people killed (Gelfenbaum and Jaffe 2003). The earthquake was probably not large enough to have caused the tsunami directly, but is thought to have triggered a submarine landslide that did generate the onshore surge (c.f. Tappin et al. 2001). This example highlights the need for the timing, frequency, and distribution of submarine landslides to be studied in detail as it can be argued that their effects can be far more damaging than terrestrial landslides.
Table 1.1. Examples of submarine landslides highlighting their type, contributing factors (triggers), size and impact. SLR = sea level rise, LGM = low glacial maximum, M = magnitude, ka = thousand years, Ma = million years (before present).

<table>
<thead>
<tr>
<th>Location, Name</th>
<th>Year</th>
<th>Margin Type</th>
<th>Type</th>
<th>Suspected Contributing Factors</th>
<th>Area (km²)</th>
<th>Volume (km³)</th>
<th>Run-out (km)</th>
<th>Impact</th>
<th>References</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Hinlopen Slide, Arctic Ocean</td>
<td>Unknown</td>
<td>Passive</td>
<td>Slide</td>
<td>Sedimentation and glacio-isostatic movement</td>
<td>2200</td>
<td>1350</td>
<td>60</td>
<td>Unknown</td>
<td>Vanneste et al. (2006)</td>
</tr>
<tr>
<td>2. Storegga Slide, Norway</td>
<td>8.2 ka</td>
<td>Passive</td>
<td>Slide/Debris flow/Tsunami</td>
<td>Retrogressive sliding by an earthquake and overpressure</td>
<td>90000</td>
<td>3000</td>
<td>800</td>
<td>10-20 m tsunami.</td>
<td>Kvalstad et al. (2005); Hill et al. (2014)</td>
</tr>
<tr>
<td>3. Agulhas, South Africa</td>
<td>1629</td>
<td>Passive</td>
<td>Tabular blocks to debris flow</td>
<td>Suspected earthquake/fluid flow</td>
<td>&gt;430</td>
<td>&gt;20</td>
<td>106</td>
<td>Unknown</td>
<td>Gee et al. (2005; 2006)</td>
</tr>
<tr>
<td>4. The Brunei Slide, NW Borneo</td>
<td>2-7 ka</td>
<td>Active</td>
<td>Debris Flow Matrix</td>
<td>Fluid flow and gas build-up</td>
<td>5300</td>
<td>1200</td>
<td>120</td>
<td>Unknown</td>
<td>Gee et al. (2007)</td>
</tr>
<tr>
<td>6. Bulli Slide, NSW Australia</td>
<td>20 ka</td>
<td>Passive</td>
<td>Slide</td>
<td>Suspected seismic disturbance</td>
<td>65</td>
<td>20</td>
<td>Unknown</td>
<td>Unknown</td>
<td>Jenkins and Keene (1992); Clarke et al. (2012; 2014)</td>
</tr>
<tr>
<td>8. Seward, Alaska</td>
<td>1964</td>
<td>Active</td>
<td>Slide/Tsunami</td>
<td>Earthquake</td>
<td>-</td>
<td>-</td>
<td>Unknown</td>
<td>10 m tsunami, 13 deaths and coastal damage</td>
<td>Lee et al. (2003)</td>
</tr>
<tr>
<td>9. Palos Verde Debris Avalanche, California</td>
<td>7.5 ka</td>
<td>Active</td>
<td>Debris Avalanche and possible tsunami</td>
<td>Earthquake</td>
<td>9.2</td>
<td>0.34-0.72</td>
<td>8</td>
<td>8-12 m tsunami</td>
<td>Bohannon and Gardner (2004)</td>
</tr>
<tr>
<td>Location, Name</td>
<td>Year</td>
<td>Margin Type</td>
<td>Failure Type</td>
<td>Suspected Contributing Factors</td>
<td>Area (km²)</td>
<td>Volume (km³)</td>
<td>Run-out (km)</td>
<td>Impact</td>
<td>References</td>
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<tr>
<td>12. Grand Banks Earthquake, Newfoundland, Canada</td>
<td>1929</td>
<td>Passive</td>
<td>Slide/Turbidity Current/Tsunami</td>
<td>M 7.2 earthquake</td>
<td>20000</td>
<td>200</td>
<td>1000</td>
<td>3-8 m tsunami, 28 deaths</td>
<td>Fine et al. (2005)</td>
</tr>
<tr>
<td>13. Afen Slide, Norwegian Basin</td>
<td>mid-Pleistocene</td>
<td>Passive</td>
<td>Debris flow</td>
<td>Seismic</td>
<td>38</td>
<td>0.14</td>
<td>Unknown</td>
<td>Unknown</td>
<td>Wilson et al. (2004); Masson et al. (2006)</td>
</tr>
<tr>
<td>14. Nice Airport, France</td>
<td>1979</td>
<td>Not Relevant</td>
<td>Slide to debris flow to tsunami</td>
<td>Pore pressure effects post construction</td>
<td>-</td>
<td>0.0087</td>
<td>2.3</td>
<td>3 m tsunami, 10 deaths and coastal damage</td>
<td>Dan et al. (2007); Ioualalen et al. (2010)</td>
</tr>
<tr>
<td>15. BIG’95, Western Mediterranean Sea</td>
<td>11 ka</td>
<td>Active</td>
<td>Slab slide to debris Flow</td>
<td>Seismicity, over steepening due to volcanic structure</td>
<td>2000</td>
<td>26</td>
<td>Unknown</td>
<td>Unknown</td>
<td>Lastras et al. (2004)</td>
</tr>
<tr>
<td>16. El Golfo Avalanche, Canary Islands</td>
<td>39-87 ka</td>
<td>Volcanic Island</td>
<td>Debris Avalanche and Slumps</td>
<td>Flank collapse</td>
<td>1500</td>
<td>150-180</td>
<td>Unknown</td>
<td>Unknown</td>
<td>Masson et al. (2006); Longpre et al. (2011)</td>
</tr>
<tr>
<td>17. The Saharan Slide, NW Africa</td>
<td>45-59 ka</td>
<td>Passive</td>
<td>Retrogressive slab slide to debris Flow</td>
<td>Rapid SLR and low stand – pore pressure build-up</td>
<td>70000</td>
<td>600</td>
<td>900</td>
<td>Unknown</td>
<td>Georgiopoulou et al. (2010)</td>
</tr>
<tr>
<td>19. Mauritania Slide Complex, NW Africa</td>
<td>10.5-10.9 ka</td>
<td>Passive</td>
<td>Slide</td>
<td>Occurred at the end of the LGM, SLR</td>
<td>30000</td>
<td>400-600</td>
<td>300</td>
<td>Unknown</td>
<td>Krastel et al. (2012)</td>
</tr>
<tr>
<td>20. Dakar Slide offshore Senegal, NW-Africa</td>
<td>1.2 Ma (min)</td>
<td>Passive</td>
<td>Retrogressive slides</td>
<td>High sediment accumulation and possible tectonic processes</td>
<td>8000</td>
<td>&gt;1000</td>
<td>Unknown</td>
<td>Unknown</td>
<td>Meyer et al. (2012)</td>
</tr>
</tbody>
</table>
The occurrence of many past submarine landslides has been suggested to be associated with rising sea levels (Lee 2009; Brothers et al. 2013; Hunt et al. 2013; Smith et al. 2013; Urlaub et al. 2013), atmospheric methane abundance (Nixon and Grozic 2006; Li and He 2012; Mountjoy et al. 2014), and earthquakes (Lee et al. 2003; Fine et al. 2005; Haeussler et al. 2014; Hjelstuen and Brendryen 2014). However, studies by Clare et al. (2014) and Geist and Parsons (2010) on the recurrence intervals of submarine landslides, demonstrates that the probability of a large slide occurring is independent of the time since the last slide. Talling et al. (2014) also showed that the correlation between landslide frequency and sea level is not strong by plotting past events against a global (eustatic) sea level curve. Error bars showed maximum and minimum ages to display a wide range (Figure 1.4). Instead, Talling et al.’s (2014) study related the frequency distribution of submarine landslide deposits to that of a large magnitude earthquake occurrence and suggested a close causal relationship. Processes that oscillate with rising sea levels such as shelf edge sedimentation rates or hydrate dissociation driven by global warming are also not considered to be major factors in generating slides (Clare et al. 2014), and went on to suggest that future sea level change in the forthcoming decades will not affect the frequency of large mass movements or be a sole causal factor. Earthquakes could be a major cause for future landslides as large magnitude earthquakes often have a temporally random occurrence (Talling et al. 2014). However, not all major earthquakes trigger submarine landslides, which suggests that the coincidence of several contributing factors may be required (Volker et al. 2011).

1.4 Types of Submarine Mass Movements and their Related Deposits

Many schemes have been proposed for the classification of submarine mass movements, for example Mulder and Cochonat (1996), Locat and Lee (2000), and Masson et al. (2006). In this work the general mass failure scheme proposed by Varnes (1958) as modified by Lee et al. (2007) will be used. It divides submarine mass movements into two types; slides and mass flows (Figure 1.5). These two types of movement are distinguished from each other according to whether or not the mass remains intact or disintegrates and mixes with water as it moves downslope (Mulder and Cochonat 1996; Marshak 2005).
Figure 1.4. Submarine landslide ages for slides >1 km$^3$ displaying their minimum and maximum age plotted against global (eustatic) sea level over the last 180 thousand years according to their landscape setting (from Talling et al. 2014).

Slides described as semi-coherent blocks are known as olistostromes, which generally slip downslope along what is thought to be a weak layer. Slides occurring on a planar, flat surface are recognised as translational slides (Figure 1.6a). Some coherent mass failures also occur as rotational slides, also known as slumps, where failure occurs along a curved slip surface (Lee et al. 2007; see Figure 1.6b).

Mass flows (gravity flows) are used to describe moving sediment that resembles a viscous fluid or disintegration of sediment during failure. Debris flows result when a heterogeneous mass disintegrates to form a slurry of mixed sediment that can support and transport larger
clasts and large blocks. Mudflows are similar to a debris flow but can be differentiated by their generally fine-grained and well-sorted sediment load. Grainflows, mudflows, and turbidity currents represent a continuum of water and sediment mixtures. Turbidity currents are sediment-laden gravity flows that transport sand and coarse sediments from shallow to deep regions (Piper and Normark 2009; Meiburg and Kneller 2010; Clare et al. 2014). These flows are often generated by the disintegration of slides or debris flows but can also be generated by mobilisation of unconsolidated near surface sediments. Liquefaction flows occur when loosely packed sediments collapse due to a rapid increase of pore water pressures or a decrease in strength and sudden external loading (Mulder and Cochonat 1996; Andrews and Martin 2000; Lee et al. 2007). Liquefaction can be induced by tidal variations (shallow water deposits), earthquake shaking, or long-period waves. Finally, a debris avalanche involves the rapid movement of rock and large blocks of material, which are thought to result from a large slide or slump disintegrating to generate vast run-out distances. This makes finding their deposits difficult as they are commonly deposited several hundreds (or even thousands) of kilometres from the failure site (de Alteriis et al. 2010).

It is important to note that submarine mass movements probably generate a variety of materials that move downslope rather than a single block or several blocks. Many mass movements probably start as a single sliding block that then disintegrates and transforms into a debris flow, grain flow, mudflow, or turbidity current. Consequently, Locat and Lee (2002) identified four important stages and characteristics that should be investigated when assessing the type and impact of a submarine mass failure:

1. Initiation - what triggering mechanisms caused failure and slide motion?
2. Disintegration on movement - material characteristics of the soil, and its ability to flow as a unit or disintegrate. This can be assessed through geotechnical and sedimentologic tests.

3. Transition into a mass flow and the ability to travel along the seafloor (run-out distance).

4. Movement on the seafloor until final deposition to obtain a run-out distance.

For example, the ‘BIG’95’ Holocene mass shed from the Ebro continental slope failed as large slab slides which were transformed into a debris flow, and then generated 26 km³ of sediment that buried 2000 km² of the adjacent abyssal plain (Lastras et al. 2004). The Grand Banks slide in Newfoundland, Canada produced a turbidity current that travelled 1000 km between 60-100 km/hour and broke 12 telegraph cables (Fine et al. 2005). Determining how a submarine mass movement is initiated is difficult and requires investigation of the failure site and characterisation of the geotechnical properties of the sediments. This information may then suggest a plausible triggering mechanism given the geologic characteristics and tectonic setting. Bathymetric mapping of the downslope deposits and sampling can determine whether or not a mass failure disintegrates on movement, transitions into a flow and runs out downslope to the abyssal plain.

1.5 Triggering Mechanisms

In order for a slope to fail, some form of trigger is needed to help set the slope in motion. Gaining knowledge about these factors is critical in understanding and evaluating the causes and risks associated with submarine mass movements. Figure 1.7 shows a flow chart of how some of the known triggering mechanisms can interact to increase stress or reduce the sediment strength subsequently causing a submarine mass failure. Rapid sedimentation, earthquakes, surface waves, and changes in sea level are considered to be the main contributing factors (Coleman and Prior 1988; Locat and Lee 2002; Sultan et al. 2004; Masson et al. 2006). Other triggering mechanisms include gas hydrate dissociation (Li et al. 2014), volcanic processes (Ward and Day 2001), creep (He et al. 2014), and human activity (Fine et al. 2005). Masson et al. (2006) highlights that not all failures and their resulting triggers are obvious as some areas have indirect factors that pre-dispose, or pre-condition, the materials for failure over long periods of time. For example, the Storegga slide in
Norway was first thought to be three separate slides that occurred in the area around 30-50 ka, 8 ka and 6 ka BP respectively (with each slide generating a tsunami) as a result of retrogressive sliding by an earthquake and overpressure of a sensitive base layer (Jansen et al. 1987; Bugge et al. 1988; Harbitz 1992). However, recent studies now suggest an interpretation that the Storegga Slide occurred instantaneously at 8.1 ka BP (Bondevik et al., 2005; Haflidason et al. 2005; Kvalstad et al. 2005; Lovholt et al. 2005; Hill et al. 2014). Hance (2003) presented a database of submarine landslides from the literature showing the relationship of triggering mechanisms with the number of slope failures (Figure 1.8). Of the 534 events studied, 366 triggering mechanisms were identified. Many slides had more than one trigger but more than 40% of these slides were attributed to earthquakes and faulting; rapid sedimentation and over-pressurising the next most important.

![Diagram of Contributing Factors to Submarine Mass Movements and Risk](image-url)

**Figure 1.7.** Contributing factors to the initiation of submarine mass movements and the risk they pose. N.B: more than one factor may contribute to a single landslide event (modified from Coleman and Prior 1988).

Clarke (2014), Clarke et al. (2012; 2014), and Hubble et al. (2012) have identified three potential conditioning factors or triggering mechanisms for along the EACM:

1. A reduction in shear strength induced by creep or pore pressure build-up.
2. Long-term modification of the slope geometry through either sedimentation of the head of the slope or erosion at the toe.
3. Infrequent large earthquakes triggering sediment liquefaction or a rapid pore pressure build-up.

For the purpose of this study, only these three processes will be described briefly below.

![Number of Slope Failures vs Triggering Mechanism](image)

**Figure 1.8.** Global slope failures and their resulting triggering mechanism (from Hance 2003, in Nadim 2012).

1) **Creep**

Creep (or secondary compression) occurs when the soil experiences constant stress and incremental deformation that slowly lowers the soils strength causing failure over-time (Mitchell and Soga 2005; Dan et al. 2007). This was the case for the 1979 Nice Harbour slope that claimed the lives of 10 people. A slide was triggered by long-term failure from creep within a sensitive clay layer that failed, triggering a slide, which transitioned into a debris flow that generated a tsunami (Dan et al. 2007; Ioulalen et al. 2010).

2) **Sedimentation and Erosional Effects**

Rapid sedimentation can cause sediment failure in areas such as prograding deltas and glacier margins (Coleman and Prior 1988). When continuous layers of low-permeability mud develop they can prevent the escape of the pore water during consolidation. Failure occurs
when the sediment load is applied via the mud layers and over-pressurises the underlying sediments such that the pore-pressure increases and equalises with the sediment load (Sultan et al. 2004).

Failures of this type were particularly common worldwide during the last sea level low-stand where rapid sedimentation was dominant and rivers and ice streams delivered sediment to the outer shelf and upper slope (Coleman and Prior 1988). Examples of failure during peak glacial periods include the Mauritania Slide Complex in NW Africa (Krastel et al. 2012), Mississippi Delta in the Gulf of Mexico (Lee et al. 2007), Storegga Slide in Norway (Bryn et al. 2005), and the Hinlopen Slide in the Arctic Ocean (Vanneste et al. 2006). On the other hand, erosion by storm waves (Prior et al. 1989; Wright and Rathje 2003; Xu et al. 2009) and bottom water currents (Weaver et al. 2000; Mienert et al. 2003; Principaud et al. 2015) also pre-condition slopes and decrease the stability by cutting back the slope toe.

3) Earthquakes

Earthquakes are considered to be the major contributing trigger for submarine mass failure (Figure 1.8) and often cause the onset of a tsunami such as the 1929 Grand Banks earthquake (Fine et al. 2005), Seward, Alaska earthquake (Lee et al. 2003), and the 1998 Papua New Guinea earthquake (Sisano Aitape Slide; Tappin et al. 2001) (Figure 1.2, Table 1.1). Wright and Rathje (2003) describe failure from earthquakes to occur in two ways:

1. **Acceleration-induced sliding:** where ground motion causes a reduction in shear strength and an increase in excess pore pressures.

2. **Liquefaction-induced sliding:** occurs in loose, cohesionless soils and are most common during short, sharp ground movements or oscillation of the sediments. The excess pore pressures to do not have time to escape causing the sediment (mainly saturated sands or cohesionless silts) to lose strength and behave as a liquid and flow downslope.

With the potential for earthquakes to generate massive submarine landslides and subsequently significant tsunamis, it is critical to identify areas that are prone to liquefaction as well as the potential volume and movement of the mass flow that might follow (Finn 2003).
CHAPTER 2
Southeastern Australia’s Submarine Landslides

2.1 Study Area Location
Southeast Queensland (QLD) is densely populated by Australian standards and typifies the Australian population’s desire to live near the coast, with 3 million of the state’s 4.6 million people residing in urban to semi-rural communities in the region between Noosa Heads in the north, through Brisbane to the Gold Coast and Coolangatta at the New South Wales (NSW) border (The State of Queensland 2013). Most of these people live within 20 km of the coast and it is well-recognised that this region’s numerous towns and cities are regularly exposed to significant risk from flooding and high-winds associated with tropical cyclones (e.g., Cyclones Steve (2000), Ingrid (2005), Monica and Larry (2006), Yasi (2011), and Oswald (2013); see BOM 2014); but it has only recently become apparent that the coastal communities of southeast QLD are also exposed to the hazard of tsunamis generated by submarine landslides shed from the continental slope (Boyd et al. 2010; Hubble et al. 2012; Clarke et al. 2014). Brisbane (including the Port of Brisbane, Brisbane River, and Brisbane Airport), the Sunshine Coast (including Noosa Heads, a popular coastal destination for tourists), Fraser Island, and many National Parks of significant national importance are all exposed to this newly identified hazard. It is self-evident that understanding the potential of these landslides to generate tsunamis is of major importance for the residents of southeast QLD (Clarke et al. 2014; Xing et al. 2014).

The area of the eastern Australian continental slope examined for this study is located offshore southern QLD (see Figure 2.1) and the work will focus on the upper and middle sections of the slope. A recent study on RV Southern Surveyor (SS) in 2008 (SS2008-V12) surveyed the adjacent area between Yamba in NSW to Noosa Heads on the Sunshine Coast in QLD (Figure 2.1a). Further high-resolution bathymetric mapping on RV Southern Surveyor in 2013 (SS2013-V01) extended the regional coverage data to Sandy Cape and provided the data that this thesis describes for the northern Fraser Island area (Hubble et al. 2012; see Figure 2.1b).
Figure 2.1. Location map of the study area along the east Australian continental margin showing the areas surveyed from, a) a previous RV Southern Surveyor voyage, SS2008/V12, and b) the survey area of the SS2013-V01 voyage in January 2013 (Adapted from Hubble et al. 2012).
2.2 Aims and Objectives

This thesis aims to investigate the origin of two medium sized submarine landslides present on the eastern Australian continental slope offshore Fraser Island. This project will build on from the results of the SS2013-V01 (Hubble 2013; Hubble et al. in press), SS2008-V12 (Boyd et al. 2010; Clarke et al. 2012; 2014; Hubble et al. 2012), and SS2006-V10 voyages (Glenn et al. 2008) by providing further information on the age, size, and extent of the landslides present in eastern Australia, which will help to constrain the frequency of submarine landslide occurrence on this section of the margin.

Very few studies involving morphological analysis, sediment testing, and geotechnical modelling have been completed on tsunamigenic submarine landslides in the Australian context. Submarine slope failures on the eastern Australian margin were first identified by Jenkins and Keene (1992) in seismic reflection profiles and GLORIA data. More recently, high-resolution, multi-beam bathymetric surveys have shown the occurrence and distribution of submarine landslides and other erosional features on the continental slope (Glenn et al. 2008; Boyd et al. 2010; Hubble et al. in press). Despite these research efforts, many questions are still left unanswered. Preliminary bulk dates derived from biostratigraphic data from the SS2008-V12 voyage offshore the Bryon Bay area in northern NSW suggest that some landslide features evident on the upper continental slope of northern NSW are geologically young (<20 ka; Boyd et al. 2010; Clarke et al. 2012; Clarke 2014). However, dates are only available for four slides which is too small a data set to inform an assessment of the timing and frequency of sliding in the area and to help identify potential triggering mechanisms that initiate slope failure.

In order to gain a better understanding of submarine landslides and to help predict the timing and frequency of these slides, two major aims relevant to this study were made for the SS2013-V01 voyage:

1. Survey and map the bathymetry of the continental slope between the Noosa Canyons and northern Fraser Island to identify submarine landslides and mass wasting features present on the slope.
2. Collect and analyse sediment cores from the upper and middle slope slide scars identified by the bathymetric survey of the area.

This thesis will focus on the bathymetry and the composition, age, and physical characteristics of the sediments collected within and adjacent to the slides. In addition, this study will investigate the stability of these slopes using geotechnical-modelling techniques. If successful, the findings from this study will help to determine if submarine landsliding is as common as elsewhere along the eastern Australian continental margin. The work will focus on two specific box-shaped submarine landslides identified and sampled on the continental slope between Wide Bay and Waddy Point during the SS2013-V01 cruise. Four cores were recovered from these features. A within slide core and an adjacent slope core was taken at each site. The specific sedimentologic and geotechnical objectives for these cores are (Figure 2.2):

1. To determine the physical and geotechnical properties of sediment taken from the four gravity cores collected.
2. To compare the morphology, sediment, and geotechnical properties of the box slide on the upper slope with the box slide on the middle slope of the continental margin and their adjacent slopes.
3. To determine a reliable average sedimentation rate for this section of the margin.
4. To obtain a detailed \(^{14}\)C and/or biostratigraphic age record of the gravity cores in order to investigate the age of the box slides and to determine whether or not their occurrence can be related to a specific geologic event such as a change in sea level or major global environmental event.
5. To compare the morphology, sediment, and geotechnical properties of the slope around Fraser Island with existing studies such as Clarke et al. (2012) and Hubble et al. (2012) further south, to be able to better determine the timing and frequency of the slides and the potential triggers that initiate slope failure along the entire south eastern Australian continental margin (EACM).
6. To investigate the potential for future landslides in the context of their ability to generate a tsunami.
2.3 Geological Context

2.3.1 Slope Formation

Cretaceous rifting and thinning of east Australia’s continental crust began around 90 Ma (Keene et al. 2008; Boyd et al. 2010), followed by seafloor spreading of the Tasman Sea around 83 Ma (Gaina et al. 2003). The final formation of this portion of the EACM in the study area occurred between about 74 Ma and 52 Ma (c.f. Hayes and Ringis 1973; Shaw 1974; Weisel and Hayes 1977; Gaina et al. 1998), and resulted in a steep continental slope.

The EACM comprises the submarine terrain extending from the coastline across the shelf and down the continental slope to the abyssal plain. Offshore, the continental basement is probably
comprised of rocks of the Maryborough and Capricorn sedimentary basins (Figure 2.3a). The Maryborough is situated both off and onshore, while the Capricorn basin is entirely offshore (Hill 1994), and lies almost wholly beneath the continental shelf and slope (Branson 1978). The steep and rugged slopes on the northern Tasman Basin have been sites for large mass movements including rotational slumping, submarine landsliding, debris flows, and turbidites (Hill 1992; 1994). The adjacent abyssal oceanic seafloor of the Tasman Basin is bounded by the continent of Australia to the west and the Lord Howe Rise-New Zealand continental block to the east (Weissel and Hayes 1977), and was formed during the Late Cretaceous and Early Tertiary due to seafloor spreading that separated the NSW/southern QLD coasts from the Lord Howe Rise (Hayes and Ringis 1973; Branson 1978).

The age, direction, and rate of seafloor spreading have been determined by magnetic anomalies occurring 84 Ma in the NE-SW direction (Hayes and Ringis 1973; Weissel and Hayes 1977; Gaina et al. 1998). Initially spreading occurred slowly at a rate of 3.1 mm yr\(^{-1}\) increasing to a constant rate of around 20 mm yr\(^{-1}\) from 79-53.3 Ma (Gaina et al. 1998). Magnetic anomalies date the age of the oceanic crust adjacent to the continental crust offshore Fraser Island at 60 Ma making this the maximum age for marine sediments in this area. Shortly after (53.3 Ma) seafloor spreading ceased in the Tasman Basin and accelerated in the Southern Ocean when the more rapid migration of Australia north towards Asia began (Falvey and Mutter 1981; Gaina et al. 1998).

The geomorphology of this margin is directly attributed to the rifting of Australia and Antarctica, and the opening of the Tasman Sea during the late Cretaceous and early Tertiary (Exon 2004; Harris et al. 2005). It has been suggested by Hubble et al. (2012) that the stability of the continental slope sediment wedge has decreased due to two geological events: 1) the reorganisation of deep oceanic currents from the growth of the Antarctic Ice Sheet in the mid-Miocene at about 15 Ma (Potter and Szatmari 2009), and 2) the tilting and structural deformation within Australia resulting from its ongoing collision into Asia which commenced in the late Miocene (Sandiford 2007). It is suspected that during the early Cenozoic there was an
Figure 2.3. a) Morphology of the Maryborough, Capricorn and northern Tasman Basin region with a contour interval of 200 m showing the location of the interpreted seismic section presented in, b) seismic profile of the lower continental slope and adjacent abyssal plain southeast of Fraser Island showing the large olistostromic block (slump mass) (from Hill 1992).
increase in the frequency and intensity of earthquakes in Australia where plate movements opened the Drake Passage 33.5 Ma between South America and Antarctica, and the Tasmanian Gateway 41 Ma between Australia and Antarctica, changing the deep-water global circulation (Exon et al. 2004; Potter and Szatmari 2009). Once both passages were open, the Antarctic Circumpolar Current (ACC) was created, isolating Antarctica with a clockwise flow from west to east that amplified the cooling of the Earth (Figure 2.4). During the Miocene epoch, a dramatic period of global change saw the east Antarctic ice sheet expand into west Antarctica creating a permanent icesheet over the entire continent (Exon et al. 2004). As a result, initial widespread deep-sea erosion and changes in patterns of deep-sea sedimentation occurred due to thermohaline circulation of the colder, denser deep waters that caused erosion of bottom sediments (Lyle et al. 2008). This process is thought to be significant in the study area as it is strongly suspected that these bottom currents were strong enough to erode sediments at the toe of the lower slope, subsequently reducing the stability of the upper and middle slope sediment deposits (c.f. Hubble et al. 2012).

At the same time the ACC intensified during the Late Cenozoic, Australia's drift northwards resulted in tilting of the entire continent as it interacted with Southeast Asia and sank nearly 200 m into Indonesia (Sandiford 2007). This has caused high levels of intraplate stress (Sandiford and Egholm 2008) and a suspected increase in the frequency and intensity of earthquakes (Leonard 2008), some of which are probably large enough (magnitude >6.5) to generate slope failure on the EACM.

### 2.3.2 The Shelf

Marshall et al. (1998) has identified three large carbonate platforms situated offshore Fraser Island along with numerous banks and hard grounds on the mid-shelf (Figure 2.5). Two are dated in the lower to upper/middle Miocene and the other is considered to be Quaternary in age. The three sedimentary units are thought to be successive intervals of outbuilding shifting seaward during periods of high sea level but are restricted by the east Australian current (EAC) winnowing outer shelf sediments (Marshall et al. 1998). The strength of these currents and
consequent winnowing of sediments are thought to be more pronounced during low sea level; given that Harris et al. (1996b) has reported present day currents on the outer shelf to occur at speeds of up to 130 cms$^{-1}$ in up to 80 m of water, the equivalent low stand currents are thought to be even more powerful. The carbonate platforms are lithified, form the shelf and create a very steep upper slope. Marshall’s upper slope sediment layer (unit 3) presents a very thin layer and shows evidence of erosion and slumping (Figure 2.5; Marshall et al. 1998).

During the Quaternary (<2 Ma), fluctuating climate, oceanography, and sea level are reflected in the sediments and geomorphic features (Keene et al. 2008). The last glacial maximum occurred ~20 ka and this time equates to when the ice sheets were at their maximum extension (Yokoyama et al. 2000; Clark et al. 2009). Sea levels were significantly lower than the present day (around -120 m) exposing most of the continental shelf, which some suspect to correlate with landslide failure (Lee 2009). Shelf carbonate production during the interglacial time offshore Noosa in southern QLD was higher than present day possibly due to an increase in

**Figure 2.4.** Major currents of the world showing current day ACC circulation isolating Antarctica from any warm currents (red) that transport heat southwards. Cold currents are shown in blue. Green circles show the location of the Drake Passage and Tasmanian Gateway (Modified from Pidwirny and Jones 1999-2014).
bottom currents during this time (Troedson and Davies 2001). At the glacial low stand, carbonate formation was suppressed as a result of further shelf exposure and minimal fluvial input. An abrupt rise in sea level occurred around 14.5 ka, marking the onset of de-glaciation (Clark et al. 2009) and sea levels from -120 m to around -56 m saw shelf flooding and a large increase in sediment accumulation offshore Noosa (Troedson and Davies 2001).

Figure 2.5. Seismic profile showing the sedimentary units and carbonate platforms on the outer shelf and upper slope offshore Fraser Island (from Marshall et al. 1998).

2.4 Continental Margin Geomorphology

Compared to the majority of the Earth’s passive continental rift margins, the EACM is steep, narrow, and sediment deficient (Jenkins and Keene 1992; Harris et al. 2005; Boyd et al. 2010). The continental slope is on average 50 km wide, where the shelf edge forms at a water depth of approximately 150 m and the abyssal plain around 4500 m (Boyd et al. 2010; Hubble et al. 2012). The continental shelf is narrow compared with the rest of Australia, and varies in width from 75 km wide between Moreton Island and Fraser Island in southern QLD to only 17 km
wide off Montague Island in southern NSW (Keene et al. 2008). Shelf width averages 25 km along the entire EACM (Harris et al. 2005) and average slopes range between 3°-9°.

Fraser Island is the largest sand island in the world and is 124 km long and 16 km wide (Marshall et al. 1998; Boyd et al. 2008). It is comprised of a series of parabolic dunes that are thought to have been episodically deposited during periods of lower sea levels, which were commonly about 60 m below present day level for most of the last glacial cycle and 120 m below today’s sea level 15-20 ka (Longmore and Heijnis 1999). At the northern end of Fraser Island lies Breaksea Spit, a subaqueous extension of Fraser Island that extends across the entire shelf allowing the shoreline and inner shelf to effectively lie at the shelves edge where shelf sands are driven over the shelf break by interactions between tidal flows and the narrow passageway of the EAC (Boyd et al. 2008; Keene et al. 2008; see Figure 2.6). Surface flows of the EAC are much narrower offshore Fraser Island and reach up to 200 cms⁻¹ along the shelf edge, due to this narrow shelf width (Marshall et al. 1998; Harris et al. 1996b).

The EACM’s slope displays a range of features that are associated with mass movements including slab slides, slumps, debris flows, box canyons, linear canyons, carbonate platform slides, plunge pools, and rare pockmarks (Boyd et al. 2010; Clarke et al. 2012; Hubble et al. 2012). Boyd et al. (2010) has identified around 46 box canyons averaging 32 km apart between the Bass Strait and the Great Barrier Reef as well as around 30 linear canyons located mainly in central NSW or offshore Fraser Island. In general, large plateaus (defined in this thesis as smooth areas of continuous continental slope devoid of canyons and other features that extends down towards the abyssal plain), and areas of canyon-incised slope tend to alternate with each other from north to south on the EACM with plateaus being more common north of Sydney. The canyons tend to dominate regions of steeper slope on the margins but are absent or poorly developed on the less steep areas or plateaus. Examples include the Clarence, Richmond, and Tweed canyons in northern NSW south of the Nerang Plateau and the Stradbroke, Centaur, Moreton, Bribie, Barwon, and Noosa canyons in southern QLD north of the Nerang Plateau (Figure 2.7). It is interesting to note that the average spacing between these
canyons is greater than the global average of 21.5 km (Harris and Whiteway 2011), suspected to be largely influenced by the strength of the material comprising the margin with bedrock commonly exposed below 3000 m water depth.

Figure 2.6. Model for the transport of coastal sand offshore Fraser Island down the continental slope via submarine canyons to the Tasman Abyssal Plain (from Boyd et al. 2008).

Harris and Whiteway (2011) assessed the global occurrence of submarine canyons from a dataset of 5849. Australia was shown to have the largest percentage (80%) of ‘blind’ canyons, meaning that the canyons were confined to the slope as opposed to incising the shelf. Submarine canyons that cut the shelf are often connected to rivers and act as a transport path for terrigenous sediment (Heap et al. 2008). These canyons are thought to be dominated by top-down erosional processes, and believed to be actively transporting present-day sediments down the continental slope. Worldwide examples of shelf-incising submarine canyons include
the Monterey (Paull et al. 2003) and Eel (Mullenbach et al. 2004) Canyons in California. Canyons that incise the shelf are more common on active margins and in the western margins of North and South America. In contrast, many of the EACM’s blind canyons are thought to erode the slope by bottom-up mass wasting (Boyd et al. 2010; Hubble et al. 2012). This retrogressive bottom-up behaviour produces features that stretch from the abyssal plain up to the middle and upper slopes as a result of deep water bottom currents that have suspected to have eroded the toe of the lower slope (c.f. Harris et al. 2005; Hubble et al. 2012). Present day deep water circulation are reported to reach peak velocities of 40 cms$^{-1}$ at a water depth of 3500 m near Coffs Harbour in northern NSW (Mata et al. 1998) and are suspected to have been much more intense during the last glacial maximum (Hubble et al. 2012; Yu et al. 2013). Canyon evolution is also said to be a response of turbidity flows cascading down and eroding the slope during Pleistocene sea level low stands (Harris and Whiteway 2011). This top-down process might explain the larger more sinuous canyons that incise the shelf as channel sinuosity is a morphological product of channel erosion (Harris and Whiteway 2011). Turbidity flows have not been reported in NSW but sand turbidites were occasionally identified from cores in southern QLD (Troedson 1997), and more recently sand has been found to cascade down the slope adjacent to Fraser Island (Boyd et al. 2008), along with widespread turbidite deposits identified in northern QLD off the Great Barrier Reef (Webster et al. 2012; Puga-Bernabeu et al. 2014).

In addition to the box and linear canyon systems seen spread along the steep rifted margins of the EACM, many slab slides and acuate slumps are also present that range in size from small common slides (<0.5 km$^3$) to large rare slides (>20 km$^3$; Boyd et al. 2010). Glenn et al. (2008) has identified several moderately large to small slides including the Bulli Slide (20 km$^3$), Shovel Slide (7.97 km$^3$), Birubi Slide (2.31 km$^3$), and the Yacaaba Slide (0.24 km$^3$) offshore Sydney in NSW. Depicted by 2D sub-bottom profiling lines, Talukder and Volker (2014) show the Shovel Slide to be three mass wasting events (Figure 2.8). A further five landslides capable of generating tsunamis have been described by Boyd et al. (2010) and analysed by Clarke et al. (2012; 2014). They are the Byron, Cudgen, Coolangatta 1 and 2, and the Bribie Bowl Slides, and are all U-shaped in cross-section backed by an amphitheatre shaped crestal zone (Figure 2.7).
For most of the slides identified along the EACM, material derived from the scars are difficult to locate downslope suggesting that the these slides are either breaking into debris flows and being dispersed quite some distance out onto the abyssal plain, or being transported as cohesive block deposits and deposited on the abyssal plain beyond the current detectable limit of the high resolution bathymetric data. Of particular interest for this study is a known olistostromic block identified in a seismic section by Hill (1992), which is located on the abyssal plain southeast of Fraser Island (Figure 2.3). This block is enormous in size, ~30 km long and at least 500 m thick, and is thought to have travelled from the continental slope as a massive slide or slump to its resting point on the abyssal plain. The late Miocene sea level low-stand is thought to have been the trigger for this olistostrome (Hill 1992). Ironically, the scar surface from where this olistostrome took off is yet to be found, leading to speculation that the entire slope (or a large portion of it) has collapsed with further erosional events and canyon systems taking in its place (c.f. Hubble et al. in press).
2.5 Continental Margin Sedimentology

Boyd et al. (2004) divides shelf sediments on the southern NSW continental shelf into three main divisions; 1) inner shelf sand, 2) mid-shelf muddy sand, and 3) outer shelf calcareous sand. The sediments of the continental slope are not well studied (Keene et al. 2008) but Hubble et al.’s (2012) study indicates that the upper slope consists of unconsolidated sandy muds which overlies older compacted, calcareous sandy silts that have been dredged from the middle slopes. These hemipelagic muds have been deposited as a vertical accretion of successive layers with their boundary surfaces parallel to the seafloor. The sediment characteristics are suspected to influence their movement downslope with the less consolidated upper slope materials probably disaggregating into sandy mudflows and turbidity currents that create submarine fans, while the strongly consolidated middle slope materials are moving as large coherent blocks or disintegrating into debris avalanches or blocky debris flows (Clarke et al. 2012; Hubble et al. 2012). Sedimentation rates on the EACM during the late Quaternary have
been determined to vary between 0.05-0.24 mka\(^{-1}\) (Troedson and Davies 2001). The thin sediment cover is thought to result from a relatively low input of terrigenous sediments (Boyd et al. 2008; Glenn et al. 2008), attributed to the continental aridity and the lack of geologically young mountains (McGowan et al. 2008; Harris and Whiteway 2011). Another factor is the lack of shelf-incising submarine canyons that breach to shallow depths and act as sediment transport carrier’s downslope (Boyd et al. 2004). This sediment deficiency is unique compared with other passive margins of similar age; for example, the eastern continental margin off North America is more than 200 km wide and contains up to 10 km of sediment with 2 km deposited since the end of the Cretaceous (Hutchinson et al. 1982; Crutcher 1983).

Despite Clarke (2014) demonstrating the ubiquity of landslide scars on the EACM, determining their age and frequency of occurrence is difficult due to a lack of suitable dated samples. Biostratigraphic dates presented in Hubble et al. 2012 for nine middle slope sediments in and around submarine slides and slumps of the EACM provide a maximum potential age for slide initiation as mid-Miocene. Clarke et al. (2012) has identified two distinct sediment units within three landslides offshore northern NSW and southern QLD where younger material overlies older sediment (Figure 2.9). Two of these cores, the Coolangatta 1 slide (GC8) and the Cudgen Slide (GC11) separated by 13 km, returned similar bulk radiocarbon ages of 20.7 and 20.1 ka respectively, suggesting they may be simultaneous events with a common trigger. Another event was shown to take place around 15.8 ka before present (Clarke et al. 2012). On a more recent scale, radiocarbon dating of seven gravity cores within slide sediments by Glenn et al. (2008) show the most recent tsunamigenic slide failure to be \(~3.7\) ka, suggesting that landsliding in the area is a common and reoccurring event through geological time.

### 2.6 Tsunami

Submarine landslides have the potential to trigger local tsunamis with high run-ups and inundation of near-by coastlines (Synolakis et al. 2002; Lee et al. 2003; Fine et al. 2005; Ioualalen et al. 2010; Hill et al. 2014). Such impact can cause devastating consequences including loss of life and damage to infrastructure and coastal facilities (Dominey-Howes and
Figure 2.9. Photographic images of three gravity cores taken inside the Coolangatta 1 Slide (GC8), Cudgen Slide (GC11) and the Byron Slide (GC12) showing boundary features. The inferred slide plane is indicated with a dashed black line and bulk radiocarbon ages are shown in yellow (ky = 1000 years before present, RCD = radiocarbon dead). See Figure 2.7 for slide locations. (taken from Clarke et al. 2012).

Goff 2009). Several studies along the EACM have been undertaken to look at the risk of tsunamis to Australians (Glenn et al. 2008; Clarke 2014; Clarke et al. 2014; Talukder and Volker 2014; Xing et al. 2014). A survey by Glenn et al. (2008) assesses high-risk areas along the central and southern NSW continental slope from tsunamigenic submarine landslides focusing on areas adjacent to population centres and infrastructure. Five zones of potential failure along the NSW continental slope were identified based on their emergent features, sediment accumulation and slope undercutting. Work has also recently been published by Clarke et al. (2014) assessing
the tsunami hazard for five upper slope slide failures on the northern NSW continental slope which showed the slide masses shed by the slide events were capable of generating tsunami waves of up to 10 m if they remained intact and achieved downslope velocities of 20 ms\(^{-1}\). Numerical modelling for tsunami hazard along the east Australian coastline based on far-field earthquakes indicated wave amplitudes of over 1.5 m offshore NSW (Xing et al. 2014). Most of the QLD coast however is said to be less vulnerable as a result of shallow waters spanning long distances and the protection of surrounding islands.

Evidence of prehistoric tsunamis have also been documented on the eastern Australian coastline including work done by Bryant et al. (1992) and Young et al. (1996) who both report marine sediment deposits well above the storm line. While these two works are highly contested and considered to be controversial, subsequent studies, for example, Dominey-Howes (2007), Courtney et al. (2012) and Goff and Chague´-Goff (2014) provide more sound geomorphic and geological evidence of tsunami inundation. Moreover, Goff and Chague´-Goff (2014) have reviewed and undertaken further research on the tsunami database for Australia that was first published by Dominey-Howes (2007). Goff and Chague´-Goff (2014) found a three-fold increase from 57 known historical tsunamis (including 2 erroneous) to 145 events, and demonstrated that at least 60 events (around 40%) have no known source, but the submarine landslide mechanism provides a plausible causal mechanism.

These studies highlight that there is a risk to Australia’s coastline from a local tsunami and a need for further research, understanding, and assessment along the continental slope for events that could pose catastrophic consequences to Australia’s populated coast.
CHAPTER 3
Geomorphology

3.1 Introduction
This chapter presents a description and interpretation of the bathymetry of the eastern Australian continental margin (EACM) offshore southeastern Queensland (QLD) between Noosa Heads and Sandy Cape, the northern tip of Fraser Island (Figure 2.1b, Chapter 2). Data was collected in water depths between 100 m and 4000 m, approximately 75 km offshore the Australian mainland east of Fraser Island onboard the RV Southern Surveyor (SS2013-V01). The features identified in the high-resolution bathymetric data for this section of the margin will also be compared to those identified on the slope to the south of the study area in previous work (c.f. Glenn et al. 2008; Boyd et al. 2010; Clarke et al. 2012; Hubble et al. 2012). It fulfills one of the primary aims of this study, as well as being a major objective for the SS2013-V01 cruise (Hubble 2013). Two box slides have been identified from this data set on the upper and middle continental slope, which are the focus of this study. An analysis of the morphometric characteristics of these two submarine landslide scars (length, width, and thickness) is presented in this section.

3.2 Methodology
Bathymetric data was acquired with a Kongsberg Simrad EM 300 multibeam echo sounder, fitted on a gondola beneath the vessels hull to obtain swath bathymetric data. The nominal sonar frequency of the 270 beams (135 each on the port and starboard sides) is 30 kHz. Swath width was controlled manually and the filter and depth settings were adjusted in response to sea state and the water depth during the survey. The adjustable settings were as follows:

Filtering:
• Spike filter range (auto, weak, medium, strong).
• Range gate (small, medium, large).

Depth Settings (used to reduce the multibeam’s time of searching for the bottom):
• Medium – 200 to 500-600 m
• Deep – 500-600 to 1000-1200 m
• Very Deep – 1000-1200 to 2000-2500 m
• Extra Deep – 2000-2500 m or greater

Performance Envelope (ping mode):
• Very shallow, shallow, medium, deep, very deep, extra deep.

For more information on the Kongsberg Simrad EM 300 on RV Southern Surveyor see Llewellyn (2005). Multibeam survey data was recorded on the RV Southern Surveyor’s onboard Seafloor Information System (SIS) (http://www.km.kongsberg.com). This data was post-processed using the Caris software package (http://www.caris.com) to produce a GIS ready XYZ data set which was merged with the existing east Australian bathymetric datasets provided from the Geosciences Australia digital elevation model (DEM) repository (http://www.ga.gov.au/scientific-topics/marine/bathymetry/50m-multibeam-dataset-of-australia-2012) to produce a DEM of the entire study area (for more information see http://www.deepreef.org/). This DEM was then analysed using Fledermaus (v7.3.3b) visualisation software (http://www.qps.nl/display/fledermaus/main).

### 3.2.1 Slide Characteristics

The length, width, headwall height, slide scar area, volume, and slope angles of the slides were all determined using Fledermaus. Landslide volume was calculated using the method described in McAdoo et al. (2000), by calculating the thickness and area, then modeling the volume of the slide as a simple wedge geometry (Figure 3.1) using equation 3.1 below:

\[
\text{Volume of slide} = \frac{1}{2}(As) \times (h \cos \alpha)
\]

(Eq.3.1)

where, thickness = \((h \cos \alpha)\), \(h\) = headscarp (headwall) height, \(\alpha\) = scar slope angle and \(As\) = area of the scar. Wedge geometry is used as the sidewalls on a landslide generally exhibit downslope erosion from the headwall down to the toe (McAdoo et al. 2000).
3.3 Geomorphic Description and Interpretation

The regional bathymetry of the southern QLD EACM is presented in Figures 3.2-3.8 and provides detailed maps of the study area. The width of the continental slope offshore Fraser Island varies between 20 and 30 km while the slope angle varies between 5° and 12°. The slope is particularly narrow and steep in comparison to continental slopes on passive margins elsewhere in the world (e.g. slope widths in the South Pacific Ocean average 34 km and slope angles average 3.8°; Harris and Whiteway 2011; Harris et al. 2014). The slope is also one of the steeper areas of the EACM (Harris et al. 2005; Heap and Harris 2008; Harris and Whiteway 2011; Harris et al. 2014). The data have enabled the identification of a range of previously undiscovered features including marginal plateaus, linear rills, ridges and gullies, canyon systems as well as slides and slumps (Figure 3.3). Descriptions of particular features of interests follow. They are the Noosa Plateau, Tin-Can Alley Canyon, Tin-Can Plateau, Wide Bay Canyon, Wide Bay Plateau, Fraser Canyon and the north Fraser Canyon slope. An agreed nomenclature has not been made in the literature to describe ‘smooth areas of continuous continental slope devoid of canyons and other features that extends down towards the abyssal plain’, so they are referred to above and throughout the remainder of this thesis (in italics) as ‘plateaus’.

3.3.1 Noosa Plateau

A relatively large marginal plateau, the “Noosa Plateau,” is located at the southern extent of the newly mapped study area and located immediately to the north of the Noosa Canyon.
Figure 3.2. The southern QLD EACM (Australia inset top left) with insets of the study area in relation to further figures. VE = Vertical exaggeration = horizontal scale/vertical scale.
Complex (Figure 3.3). Its morphology is similar to that of the larger, more gently sloping marginal Nerang Plateau located approximately 80 km to the south, hence its classification as a marginal plateau (Clarke 2014). The Noosa Plateau is approximately 20 km wide just below the shelf break at 500 m water depth, and 40 km wide at its base, which is around 2600 m above the abyssal plain. This moderately steep (~9°), but smooth sloping, surface plateau appears to have been experiencing active deconstruction in the recent geologic past with evidence for the shedding of upper slope slabs around 600 m and incision of a narrow linear canyon 2 km wide and 20 km long on the southern side of the slope (Figure 3.3, inset).

Further north, two identified but previously unknown canyon systems and ancient slides are evident in the new high-resolution bathymetry. They are the ‘Tin-Can Alley Canyon Complex,’ and the ‘Wide Bay Canyon Complex,’ as well as new features within the named but poorly imaged ‘Fraser Canyon Complex’ (c.f. Boyd et al. 2008; see Figures 3.3 and 3.4, Table 3.1). All these features present evidence for recent mass wasting events and ongoing erosion through the presence of numerous landslides, linear rills and erosional scour.

### 3.3.2 Tin-Can Alley Canyon Complex

A series of small ridges and linear gullies resembling terrestrial rills are located offshore from Double Island Point between the Noosa Plateau and the Tin-Can Alley Canyon Complex (Figures 3.4 and 3.5). They are developed from the shelf edge down to the mid-slope (1600-2000 m water depth) with a typical spacing of 1-2 km. The morphology of this area is consistent with top-down scour (c.f. Heap and Harris 2008; Harris and Whiteway 2011; Harris et al. 2014), which suggests that sand delivered to the shelf edge by the East Australian Current (EAC) is cascading downslope regularly (c.f. Boyd et al. 2008). A relatively smooth un-failed region of slope 4.5-5 km wide separates these rills from the relatively straight and narrow Tin-Can Alley Canyon Complex (Figure 3.4). Headwall scars 500-600 m in height extending 32 km along the upper and middle slope are located between the Tin-Can Alley and Wide Bay Canyons. The headwall at the northern end curves deeper down the slope following a ridgeline to 2000 m water depth and delineates the crest of the southern slope of the Wide Bay Canyon Complex. Named the Inskip Slide, this scarp unequivocally indicates a large mass failure that probably affected the entire slope either remaining intact or disintegrating into a debris flow downslope and onto the abyssal plain (Hubble et al. in
Figure 3.3. Morphology of the entire study area with a close-up of a narrow linear canyon incised through the Noosa Plateau (inset). VE = Vertical exaggeration. For depth colour bar and exact location see Figure 3.2.
Figure 3.4. Continental margin morphology offshore Double Island Point showing newly discovered canyon systems, slumps and marginal features. VE = Vertical exaggeration. For depth colour bar and exact location see Figure 3.2.
press). It is possible that this scarp is related to an olistostromic block identified by Hill (1992) (or one like it), as its downslope length is 30 km and its similar position on the seafloor are approximately in alignment (Figure 2.3, Chapter 2).

3.3.3 Wide Bay Canyon Complex
The Wide Bay Canyon Complex is fed by three major tributaries and debouches to the abyssal plain through an easterly-directed movement. Two larger tributaries coalesce to form the main channel and a small side tributary attached that joins at 2300 m water depth (Figures 3.4 and 3.6, Table 3.1). It is impressive in its size with an amphitheater shaped head incised into the shelf edge at 350 m, and a sinuous deep channel stretching around 30 km long. A flat canyon floor is developed in the base of the canyon; its incised meanders connect from the canyon head for ~20 km of the length of this feature before opening up to form a 4 km wide mouth where the canyon connects to the abyssal plain marking a clear transportation network from the shelf to deeper waters. A large mass slump, named the Wide Bay Canyon Slide (similar to the Inskip Slide on the southern flank) has developed on the northern canyon flank (Hubble et al. in press; see Figures 3.4 and 3.6c). Its headwall scarp height is 150-200 m and extends downslope from 900 m to 2500 m water depth marking out the northern boundary of the Wide Bay Canyon. This canyon wall presents an irregular “lumpy” surface with several indistinct linear grooves developed in the lower portion of the wall (Figures 3.4 and 3.6d). Two other riled areas are evident at the heads of the Tin Can Alley Canyon and the Wide-Bay Canyon, which supports a top-down erosion origin for the rills in Figures 3.5b and c.

3.3.4 Wide Bay Plateau
A second large plateau, the Wide Bay Plateau, separates the Wide Bay Canyon Complex from the Fraser Canyon Complex (Figures 3.3 and 3.7). It is approximately 15 km wide near the shelf (800 m water depth) and 30 km wide at its base (2500 m water depth) with average slopes ~5°. Erosional features, steep gullies, and lineation’s are seen at the toe of the plateau and are thought to be a result of bottom currents undercutting the steeper slope ~10° (Figure 3.7). A moderately large translational, box-shaped slab slide is located in the middle of the Wide Bay Plateau at a water depth of ~1500 m and a slope of ~5° (Figure 3.7c-e and feature 1 in Figure 3.8a). This feature is 11 km² in area and 100-150 m thick
Figure 3.5. Morphology showing the series of linear rills present along the entire study area as a result of top-down incision. Insets show rilled features, a) on the slopes south of the Tin-Alley Canyon Complex, b) the heads of the Tin-Can Alley Complex, c) the heads of the Wide Bay Canyon Complex, d) the upper slope of the Fraser Canyon Complex and e) north of the Fraser Canyon Complex on the continental slope. VE = Vertical exaggeration. For depth colour bar and exact location see Figure 3.2.
Table 3.1. Morphologic Characteristics of the Canyon Complexes (Terminology modified from Puga-Bernabeu et al. 2013).

<table>
<thead>
<tr>
<th></th>
<th>Tin-Can Alley Canyon Complex</th>
<th>Wide Bay Canyon Complex</th>
<th>Fraser Canyon Complex</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Canyon Head</strong></td>
<td>Linear and triangular starting along the shelf edge (300 m).</td>
<td>Amphitheatre shaped and dendritic starting along the shelf edge (300 m).</td>
<td>Multiple; triangular shaped starting at the shelf edge boundary. Many landslides at head transitioning into canyon systems.</td>
</tr>
<tr>
<td><strong>Channel</strong></td>
<td>Straight</td>
<td>Sinuous</td>
<td>Transition from straight to sinuous downslope.</td>
</tr>
<tr>
<td><strong>Cross-Sectional Profile</strong></td>
<td>Transition from V-shape to U-shape downslope.</td>
<td>V-shaped at canyon head. Middle, lower slopes and minor tributary on the north flank U-shaped. Wide canyon floors on main tributary.</td>
<td>Transition from V-shape to U-shape downslope.</td>
</tr>
<tr>
<td><strong>Width</strong></td>
<td>Relatively uniform.</td>
<td>Relatively uniform.</td>
<td>Relatively uniform with slight decrease downslope.</td>
</tr>
<tr>
<td><strong>Canyon Wall Gradient</strong></td>
<td>Steep gradient ~17° in the upper part of the canyon, decreasing to 10° on the middle and lower slopes.</td>
<td>Relatively consistent throughout (10-15°), with the lower northern flank ~8°.</td>
<td>Highest at shelf edge ~15°, slowly decreasing downslope.</td>
</tr>
<tr>
<td><strong>Incision</strong>*</td>
<td>Maximum in the upper part of the slope canyon decreasing downslope.</td>
<td>Maximum on the southern flank of the middle slope section (1500 m), decreasing downslope.</td>
<td>Maximum locally down the entire slope.</td>
</tr>
<tr>
<td><strong>Other Features</strong></td>
<td>Wall gullies generally absent from middle slopes.</td>
<td>Large landslide on northern flank resulting in wall gully partially absent.</td>
<td>Canyon head largely affected by a series of box-shaped landslides.</td>
</tr>
</tbody>
</table>

* Canyon incision is the depth difference between the canyon axis and adjacent interfluvies.
Table 3.2a). This slide named the ‘Middle Fraser Island Middle Slope Slide’ (hereafter Middle Slope Slide) was selected as a coring target and two gravity cores were taken from this feature, one within and one adjacent (Hubble 2013). The gravity core inside the slide was taken with the intention that it would penetrate to the base of the slide, enabling the age of failure to be ascertained (see Chapter 4). Besides the box slide and the erosional toe, there are several other slide features evident but these are subdued and indistinct possibly due to burial or post-event abrasion.

![Figure 3.6. The Wide Bay Canyon Complex showing a) plan view, b) delineation of canyon outline (dotted lines) with major (bold) and minor tributaries, c) south-west and d) northwest facing views. VE = Vertical exaggeration. For depth colour bar see Figure 3.2.](image)

3.3.5 Fraser Canyon Complex

The Fraser Canyon Complex is located in the north of the study area and is approximately 70 km long (Figures 3.3 and 3.8a). Compared to the rest of the canyon systems located to the

3-11
south of the study area, the Fraser Canyon Complex is much steeper with a slope ~12°. A narrow, sinuous canyon displaying one tributary is present at the southern end of the Fraser Canyon Complex and is incised between the northern side of the Wide Bay Plateau and a small, slightly abraded plateau (un-failed slope) 5 km wide that was probably an extension of the Wide Bay Plateau’s upper slope. Extensive riled, tapered trapezoidal, wedge-shaped features that are similar in general appearance to box slides have shed from the upper slope of the Fraser Canyon Complex to 1500 m water depth spanning across the entire canyon system (features 2-11 in Figure 3.8a). These slide remnants have produced no obvious rubble bodies or debris deposits, and they probably disintegrated and spilled onto the abyssal plain fans. The canyon headwalls are very steep around 30° at the shelf edge, slowly decreasing downslope to around 12° extending all the way to the lower slopes. Below these slides, canyons and rills have developed scouring the mid to lower slopes, taking the form of spurs and valleys (Figure 3.5d). A major canyon mouth 1-1.5 km wide is situated at the southern end of the Fraser Canyon Complex. It connects to feature 2 in Figure 3.8a and broadens to a V-shaped riled feature that provides sediment to the abyssal plain for slide features 2-7 (Figure 3.8a). Adjacent to the north, a second narrow sinuous canyon network is present starting at the shelf edge on the upper slope down to the abyssal plain with a mouth around 700 m wide and sidewalls around 500 m in height. Two flat but abraded plateau-like regions offshore from Waddy Point (both around 2 km wide between slide features 9 and 10, and slide features 10 and 11 in Figure 3.8a) are present and terminate on the middle and lower slopes respectively. They are interpreted to be un-failed slope segments.

Two cores were taken from the most northern slide to establish the nature and age of the materials (see Chapter 4; feature 11 in Figure 3.8a-d). Named the ‘North Fraser Island Upper Slope Slide’ (hereafter Upper Slope Slide), this slide is situated at a water depth of ~900 m and its smooth, sharply defined morphology and the absence of rills suggests that the slab has been removed relatively recently and possibly as a single, intact mass. The whole slide is estimated to be 25 km² in area and 200-300 m thick (Table 3.2b). Downslope of the Upper Slope Slide, a straight canyon with an incised v-shaped section, connects the middle slope area to the abyssal plain. Its mouth is 2 km wide where it debouches to the abyssal plain.
The upslope terminations of all of the slides within the Fraser Canyon Complex are situated beneath and/or outboard from the buried shelf-edge Miocene reef complex identified by Marshall et al. 1998 (see Figure 3.3). Portions of the reef complex material may have acted as a slide-head surcharge load (i.e. a driving block) or the reef-edge may have been exposed when the slope slides removed the toe support. Similar material to the described Miocene reef has been identified both north of Fraser Island and south near Tweed Heads, and this shelf-edge feature probably extends as far south as Yamba in NSW (Marshall et al. 1998; Boyd et al. 2010; DiCaprio et al. 2010; Hubble 2013; Pers. Comm., T. Hubble, 3 December 2014). This reef is a substantially well-developed feature comprised of well-lithified, highly
consolidated sediments that help create the steep crestal scarp evident on the upper slope in this area (Marshall et al. 1998).

Like the linear rill morphology that has been identified south of the Tin-Can Alley Complex, the presence of rills on the upper slope of the Fraser Canyon Complex suggests top-down scour (c.f. Heap and Harris 2008; Harris et al. 2011; 2014). It is probable that terrestrially derived and shelf-derived sands that spill over the shelf break are responsible for the scour driven south by the EAC. It is strongly suspected that sand waves migrate over the shelf edge where this material cascades downslope onto the abyssal plain, and is described to occur immediately north of the Fraser Canyon Complex (Boyd et al. 2004; 2008; 2010). Sand from Breaksea Spit is incising the slope, creating channels, and a series of linear rills and small canyons that are slowly incising, abrading and modifying the slopes appearance (see Figure 2.6, Chapter 2 and Figure 3.5e).

3.3.6 Un-Failed Slopes

It is also important to note that there are various areas along the study area section of the EACM where portions of the upper slope remain intact, for example, those described in sections 3.3.2 and 3.3.5 (Figures 3.4 and 3.8a). Offshore from Waddy Point inside the Fraser Canyon Complex, there is an area that appears to have remained attached to the Miocene reef. These short sections of the slope show little sign of erosional incision (Figure 3.8a). Other potential failure sites have been identified by Clarke et al. (2014) and Clarke (2014), including an un-failed area adjacent to the Bryon Slide, and a large intact block offshore Moreton Island with obvious tension cracks along the head (see Figure 2.7d, Chapter 2). Given the abundance of these neighbouring mass wasting features, it is obvious that there is a significant potential for further future failure events.
Figure 3.8. a) The Wide Bay Plateau and Fraser Canyon Complex showing the location of the Middle Slope Slide (feature 1) and the Fraser Canyon Complex presenting numerous wedge-shaped features (features 2-11). Feature 11 represents the Upper Slope Slide with core locations shown in b) plan view, c) 3D front, and d) 3D side facing views at the northern end of the Fraser Canyon Complex. VE = Vertical exaggeration. For depth colour bar and exact location see Figure 3.2.
Table 3.2. Summary of slide dimensions for a) the Middle Fraser Island Middle Slope Slide, and b) North Fraser Island Upper Slope Slide.

### a) Middle Fraser Island Middle Slope Slide

<table>
<thead>
<tr>
<th>Latitude</th>
<th>Longitude</th>
<th>Water Depth(^1) (m)</th>
<th>Slope Angle (°)</th>
<th>Adjacent Slope Angle(^2) (°)</th>
<th>Headwall Height (m)</th>
<th>Headwall Slope (°)</th>
<th>North Sidewall Height (m)</th>
<th>South Sidewall Height (m)</th>
<th>Length (m)</th>
<th>Width (m)</th>
<th>Approx. Area (km(^2))</th>
<th>Approx. Volume (km(^3))</th>
</tr>
</thead>
<tbody>
<tr>
<td>25.35°S</td>
<td>153.97°E</td>
<td>1530</td>
<td>5.4</td>
<td>5.2</td>
<td>148.4</td>
<td>20.1</td>
<td>97.4</td>
<td>108.7</td>
<td>3910</td>
<td>2900</td>
<td>11.3</td>
<td>0.8</td>
</tr>
</tbody>
</table>

### b) North Fraser Island Upper Slope Slide

<table>
<thead>
<tr>
<th>Latitude</th>
<th>Longitude</th>
<th>Water Depth(^1) (m)</th>
<th>Slope Angle (°)</th>
<th>Adjacent Slope Angle(^2) (°)</th>
<th>Headwall Height (m)</th>
<th>Headwall Slope (°)</th>
<th>North Sidewall Height (m)</th>
<th>South Sidewall Height (m)</th>
<th>Length (m)</th>
<th>Width (m)</th>
<th>Approx. Area (km(^2))</th>
<th>Approx. Volume (km(^3))</th>
</tr>
</thead>
<tbody>
<tr>
<td>24.76°S</td>
<td>153.59°E</td>
<td>880</td>
<td>8.8</td>
<td>7.6</td>
<td>285.5</td>
<td>34.1</td>
<td>184.4</td>
<td>235.1</td>
<td>5147</td>
<td>4884</td>
<td>25.1</td>
<td>3.5</td>
</tr>
</tbody>
</table>

\(^1\) Water depth measured in the centre of each landslide scar.

\(^2\) Average of three slopes on the north side of the slide where GC2 was cored. The south side is much steeper averaging ~15.6°.
3.4 Synthesis of Geomorphology

The EACM displays a diverse array of geomorphic features including landslides, deep submarine canyon systems, marginal plateau’s, ridges, gullies, and linear rills that have all been formed by the process of a long and varied geomorphic history (Glenn et al. 2008; Heap and Harris 2008; Boyd et al. 2010; Clarke et al. 2012; Hubble et al. 2012; see section 2.3, Chapter 2). Submarine landslides are a common process along the entire EACM with previous work demonstrating similar slides to be common in northern NSW, and riled slopes the dominant feature in southern QLD (see Figure 2.7, Chapter 2; Figures 3.3 and 3.5). Compared to the rest of the Australian continental margin, east Australia (in particularly offshore Fraser Island) has a very narrow continental shelf and steep slope with a large abyssal plain and deep ocean floor (Heap and Harris 2008; Harris et al. 2011; 2014). The margin appears to be undergoing active erosion with the southern QLD margin experiencing both top-down and bottom-up processes that are responsible for shaping the continental margin, particularly the large, extensively riled submarine canyons. These two processes and the Middle and Upper Slope Slides are discussed below.

3.4.1 Top-Down (Progressive) Processes

Top-down processes are thought to be caused by either or both turbidity and hyperpycnal density flows that are produced along the shelf and progress downslope. These phenomena generate axial incisions in canyons along the continental margins (c.f. Pratson and Coakley 1996; Baztan et al. 2005; Lo lacono et al. 2014a). In the case of the southern QLD continental margin, hyperpycnal density flows are currently not considered to occur as these flows are usually generated by adjacent river systems where the interactions between sediment-laden water and oceanic water leads to erosion of the seafloor (Mulder and Alexander 2001; Mulder et al. 2003; Canals et al. 2006; SEPM STRATA 2015). Unlike the canyons in northern NSW that are situated in front of major rivers such as the Richmond, Clarence, Tweed, and Brisbane Rivers, the majority of the canyons in the study area do not appear to be connected to any major river system offshore except for the Mary and Burnett Rivers, although these two rivers
probably do connect to the Tin-Can Alley and Wide Bay Canyon systems during low-stands of sea level. Currently, they deliver their terrestrial material to the areas inshore of Fraser Island.

Turbidity flows are defined as a gravity driven flow of suspended sediment (mainly sands and coarse material) from the shelf down into deeper waters (Piper and Normark 2009; Meiburg and Kneller 2010; Talling et al. 2014). These flows are well known to incise and erode continental margins, and their effects are apparently evident in this study by the large number of linear rills present along the entire study area (Figure 3.5; N.B. this work describes a turbidite for this area in section 4.3.1, Chapter 4). The rills are not only seen along the upper slopes of the continental margin but also within the canyon head walls that have incised into the shelf and down through the canyon system. This suggests that the rills present just south of the Tin Can Alley Complex are young and possibly representative of a new canyon system that is yet to form (c.f. Pratson and Coakley 1996; see Figure 3.5a).

The source of the sediment responsible in the generation of the turbidity flows along the continental margin offshore Fraser Island is the large sand island itself and the shelf sands. Fraser Island acts as a sediment trap at the northern end along Breaksea Spit where interactions between tidal flows, longshore drift, and the EAC transport these shelf sands down the continental slope to the immediate north of the study area (Boyd et al. 2008; see Figure 2.6, Chapter 2). This sand is thought to be a major contributor to slope erosion in this area, evident by the presence of numerous top-down features such as linear rills, ridges, and gullies that have scoured and abraded the slope (Figure 3.5). Within the rilled area north of the Fraser Canyon Complex described by Boyd et al. (2008), the slope is undergoing constant change whereby sands from Breaksea Spit probably spill down and abrade the slope (Figure 3.5e). This suggests that top-down processes may be currently more dominant than the retrogressive bottom-up erosional processes in the area to the north of the Wide Bay Canyon.

Top-down processes are more common in moderate to high sediment supply margins near coastal and fluvial inputs, and more frequent during active glacial phases such as low sea level
stands (Canals et al. 2006; Harris and Whiteway 2011; Lo Iacono et al. 2014a). The EACM is apparently generally disconnected from sediment supplied to the inner shelf (Boyd et al. 2010; Harris and Whiteway 2011). However, the unique sand supply derived from Fraser Island apparently provides sand that spills down the slope and abrades it.

### 3.4.2 Bottom-Up (Retrogressive) Processes

Bottom-up processes result from mass-movements that take place on the lower slopes and retrogress upwards towards the shelf, widening canyons and eroding the slopes (c.f. Canals et al. 2000; Lo Iacono et al. 2011; Micallef et al. 2012; Lo Iacono et al. 2014a). This process is more common on margins that are sediment deficient with high gradient slopes comprised of bedrock and subjected to high seismicity (Micallef et al. 2012; Lo Iacono et al. 2014a). Bottom-up processes are evident along the entire EACM (Glenn et al. 2008; Boyd et al. 2010; Clarke et al. 2012; Hubble et al. 2012; Harris et al. 2014). In this study, they are evident on the lower slopes of the southern QLD margin apart from the slope immediately north of the Fraser Canyon Complex, and are more obvious on the slopes surrounding the Wide Bay Canyon and at the toe of the Wide Bay Plateau (Figures 3.3 and 3.7b). The presence of two large mass slumps, the Inskip and Wide Bay Canyon Slides, evident on the slopes south of the Wide Bay Canyon Complex and on its northern flank (Figure 3.4) is consistent with the model proposed by Hubble et al. (2012). This model posits that bottom currents have eroded the toe of the lower slopes, causing a loss of support destabilising the lower and middle slopes (c.f. Mata et al. 1998; Micallef et al. 2014). However, this model also suggests that an event such as a large earthquake would also be needed to trigger or cause slope failure.

### 3.4.3 The Middle and Upper Slope Slides: Local and Global Comparisons

Compared to the continental margin in northern NSW, submarine landslides on the southern QLD margin are not as numerous with around ten translational, box slides confined to the upper slopes of the Fraser Canyon Complex and a single box slide present on the middle slope of the Wide Bay Plateau (Figure 3.8). Two large mass failures, the Inskip and Wide Bay Canyon Slides (~10-20 km wide) encompassing the entire middle to lower slopes next to the Wide Bay Plateau.
Canyon are also evident (Figure 3.4). To the south of this study area, not only are the slides more numerous, but the failure type and slope angle also changes. Numerous rotational, U-shaped landslides are evident and dispersed along the upper and middle slopes from Noosa Heads in QLD and tabular translational slides on the Yamba Plateau in NSW (Boyd et al. 2010; Clarke et al. 2012; Hubble et al. 2012; see Figure 1.6, Chapter 1). These slides are similar to that described by Varnes (1978), and include the Byron Slide on the upper slope offshore Byron Bay (Clarke et al. 2012) and a series of arcuate slides on the mid-slopes just south of the Noosa Canyon (Hubble et al. 2012). The North Fraser Island Upper Slope Slide and the Middle Fraser Island Middle Slope Slide occur on steep slopes averaging 9° and 5° respectively (Table 2.2). This can be compared with the Byron and Cudgen Slides studied in NSW that occur on slopes averaging just 3° on the Nerang Plateau and the upper slopes of the northern NSW continental margin respectively (Clarke et al. 2012; Clarke 2014).

Translational landslides are thought to result from sliding on a planar surface such as a bedding surface (Hampton et al. 1996; Lee et al. 2007). This suggests that the surface sediment on the continental slope offshore Fraser Island may present weak inhomogeneous bedding planes that have caused the Upper and Middle Slope Slides to fail as blocks or slabs. Further analysis into the sedimentology and structure of the sediment both within and adjacent to both landslides will be investigated in the following chapters (Chapters 4 and 5). Examples of translational, box-shaped submarine landslides globally, include the Currituck Slide along the US continental margin (Locat et al. 2009), and a few translational slides present along the Lofoten-Vesteralen continental margin in northern Norway (Rise et al. 2013), and the south Balearic continental margin in the western Mediterranean which has many similarities to that of the southern QLD continental margin including no major adjacent rivers, sediment starved margin, slope ~5°, and their landslide failures associated with canyon heads and flanks (Lo Iacono et al. 2014b).
3.5 Conclusions

High-resolution multi-beam bathymetry was collected and analysed along the EACM offshore Fraser Island in southern QLD, onboard the RV Southern Surveyor (SS2013-V01). Data were used to identify mass wasting features in this area to develop an understanding of the extent of these features and the processes involved in their formation. The key findings include:

1) The southern QLD continental margin is an area of relatively steep slopes (~5-12°), extensive canyon systems and linear rills, while shallower slopes (~3°) and submarine landsliding are more prominent south of the margin in northern NSW.

2) Two translational, box-shaped, submarine landslides were identified as the ‘Middle Fraser Island Middle Slope Slide’ (Middle Slope Slide) and the ‘North Fraser Island Upper Slope Slide’ (Upper Slope Slide). The Middle Slope Slide is situated to the south of the Fraser Canyon Complex on the Wide Bay Plateau in 1500 m of water. The slide scar is estimated to be 11 km² in area and 100-150 m thick. The Upper Slope Slide is situated at a water depth of approximately 900 m at the northern end of the Fraser Canyon Complex. The head of this slide is probably defined by a structural surface comprised at the seaward edge of a Miocene reef complex located beneath the continental shelf edge and this slide scar is estimated to be 25 km² in area and 200-300 m thick. Note that a portion of the outer reef may have helped to drive the slope downslope.

3) The continental margin offshore Fraser Island is an active system that presents both top-down incision and bottom-up (retrogressive) erosion.

4) Turbidity flows, generated by shelf sands around Fraser Island are probably cascading down the slope cutting linear rills, ridges, and gullies into the slope both in the canyon head walls and on the continental slope itself.

5) The morphology of the lower slope is consistent with bottom currents scouring and destabilising the lower slopes, as well as cutting “bottom-up”, generating canyons in the lower slope.

6) The potential for future failures similar to those described is highly likely given the abundance of the mass wasting features that have been identified.

7) There is no bathymetric evidence for the deposition of slide debris on the slope.
CHAPTER 4

Sedimentology, Radiocarbon and Biostratigraphy Dating

4.1 Introduction

This chapter presents a description of upper to mid continental slope sediments collected from the eastern Australian continental margin (EACM) in the study area, and aims to establish the geological and sedimentological characteristics of the materials in which geologically recent submarine landsliding has occurred throughout the late Neogene (Hubble et al. in press). The material consists of four gravity cores between 0.43 and 5.65 m long that were collected onboard RV Southern Surveyor offshore Fraser Island in southern Queensland (QLD) (SS2013-V01; Hubble 2013). These cores were collected from within or adjacent to two box slides on the southern QLD EACM located on the Wide Bay Plateau to the north of the Wide Bay Canyon and on the upper slope of the Fraser Canyon Complex, previously identified as the Middle Slope Slide and the Upper Slope Slide (Figure 4.1).

Three of the four cores presented boundary surfaces that are identified by a sharp colour-change boundary; small increases in sediment stiffness; and distinct gaps in radiocarbon (\(^{14}\text{C}\)) ages of at least 30 thousand years (ka) before present (BP). These boundary surfaces are variously interpreted to represent abrasion and removal of sediment by turbidity flows; detachment surfaces or retrogressive slide plane surfaces within the main landslide; or a period of non-deposition of sediments. The topmost, young sediments deposited above the boundary features are believed to represent recent hemipelagic, sediment drape.

Sedimentological data and accelerator mass spectrometry (AMS) \(^{14}\text{C}\) isotopic dates for the cored sediments are reported. The data are then interpreted in the context of the morphology of the landslides as evident in the multibeam bathymetry.
Figure 4.1. Morphology of the southern QLD continental margin showing the location of the two translational box slides with the location of their gravity cores in a) the Middle Slope Slide and b) the Upper Slope Slide offshore Fraser Island. VE = Vertical exaggeration. For depth colour bar see Figure 3.2, Chapter 3.
4.2 Methodology

4.2.1 Core Retrieval and Technique
Sub-surface sediment samples were collected using a gravity corer (GC) consisting of a one tonne load, winch core head and a PVC-lined, steel core barrel. This device was deployed from the stern A-frame of the ship. The core barrel (90 mm in diameter and 6 m in length) was deployed by means of an automated, tracked, hydraulic deployment system (aka Thomas the Tank Engine) (Figure 4.2).

The gravity cores were collected for sedimentological, stratigraphic, and geotechnical analysis, and the four cores were located in such a way to provide a “within-slide” core and a reference core from the adjacent slope (Figure 4.1). A total of 11.05 m of core was obtained: GC1 (1.33 m), GC2 (5.65 m), GC3 (3.64 m) and GC4 (0.43 m) (see Table 4.1 for details). In both cases, the within slide core was significantly longer in comparison to its adjacent reference core (more than four times longer). All cores were secured on deck upon completion, cut into 1 m sections for ease of handling, tape sealed with PVC end caps and labeled using Geoscience Australia’s standard protocols. Cores were stored horizontally at 3-4°C. GC1 and GC3 were split on board, while GC2 and GC4 were split in The University of Sydney core laboratory. Cores were split in half according to conventional protocols by cutting the PVC liners with a circular saw and ‘slicing’ the sediment cylinder in half with a drawing wire. Two 20 cm sections of GC3 (1F and 5B) were retained for geotechnical testing. These results are presented in in Chapter 5.

4.2.2 Radiocarbon Dating
To address the research objectives three and four given in section 2.2, Chapter 2; “To determine a reliable average sedimentation rate for this section of the margin,” and “To obtain a detailed 14C and/or biostratigraphic age record of the gravity cores in order to investigate the age of the box slides and to determine whether or not their occurrence can be related to a specific geologic event such as a change in sea level or major global environmental event,” radiocarbon dating was determined by AMS 14C dating on 19 sub-samples from the four gravity cores. Radiocarbon dates were obtained from planktonic
foraminifera assemblages in GC1, GC2, and GC3 as well as bulk samples from GC4. For samples with radiocarbon ages greater than 50 ka BP, foraminifera and nannofossil biostratigraphy was used to constrain their ages, as this material is considered ‘radiocarbon dead’ and well beyond the limit of conventional radiocarbon $^{14}$C dating techniques.

![Photographic images of the gravity corer onboard the RV SS2013-V01 cruise showing, a) the gravity corer being deployed into the ocean via a hydraulically operated cradle and the ship’s coring winch; b) the corer lying flat with the empty PVC-lined core barrels stowed adjacent and; c) scientific personnel retrieving a gravity core in 1 m increments.](image)

**Figure 4.2.** Photographic images of the gravity corer onboard the RV SS2013-V01 cruise showing, a) the gravity corer being deployed into the ocean via a hydraulically operated cradle and the ship’s coring winch; b) the corer lying flat with the empty PVC-lined core barrels stowed adjacent and; c) scientific personnel retrieving a gravity core in 1 m increments.

The planktonic foraminifera species *Globigerinoides ruber* was chosen as it is common along the entire EACM and has been used in previous sedimentological studies for radiocarbon dating (Troedson and Davies 2001; Clarke 2014). Only a single species was selected as it was in abundance and different species are thought to give different ages due to the Barker Effect (Broecker and Clark 2011), where different species have different residence times and a likelihood of fragmentation. Pristine planktonic species are ideal for dating and preferred to benthic species as it can be inferred that they have not been abraded or eroded, and removed from pre-existing sediment if the tests are entire, unbroken or transported and un-abraded material. This minimises any potential time lag between death of skeletal organism and the time of deposition (Woodroffe et al. 2007).
Table 4.1. Location and recovery statistics for the four gravity cores taken within and adjacent to the Middle and Upper Slope Slides. See Figure 4.1 for submarine landslide and core locations.

<table>
<thead>
<tr>
<th>Slide</th>
<th>Locality</th>
<th>Core</th>
<th>Latitude</th>
<th>Longitude</th>
<th>Target</th>
<th>Actual Water Depth (m)</th>
<th>Total Recovery (m)</th>
<th>No. of Sections</th>
</tr>
</thead>
<tbody>
<tr>
<td>Middle Fraser Island</td>
<td>North of Wide Bay Canyon, offshore the southern tip of Fraser Island on the Wide Bay Plateau.</td>
<td>GC3</td>
<td>25.21°S</td>
<td>153.58E</td>
<td><strong>Within</strong> the upper portion of a slide developed in the middle slope deposits on the Wide Bay Plateau.</td>
<td>1531</td>
<td>3.64</td>
<td>6 (incl. 2 geotechnical samples)</td>
</tr>
<tr>
<td>Middle Fraser Island</td>
<td></td>
<td>GC4</td>
<td>25.20°S</td>
<td>153.58°E</td>
<td>Slope <strong>adjacent</strong> to box slide.</td>
<td>1422</td>
<td>0.43</td>
<td>1</td>
</tr>
<tr>
<td>North Fraser Island Upper</td>
<td>Offshore Fraser Island (Sandy Cape) within the Fraser Canyon Complex.</td>
<td>GC1</td>
<td>24.43°S</td>
<td>153.36°E</td>
<td>Near the crest of a slide <strong>adjacent</strong> to a scarp on the northern side.</td>
<td>1069</td>
<td>1.33</td>
<td>2</td>
</tr>
<tr>
<td>Upper Slope Slide</td>
<td></td>
<td>GC2</td>
<td>24.45°S</td>
<td>153.37°E</td>
<td>Upper slope <strong>within</strong> box slide.</td>
<td>1092</td>
<td>5.65</td>
<td>6</td>
</tr>
</tbody>
</table>
Foraminifera tests with these characteristics were extracted by gently disaggregating samples of around 2-4 cm³ of sediment in water and removing the mud fraction by washing through a 63 µm sieve. The coarse fraction was then placed through a filter suction pump to remove the water then dried in a 40°C oven ready for picking. Two samples in GC1 contained very coarse-grained sand and shell material up to 1000 µm in diameter, which is significantly larger than the target foraminifera that are typically around 100-400 µm. The coarser sands were removed by washing the material through both a 63 µm and 500 µm sieve, keeping the 63-500 µm fraction for picking. Well-preserved *G. rubers* were identified and hand-picked under a binocular microscope to acquire a sample size of 6-7 mg which is the minimum sample size required for reliable AMS ¹⁴C ages (Figure 4.3). Bulk radiocarbon samples in GC4 were prepared by sub-sampling 2-4 cm of sediment from the core and placing in a sealed tube. Foraminifera and bulk samples were all sent to the CHRONO Radiocarbon Dating Facility at Queens University in Belfast, United Kingdom for dating.

Dates were received in conventional ¹⁴C years BP and converted to calibrated calendar ages after Stuiver and Reimer (1993). Median calibrated ages (BP) were calculated in CALIB V6.1.0 (Stuiver and Reimer 2011) using the marine calibration curve Marine09.14c data set (Reimer et al. 2009) with a reservoir correction value (ΔR) of 8 ± 25 years (the average for data offshore Stradbroke Island; see http://calib.qub.ac.uk/marine/; Ulm et al. 2009) and reported here with 2σ errors. Some dates could not be calibrated as they fell outside the calibration range (0-55 ka BP; e.g. GC1/1B/45cm).

The results of all 19 radiocarbon dates are presented in Table 4.2. Note that GC1 and GC2 present sequence dates that suggest interruption of the depositional sequence while GC3 and GC4 present dates consistent with uninterrupted deposition.

### 4.2.3 Biostratigraphic Dating

Conventional foraminifera and nannofossil biostratigraphy techniques were used on the basal materials within the gravity cores to date the maximum ages of the materials present in the
sites. In two cases (GC1 and GC4, short cores) relatively ancient materials (lower Pleistocene and upper Miocene) was sampled. This material presented as compacted and dense.

Figure 4.3. Foraminifera images showing correct identification of *Globigerinoides ruber* identified by a) Yassini and Jones (1995) showing side view (1093) and side and spiral views (1094-1097) against, b) sub-samples from GC1/18/37.5cm in this study picked from a size fraction coarser than 63 µm.

Foraminifera biostratigraphy samples were prepared in the same way as the foraminifera radiocarbon samples (disaggregated and sieved through a 63 µm sieve) and sent for to A/Prof Stephen Gallagher from the University of Melbourne for species identification and age determination. The results are presented in Table 4.3. Nannofossil biostratigraphy samples were prepared by placing a toothpick sample of sediment only a few mm$^3$ onto a simple smear slide. Each slide was viewed under a light microscope with an x100 oil-immersion objective lens. Slides were viewed under both plane-polarised and cross polarised (XPL) light as the size, composition, and structure of each species show distinct differences under the different light
sources (Bown 1998). The results are presented in Table 4.4. A combination of both biostratigraphy and nannofossil dating allows the age of particular sections of the cores (especially the bases of GC1 and GC4) to be determined with a high degree of confidence. The data are collated in figures 4.8 and 4.10.

Table 4.2. Foraminifera $^{14}$C radiocarbon dates for the four gravity cores taken within and adjacent to the Upper and Middle Slope Slides.

<table>
<thead>
<tr>
<th>Core</th>
<th>Section</th>
<th>Depth (cm)</th>
<th>Conventional $^{14}$C Age (BP)</th>
<th>Median Calibrated Age (2$\sigma$) (BP)</th>
<th>Corrected $^{14}$C Error (±)</th>
<th>2$\sigma$ Calibrated Age Range (95.4% Probability) (BP)</th>
</tr>
</thead>
<tbody>
<tr>
<td>GC1</td>
<td>2A</td>
<td>16</td>
<td>12,870</td>
<td>14,564</td>
<td>119</td>
<td>14,157-15,016</td>
</tr>
<tr>
<td></td>
<td>2A</td>
<td>23.5</td>
<td>27,871</td>
<td>31,613</td>
<td>556</td>
<td>31,185-32,397</td>
</tr>
<tr>
<td></td>
<td>1B</td>
<td>37.5</td>
<td>26,807</td>
<td>31,014</td>
<td>481</td>
<td>30,587-31,291</td>
</tr>
<tr>
<td></td>
<td>1B</td>
<td>45</td>
<td>&gt;48,455</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>1B</td>
<td>82</td>
<td>&gt;46,118</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>GC2</td>
<td>6A</td>
<td>6.5</td>
<td>3,561</td>
<td>3,441</td>
<td>86</td>
<td>3,341-3,556</td>
</tr>
<tr>
<td></td>
<td>6A</td>
<td>16</td>
<td>7,924</td>
<td>8,379</td>
<td>89</td>
<td>8,292-8,492</td>
</tr>
<tr>
<td></td>
<td>6A</td>
<td>20.5</td>
<td>37,341</td>
<td>41,810</td>
<td>1223</td>
<td>40,888-42,745</td>
</tr>
<tr>
<td></td>
<td>6A</td>
<td>51</td>
<td>46,824</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>5B</td>
<td>83</td>
<td>&gt;54,139</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>GC3</td>
<td>6A</td>
<td>20.5</td>
<td>9,742</td>
<td>10,592</td>
<td>121</td>
<td>10,469-10,770</td>
</tr>
<tr>
<td></td>
<td>4C</td>
<td>55</td>
<td>16,666</td>
<td>19,412</td>
<td>208</td>
<td>18,934-19,177</td>
</tr>
<tr>
<td></td>
<td>4C</td>
<td>87</td>
<td>21,641</td>
<td>25,364</td>
<td>279</td>
<td>24,961-25,864</td>
</tr>
<tr>
<td></td>
<td>4C</td>
<td>138</td>
<td>29,563</td>
<td>33,807</td>
<td>702</td>
<td>32,916-34,633</td>
</tr>
<tr>
<td></td>
<td>3D</td>
<td>187</td>
<td>40,698</td>
<td>43,945</td>
<td>1,170</td>
<td>42,200-45,828</td>
</tr>
<tr>
<td></td>
<td>3D</td>
<td>239</td>
<td>44,589</td>
<td>47,316</td>
<td>1,973</td>
<td>44,417-50,000</td>
</tr>
<tr>
<td>GC4*</td>
<td>1A</td>
<td>4</td>
<td>4,549</td>
<td>4,745</td>
<td>84</td>
<td>4,605-4,841</td>
</tr>
<tr>
<td></td>
<td>1A</td>
<td>12.5</td>
<td>20,433</td>
<td>23,922</td>
<td>218</td>
<td>23,514-24,314</td>
</tr>
<tr>
<td></td>
<td>1A</td>
<td>41.5</td>
<td>40,729</td>
<td>44,001</td>
<td>1,438</td>
<td>41,816-46,416</td>
</tr>
</tbody>
</table>

* Samples bulk dated.
**Table 4.3.** Foraminifera biostratigraphy dating for the base of the four gravity cores taken within and adjacent to the Upper and Middle Slope Slides.*

<table>
<thead>
<tr>
<th>Core</th>
<th>Section</th>
<th>Depth (cm)</th>
<th>Age (BP)</th>
<th>Biostratigraphy</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>GC1</td>
<td>1B</td>
<td>118.5</td>
<td>0-0.45 Ma</td>
<td>PT1b; Holocene to Pleistocene</td>
<td>Presence of <em>Glaborotalia hirsuta</em> (Overlap age of 0.44 and 0.45 Ma, see Table 4.4).</td>
</tr>
<tr>
<td></td>
<td>1B</td>
<td>126</td>
<td>0-2.58 Ma</td>
<td>PT1b-PL5; Holocene to Pleistocene</td>
<td>Presence of <em>G. truncatulinoides</em> (Overlap age of 1.93 and 2.58 Ma, see Table 4.4).</td>
</tr>
<tr>
<td>GC2</td>
<td>1F</td>
<td>556</td>
<td>0-0.45 Ma</td>
<td>PT1b; Holocene to Pleistocene</td>
<td>Presence of <em>G. hirsuta</em></td>
</tr>
<tr>
<td>GC3</td>
<td>2E</td>
<td>340.5</td>
<td>0-0.45 Ma</td>
<td>PT1b; Holocene to Pleistocene</td>
<td>Presence of <em>G. hirsuta</em></td>
</tr>
<tr>
<td>GC3</td>
<td>1F</td>
<td>359.5</td>
<td>0-0.75 Ma</td>
<td>PT1a; Holocene to Pleistocene</td>
<td>Presence of <em>G. hessi</em></td>
</tr>
<tr>
<td>GC4</td>
<td>1A</td>
<td>40</td>
<td>5.92-8.43 Ma</td>
<td>M14-M13b; upper Miocene</td>
<td>Presence of <em>Globoquadrina dehiscens</em> and <em>Candeina nitida</em></td>
</tr>
</tbody>
</table>

*Analysis performed by A/Prof Stephen Gallagher of the University of Melbourne.

**Table 4.4.** Nannofossil biostratigraphy dating for the base of the four gravity cores taken within and adjacent to the Upper and Middle Slope Slides.*

<table>
<thead>
<tr>
<th>Core</th>
<th>Section</th>
<th>Depth (cm)</th>
<th>Age (BP)</th>
<th>Biostratigraphy</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>GC1</td>
<td>1B</td>
<td>118.5</td>
<td>0.44¹-3.92⁸ Ma</td>
<td>NN20/19-NN18; Pleistocene to Pliocene</td>
<td>Presence of <em>Pseudoemiliania lacunosa</em> (Overlap age of 0.44 and 0.45 Ma, see Table 4.4).</td>
</tr>
<tr>
<td></td>
<td>1B</td>
<td>128</td>
<td>1.93¹-66.04⁸ Ma</td>
<td>NN19/18-Paleocene; Pleistocene to upper Paleocene</td>
<td>Presence of Discoaster spp.† (Overlap age of 1.93 and 2.58 Ma, see Table 4.3).</td>
</tr>
<tr>
<td>GC4</td>
<td>1A</td>
<td>41.5</td>
<td>1.93¹-10.55⁸ Ma</td>
<td>NN19/18-M13b; Pleistocene to upper Miocene</td>
<td>Presence of Discoaster brouweri, <em>D. variabilis</em> and <em>D. assymetricus</em></td>
</tr>
</tbody>
</table>

*Guidance with species identification given by Dr. Alan Baxter from the University of New England.

¹ Last appearance, ⁸ First appearance.

† Sample heavily recrystallised allowing only identification of the *Genus* to be made.

### 4.2.4 Core Logging and Grainsize Analysis

Cores were laid out in sequence, photographed, and visually logged. The lithology of each core was logged and colour classified using Oyama and Takehara (1967) soil colour chart. Subsamples were taken (~0.7 g) for grainsize analysis from each core at regular intervals (~50 cm) or where a distinct colour change or an obvious grainsize variation was visually apparent. This material was analysed with a Mastersizer 2000 particle sizer to determine grainsize and mean
grainsize distribution. The results were then plotted and the material classified based on the Unified Soil Classification System (USCS) using the ASTM D 2487 standard procedure (Table 4.5). Engineering physical property data, for example, Atterberg Limit tests, was used to determine the USCS soil classification and the results are presented in Chapter 5, section 5.4.1. ‘Sand, Silt, Clay’ ternary plots were created for each core using the statistical program GRADISTAT 4.0 (Blott and Pye 2001). Finally, grainsize particles were binned into clays (0.002-2 µm), silts (2-60 µm) and sands (60-2000 µm) using British standards in Craig (2004).

4.3 Core Descriptions
The longer within slide gravity cores (Upper Slope Slide, 565 cm; Middle Slope Slide, 364 cm) present bioturbated, weakly layered, hemipelagic, Pleistocene and Holocene muds. Cores taken adjacent to both slides are short (Upper Slope Slide, 133 cm; Middle Slope Slide, 43 cm) and terminate in stiff muds of lower Pleistocene and upper Miocene respectively (Tables 4.3 and 4.4). Full lithological descriptions with the soil classifications for each core is presented in Table 4.6, followed by their grainsize distribution curves in Figure 4.4, and percentage logs with depth for grainsize distribution in Figure 4.5. The muddy sediments shown in a ‘Sand, Silt, Clay’ ternary plot are generally sandy silts (Figure 4.6a) with low clay contents varying between 4% and 15% for all samples (Figures 4.4 and 4.5). The cross-sectional profiles of each of the four photographed cores are shown in Figure 4.8 with the interpretations of each gravity core discussed below.

4.3.1 Gravity Core 1: Adjacent to the North Fraser Island Upper Slope Slide
GC1 (133 cm) was taken on the continental slope adjacent to the Upper Slope Slide offshore northern Fraser Island (Figures 4.1b and 4.8). A full lithological description of GC1 is presented in Table 4.6, and its ‘Sand, Silt, Clay’ ternary plot in Figure 4.6b. The top most sediment layer within the core (0-19 cm) is a thin hemipelagic mud (43% sand, 50% silt) similar to those described for the eastern Australian upper continental slope in NSW and southern QLD (Hubble and Jenkins 1984a and b; Troedson and Davies 2001; Glenn et al. 2008; Clarke et al. 2012; Hubble et al. 2012). These muds have low contents of clay (~10%; Figures 4.4 and 4.5).
Sedimentation rates for this top hemipelagic mud layer are approximately 0.011 m ka\(^{-1}\), suggesting present day rate of sediment accumulation on the slopes adjacent to the Upper Slope Slide is very slow ~1 m per 100 ka (Figures 4.7 and 4.8).

**Table 4.5.** Unified Soil Classification System (USCS) chart using the ASTM D 2487 standard procedure (modified from Holtz et al. 2011).

<table>
<thead>
<tr>
<th>MAJOR DIVISIONS</th>
<th>GROUP SYMBOL</th>
<th>GROUP NAME</th>
</tr>
</thead>
<tbody>
<tr>
<td>Coarse grained soils</td>
<td>Clean gravel &lt;5% smaller than No. 200 Sieve</td>
<td>GW</td>
</tr>
<tr>
<td></td>
<td>Gravel with &gt;12% fines</td>
<td>GP</td>
</tr>
<tr>
<td></td>
<td>Clean sand</td>
<td>GM</td>
</tr>
<tr>
<td></td>
<td>Sand with &gt;12% fines</td>
<td>GC</td>
</tr>
<tr>
<td></td>
<td></td>
<td>SW</td>
</tr>
<tr>
<td></td>
<td></td>
<td>SP</td>
</tr>
<tr>
<td></td>
<td></td>
<td>SM</td>
</tr>
<tr>
<td></td>
<td></td>
<td>SC</td>
</tr>
<tr>
<td>Fine grained soils</td>
<td>Inorganic</td>
<td>ML</td>
</tr>
<tr>
<td></td>
<td></td>
<td>CL</td>
</tr>
<tr>
<td></td>
<td>Organic</td>
<td>OL</td>
</tr>
<tr>
<td></td>
<td>Inorganic</td>
<td>MH</td>
</tr>
<tr>
<td></td>
<td></td>
<td>CH</td>
</tr>
<tr>
<td></td>
<td>Organic</td>
<td>OH</td>
</tr>
<tr>
<td>Highly organic soils</td>
<td></td>
<td>Pt</td>
</tr>
</tbody>
</table>

Visual inspection suggests that this layer of sand (23 cm thick) is normally graded (weakly) while the contacts with the mud layers above and below are sharply defined. The sand to mud interface above the turbidite was \(^{14}\)C dated at 14.6 ka BP and indicates the time when the sand was deposited on the continental slope. The age of the sands within the deposit is 31 ka BP (see...
Table 4.6. Lithological classification of gravity cores based on USCS (see Table 4.5) and Oyama and Takehara (1967) soil colour chart (see Figure 4.10 for graphical lithological log).

<table>
<thead>
<tr>
<th>Core</th>
<th>From (cm)</th>
<th>To (cm)</th>
<th>Geological Class</th>
<th>Engineering Class and Lithological Description</th>
</tr>
</thead>
</table>
| GC1  | 0         | 19      | Bioclastic, hemipelagic, sandy silt | Sandy elastic silt (MH)  
Sandy elastic silt (MH) with the upper 9 cm light yellow (5Y 7/4) in colour with a thin layer of grey material (7.5Y 6/1) grading to greyish olive (5Y 6/2). |
|      | 19        | 42      | Fine, gravelly, bioclastic sand | Sand with silt (SP-SM)  
Prominent section of poorly graded light yellow (7.5Y 7/3) coarse sand (possible turbidite feature). |
|      | 42        | 133     | Bioclastic, hemipelagic, sandy silt | Sandy elastic silt (MH)  
Generally uniform section of light grey (7.5Y 7/1) sandy silt with a distinct colour change at 123 cm to a stiff grey (7.5Y 5/1) showing evidence of a possible erosional surface. |
| GC2  | 0         | 565     | Bioclastic, hemipelagic, sandy silt | Elastic silt with sand (MH)  
Uniform core section of fine sandy clay silts. The upper 7 cm is light yellow (5Y 7/3) in colour followed by a 12 cm section between 7 and 19 cm of grey sediment (7.5Y 6/1) with streaks of bioturbated light grey (7.5Y 8/2) sediment. This light grey colour takes dominance at a distinct hiatus at 19 cm. Colour changes to greyish olive (7.5Y 6/2) at 84 cm. From 466 cm to the base of the core at 565 cm the core is predominately light grey (7.5Y 7/1) with streaks of greyish olive (7.5Y 6/2). |
| GC3  | 0         | 24      | Bioclastic, hemipelagic, sandy silt | Sandy elastic silt (MH)  
Light yellow (7.5Y 7/3) fine sandy coarse silt. |
|      | 24        | 44      | Triaxial sample | Core used for geomechanical testing. |
|      | 44        | 102     | Bioclastic, hemipelagic, sandy silt | Sandy elastic silt (MH)  
Fine sandy coarse silt darkens to greyish olive (7.5Y 6/2) with slight discolouration and iron oxide staining at 19 cm. |
| GC4  | 102       | 195     | Silty sand | Silty sand (SM)  
Grades from medium to fine grey (10Y 5/1) to olive grey (10Y 5/2) silty sand. |
|      | 195       | 357     | Hemipelagic, sandy, elastic silt | Sandy elastic silt (MH)  
Olive grey (10Y 5/2) fine sandy coarse silt changing to light grey (10Y 7/2) at 325 cm, then to greenish grey (7.5Y 6/1) up to 357 cm. |
|      | 357       | 364     | Hemipelagic, sandy, elastic silt | Sandy elastic silt (MH)  
Distinct colour change below a boundary surface at 357 cm to a darker greenish grey (7.5Y 5/1) |
|      | 0         | 4       | Stiff silty sand | Silty sand (SM)  
Coarse silty sand of light yellow (5Y 7/3) colour with the upper 3 cm oxidised. |
|      | 4         | 43      | Stiff, mottled, bioturbated, silt with sand | Elastic silt with sand (MH)  
Light yellow (5Y 7/3) fine sandy coarse silt. |
Figures 4.8 and 4.10 for lithology). The base of this sand unit is incised into the underlying mud, which is >48 ka BP, i.e. radiocarbon dead. This graded sand layer is interpreted to be a grain flow or turbiditic sand deposit that has abraded the underlying mud unit and removed a thickness of material representing at least 30 ka of mud slope deposition (Table 4.2). Sedimentation rates were unable to be quantified for this underlying mud layer due to the sediments being radiocarbon dead.

The sandy (33%) silt (54%) unit (hemipelagic muds with 13% clay) below the turbidite sands is uniform in appearance, light grey (7.5Y 7/1) in colour and extends for 81 cm down core (Table 4.6). Towards the base of GC1 at 123 cm, there is a distinctive colour change from light grey (7.5Y 7/1) to grey (7.5Y 5/1) silt, observed with a dominant truncated flame structure between this transition (Figure 4.9b). Several black consolidated mud lumps roughly 5 mm in diameter were also found directly above. This darker brownish grey material is a stiff older unit that has stopped the gravity corer from penetrating further. Grainsize analysis of this bottom layer of sediment demonstrates a distinct change from sandy silts, to a silty (49%) sand (50%), with almost no clay content (1%; Figure 4.5).

Biostratigraphic ages were determined for the basal sediments of GC1 shown in Figures 4.8 and 4.9b. The softer silts just above the contact with the stiffer basement silts contained the foraminifera Globorotalia hirsuta that first appeared 0.45 million years (Ma) BP, giving this the maximum age of the above-contact sediment (Table 4.3). The nannofossil Pseudoemiliania lacunosa, which last appeared 0.44 Ma BP (Table 4.4; Bolli et al. 1985; Raffi et al. 2006; Young et al. 2014), is also present in this material and enables the age of this sediment to be very tightly constrained at 0.44-0.45 Ma BP (and provides an unusually precise date).

The stiff basal mud sediments (126-133 cm) contain the foraminifera Globorotalia truncatulinoides, which has an age range of 0-2.58 Ma BP (Table 4.3). Nannofossils are also present in this material, in particular Discoaster spp. This group of organisms went extinct at
Figure 4.4. Cumulative a) and normal b) grainsize distribution curves against particle diameter plotted on a log scale for typical muds in GC1 (blue), GC2 (red), GC3 (green) and GC4 (purple). NB. GC1 includes turbidite sands.
Figure 4.5. Grain size distribution variation (clays, silts and sands) with depth in the gravity cores a) GC1, b) GC2, c) GC3 and d) GC4 using British standards in Craig (2004). Markers (−) placed adjacent to the right of the columns indicate the points within the cores where grain size samples were taken.
1.93 Ma BP (Table 4.4; Bolli et al. 1985; Raffi et al. 2006; Young et al. 2014). Unfortunately the nannofossils in this sample were heavily re-crystallised and neither the species nor the genus could be accurately identified (Pers. Comm., A. Baxter, 18 November 2014). Nevertheless, given the 0.44-0.45 Ma BP age of the softer silts above, and the 1.93-2.58 Ma BP age of the stiffer silts below, it can be stated that this surface represents a prolonged hiatus between the two surfaces. At least 1.5 Ma of sediment has either not been deposited, or has more likely been eroded and removed given the disturbance evident at the boundary. Furthermore, with both the maximum age of the foraminifera *G. truncatulinoides*, and minimum age of the nannofossils *Discoaster spp.* present at the base of GC1 below 123 cm, the depositional age of this material is constrained to the lower Pleistocene between 1.93 Ma and 2.58 Ma BP. This age is regionally significant as it provides a maximum age the development of the morphology of the upper slope offshore Fraser Island where this core was taken and indicates that the slope developed at this site is effectively an erosional unconformity with the causal mechanisms contemporaneous with and probably related to the expansion of the global ice-pack in the early Pleistocene.

4.3.2 Gravity Core 2: Inside the North Fraser Island Upper Slope Slide

GC2 was the longest of the four cores collected in the study area. It is 565 cm in length and was taken inside the Upper Slope Slide offshore northern Fraser Island (Figure 4.1b and 4.8). The core has apparently penetrated the near surface sediment drape (565 cm thick) and the slide plane surface is located at a depth beyond the reach of the gravity corer. A full lithological description of GC2 is presented in Table 4.6, and its ‘Sand, Silt, Clay’ ternary plot in Figure 4.6c.

The top sediments (19 cm) within this core comprised of sandy (30%), clay (7%) silts (55%) with a colour change from light yellow (7.5Y 7/3) to grey (7.5Y 6/1). A more distinct colour change is seen below these top sediments with dominantly grey sediment overlying light grey (7.5Y 8/2) material (Figures 4.8 and 4.10). Disturbed near parallel dismembered mud lumps the same light grey colour are seen dislodged within the above grey materials, suggesting this boundary feature is an erosional surface as mud lumps are typical features of mass transport processes
Figure 4.6. Ternary plots created using the statistical program GRADISTAT 4.0 (Blott and Pye 2001) for a) all cores, b) GC1, c) GC2, d) GC3, and e) GC4, within the hemipelagic muds (black dots) and turbidite sands (blue dots).
(Almagor and Schilman 1995; Wilson et al. 2004). Radiocarbon dates above and below this distinct colour change (19 cm) confirms the likely erosion of this boundary feature as the age changes significantly across this contact from 41.8 ka BP below this boundary, to 8.4 ka BP above, evident of a cryptic hiatus with around 33 ka of sediment ‘missing’ (Table 4.2, Figure 4.8). Sedimentation rates are around 0.019 mka\(^{-1}\) above this surface boundary suggesting present day rate of sediment accumulation inside the Upper Slope Slide is slow \(\sim\)1 m per 50 ka (Figure 4.7).

![Image](image_url)

**Figure 4.7.** Age-depth plots for mean calibrated foraminifera \(^{14}\)C radiocarbon ages for GC1, GC2, and GC3.Projected ages using linear regression are shown just above the boundary surface in GC3/1F/356cm shown by dashed lines. NB. See Figure 4.8 for photographic core logs with age-depth locations.

Below this surface boundary, the remaining 546 cm of core is uniform in appearance, mainly comprised of silts (55%), with sands (29%) and small clay content (16%; Figures 4.4 and 4.5). At 51 cm from the surface, the sediments were dated radiocarbon dead (conventional age 47 ka BP; see Table 4.2). Biostratigraphic examination of the sediment at the base of GC2 at 556 cm indicates that it contains a very diverse, tropical fauna (Pers. Comm., S. Gallagher, 7 October
Figure 4.8. Photographic images of the four gravity cores taken adjacent to and inside of the Upper (GC1 and GC2) and Middle (GC4 and GC3) Slope Slides respectively. Insets A-D highlight identified boundary surfaces (dotted lines) with their close-up images presented in Figure 4.9. ¹⁴C dates are in thousand years (ka) and biostratigraphy ages marked * are in million years (Ma) before present (BP). RCD = ‘radiocarbon’ dead. *Contains an un-split core (section 5B) for triaxial testing. Section 1F also used for triaxial testing is missing a cylindrical section of sediment. See Figure 4.1 for core locations.
2014). It was not possible to determine a precise date for this material, but the presence of the foraminifera *G. hirsuta* constrained the base of the core to being no older than 0.45 Ma BP (Table 4.3).

Figure 4.9. Close-up images of the four boundary surfaces identified within the gravity cores offshore Fraser Island; a) turbidite within GC1, b) erosional unconformity at the base of GC1, c) slide event at the top of GC2, d) slide event at the base of GC3. See Figure 4.8 for entire core images and sediment ages.
4.3.3 Gravity Core 3: Inside the Middle Fraser Island Middle Slope Slide

A long core (364 cm), GC3, was taken inside the Middle Slope Slide on the middle slopes of the Wide Bay Plateau, offshore Fraser Island (Figure 4.1a and 4.8). A full lithological description of GC3 is presented in Table 4.6, and its ‘Sand, Silt, Clay’ ternary plot in Figure 4.6d. The core comprised of 357 cm of homogenous, bioclastic, hemipelagic, mud (45% sand, 47% silt) with clay (7%; see Figures 4.4 and 4.5). This core contained higher sand content within the hemipelagic muds compared to the rest of the cores with a mean grain size of 49 µm (Figures 4.4 and 4.6).

The $^{14}$C ages plotted against depth for GC3 is presented in Figure 4.7. Ages increased linearly from 10.6 ka BP at 20.5 cm to 47.3 ka BP at 239 cm from the surface (Table 4.2). Linear regression analysis showed a good age-depth correlation ($R^2 = 0.98$) with an average sedimentation rate of approximately 0.057 m ka$^{-1}$ suggesting present day rate of sediment accumulation inside the Middle Slope Slide is ~1 m per 18 ka (Figure 4.7). This is the only core of the four studied here where the radiocarbon ages can give us reliable sedimentation rates (N.B. located within a protected hollow on the slope).

Within the 20 cm long base sample (section GC3/1F) separated for triaxial testing, a suspected slide boundary surface was identified 357 cm from the top of the core (Figure 4.9d). Softer sediments of green grey (7.5Y 6/1), coarse sandy silts overlie a distinct boundary surface of a darker green grey appearance below (7.5Y 5/1; see Table 4.6). The grain size distribution appeared to be very similar but the sediment below was much stiffer. Based on extrapolation of the sedimentation rate beyond the limit of datable material in the core, the projected ages at the base of the homogenous unit, just above the boundary feature in GC3/1F (356 cm) equated to ~71 ka BP [using the regression equation of $y = 0.0057x - 51.12$] (Figure 4.7). This means that the minimum age of the boundary feature (thought to be a slide surface) shown in Figures 4.8 and 4.9d is ~71 ka BP. Biostratigraphy ages of the sediments at the base of GC3 are not tightly constrained, but the sediments below the boundary feature were shown to most likely be older than the sediments above. Foraminifera biostratigraphy dating showed the sediments...
Figure 4.10. Lithological logs showing the four boundary surfaces (inset) with $^4$C and biostratigraphy ages (marked *) within the gravity cores. RCD = radiocarbon dead, ka = thousand years, Ma = million years before present. See Table 4.5 for USCS classification and Table 4.6 for lithological descriptions.
immediately below the boundary feature at 359.5 cm, to be no older than 0.75 Ma BP due to the presence of *G. hessi* (Table 4.3).

### 4.3.4 Gravity Core 4: Adjacent to the Middle Fraser Island Middle Slope Slide

GC4 is a short core (43 cm) taken on the slope adjacent to the Middle Slope Slide on the middle slopes of the Wide Bay Plateau, offshore Fraser Island (Figure 4.1a and 4.8). A full lithological description of GC4 is presented in Table 4.6, and its ‘Sand, Silt, Clay’ ternary plot in Figure 4.6e. The surface sediment (0-4 cm) is a silty (38%) sand (53%) with low clay (9%), and is light yellow (5Y 7/3) in colour with the upper 3 cm oxidised. Below 4 cm from the surface, the sediment grades into stiff, mottled, bioturbated sandy (31%) silt (67%), with very little clay content (<2%; see Figures 4.5, 4.6 and 4.8).

A biostratigraphic age was determined for the base of GC4. The stiff silts returned an upper Miocene age of 5.92-8.43 Ma BP due to the presence of the foraminifera *Globoquadrina dehiscens*. This age is completely inconsistent with the bulk radiocarbon date of 44 ka BP taken at the same depth (40-41.5 cm; see Tables 4.2 and 4.3). It should be noted that the biostratigraphy sample was not contaminated or taken from a recent burrow and the presence of *G. dehiscens* confirms that the sediment at 40-41.5 cm can be no younger than 5.92 Ma BP as this is the time the species went extinct. There is no evidence of abrasion indicative of recent reworking on the surfaces of the foraminifera tests (Bolli et al. 1985; Young et al. 2014). Hence the minimum biostratigraphic age of 5.92 Ma BP suggests that this surface material has been exposed at the seafloor due to erosion and that there has been an exchange of young carbon into the old foraminifera tests. Nannofossil biostratigraphy also showed the presence of numerous *Discoaster spp.* that were present between 1.93-10.55 Ma BP, further confirming the late Neogene age determined from the foraminifera biostratigraphy (Table 4.4). In other words, the young radiocarbon age is attributed to the introduction of young carbon into the upper Miocene material, possibly by microbial action (c.f. Harris et al. 1996a; Walker 2005). Note, that it is recognised that while the source of the young carbon is something of an enigma, it might not be entirely unexpected in shallow surface sediments with low sediment accumulation rates.
that have been undisturbed for such a long period of time (Almagor and Schilman 1995). In contrast, the two separate biostratigraphic ages are consistent with one another and confirm that this layer of sediment is quite old (upper Miocene). As with GC1, this upper Miocene age for the material that forms the slope on the Wide Bay Plateau is highly significant as it also indicates that the surface is an erosional unconformity and provides a maximum age for the formation of this regional geomorphic feature.

4.4 Synthesis of Sedimentology, Radiocarbon and Biostratigraphy Dating

The sedimentology of the cored material recovered from the continental slope offshore Fraser Island is quite uniform with material recovered from within and adjacent to the Middle and Upper Slope Slides consisting of Pleistocene muds (47-58% silt, 30-55% sand, and 4-15% clay). The low clay content and coarser sediments shown in the ternary plots for all cores (Figures 4.6) is surprising and suggests that these sandy muds are possibly derived from aeolian wind-blown material derived from the Australian continent (c.f. Hesse 1994; McGowan et al. 2008). The sediments also present an abundance of skeletal pelagic foraminifers and nannofossils that have provided a reliable source for radiocarbon and biostratigraphy dating. The composition and texture of the sediments is consistent with that found across the rest of the EACM, displaying hemipelagic, unconsolidated, sandy muds (Hubble and Jenkins 1984a and b; Troedson and Davies 2001; Glenn et al. 2008; Clarke et al. 2012; Hubble et al. 2012).

4.4.1 Oceanic Currents along east Australia

Present day southward flow of the east Australian current (EAC) along the east coast of Australia and its separation at 32°S to form the eastward flow, known as the Tasman Front which heads towards the north of New Zealand, is suggested to have shifted during the last glacial period (~110-11 ka BP; Kawagata 2001; Bostock et al. 2006). Sometime in the late Pleistocene, the separation of the EAC to the Tasman Front shifted north towards 25-26°S through changes in sea surface temperatures (Bostock et al. 2006). This shift is significant for this study as the Fraser Canyon Complex is situated at this latitude, directly beneath the Tasman flow separating the EAC at the Glacial Maximum (see Table 4.1 for latitude). Erosion
generated by vortexes at this time was probably high and/or sediment deposition was low. This was despite a weakening of the EAC at lower latitude (25°S) than at present day due to weaker trade winds and suppressed El Nino conditions during the glacial maximum (Bostock et al. 2006). At the same time westerly winds from Antarctica were higher and maximum bottom-water production was also more intense. It wasn’t until 11-12 ka BP when the EAC retreated back to 32°S due to a La Nina event that the trade winds and the EAC flow increased (Bostock et al. 2006). Both of these effects, particularly the bottom-water production, are considered to have played key roles in leading to both top-down and bottom-up erosion of the slope with sediment removed from the slope as a result of these currents. These phenomena, in combination with the occurrence of the large-scale mass wasting events identified in the bathymetry, are responsible for the deconstruction and erosion of the margin described in chapter 3. The important relevance of these two currents to sedimentology is discussed below.

4.4.2 Sediment Accumulation Rates
A unique dataset has been collected for this part of the EACM offshore Fraser Island where the sediment is slow to accumulate. Material is accumulating within the ‘protected’ submarine landslide “hollows”, while the adjacent slopes are being abraded and are consequently relatively bare of sediment. Cores taken from inside the landslide scars were long (GC2 inside the Upper Slope Slide = 5.65 m, GC3 inside the Middle Slope Slide = 3.64 m) and presented upper Pleistocene hemipelagic muds (Figure 4.8). In contrast the cores taken from the adjacent slopes were short (GC1 on the upper slope = 1.33 m, GC4 on the middle slope = 0.43 m) and terminated in stiff muds of lower Pleistocene and upper Miocene age respectively (Figure 4.8). It is suggested that the protection of the sediments within both landslides is due to their geometry and detachment of current flow from the seafloor such that it travels directly south overtop of the sidewalls of the slides (c.f. Bostock et al. 2006; see section 4.4.1). At the same time, the currents attack the steep upper slope causing erosional incision and sediment failure.

A reliable average sedimentation rate for the middle slope on the Wide Bay Plateau of approximately 0.057 mka⁻¹ or 1 m every 18 ka during Pleistocene to Recent times was
determined from GC3, inside the Middle Slope Slide. Due to a small sample size and termination into radiocarbon dead sediments, it is plausible that the present day slope surface sediments (top 19 cm) adjacent to (GC1) and within (GC2) the Upper Slope Slide have slow sedimentation rates of 0.011 mka\(^{-1}\) (1 m every 100 ka) and 0.019 mka\(^{-1}\) (1 m every 50 ka) respectively. The rates of sediment accumulation along the EACM is significantly low for global standards where continental margins are considered low when deposition is <1 mka\(^{-1}\) (Urlaub et al. 2013; Ai et al. 2014). Other ‘sediment-starved’ continental margins include the northwest African margin (e.g. Dakar Slide, 0.005-0.04 mka\(^{-1}\); Meyer et al. 2012) and the eastern Canadian margin (e.g. Grand Banks, 0.1 mka\(^{-1}\); Huppertz and Piper 2009). Maximum accumulation rates offshore Fraser Island in this study (0.011-0.057 mka\(^{-1}\)) is consistent with measured rates elsewhere along the EACM. Packham 1983, recorded rates in southern NSW to range between 0.05-0.16 mka\(^{-1}\) during Pleistocene to Recent times and 0.03-0.05 mka\(^{-1}\) for Miocene to Pleistocene sediment, while Clarke et al. (2014) calculated Pleistocene to Recent sediment between 0.02-0.12 mka\(^{-1}\) in northern NSW. The dates were also similar to that in the central Mediterranean (around 0.06 mka\(^{-1}\); Micallef et al. 2014). These low rates of sediment accumulation are not thought to enable rapid loading or favour the development of excess pore-pressures, which suggests these processes are not pre-conditioning factors for failure (Micallef et al. 2014). If this is the case, then some other trigger or multiple triggers is required to generate its slope failures.

The EACM, in particular offshore Fraser Island, is a margin that has undergone significant erosion and mass wasting processes in the geological past. Maximum sedimentation rates in this study were shown to be extremely slow between 0.011-0.057 mka\(^{-1}\) and much of the slope is being abraded or removed. If the measured rates are consistent with long-term accumulation, and given the formation and completion of the EACM between 90 and 65 Ma BP respectively (Gaina et al. 1998; Boyd et al. 2010), the sediment wedge on the continental slope would be estimated to be 3.5 km thick. However, seismic data shows the sediment wedge for the continental slope offshore Fraser Island to be thin varying from 0 to 1 km (Hill 1992),
meaning over 2.5 km of material is missing from the continental slope. This suggests that a significant amount of material has shed from the slope down to the abyssal plain.

4.4.3 Dating the Boundary Surfaces

Determining the age of the sediments within the gravity cores is considered one of the most significant results of this study as they provide an estimate of the maximum age of failure for these two submarine box slides, as well as fairly reliable maximum rates of sedimentation (described above in section 4.4.2). These ages can then be compared with the rest of the EACM to help determine whether failure occurred from a significant geologic event or is slowly shedding over-time. Although the sediments are relatively uniform between the cores, a few striking differences were present. All four cores showed evidence of more than one depositional unit with distinct age gaps (hiatuses) across their boundary surfaces. GC4 was less obvious visually, as a boundary surface cannot be seen but radiocarbon and biostratigraphy ages indicate the presence of a hiatus (Tables 4.2, 4.3 and 4.4, Figures 4.8 and 4.9). The remaining cores (GC1, GC2, and GC3) penetrated boundary surfaces that showed a distinct colour change above and below each boundary surface (Figure 4.9).

As the base of each of the four gravity cores were radiocarbon dead (>50 ka BP), biostratigraphy was used to help determine the ages of the Upper and Middle Slope Slides (Tables 4.3 and 4.4). The determined ages at the base of each of the cores were mostly in the Pleistocene except for GC4 taken on the slope on the Wide Bay Plateau, which returned an upper Miocene age. The Upper Slope Slide core did not successfully reach the slide plane surface of the main event, but showed evidence of failure at 19 cm from the surface that occurred ~8.4 ka BP (Figure 4.8). The same most likely occurred with the Middle Slope Slide, with a surface boundary at 357 cm from the surface occurring about 70 ka BP. However, the sediment below this boundary was unable to be tightly constrained (Table 4.3). A discussion of the boundary surfaces and possible timing of the two landslides is provided below.
4.4.3.1 Turbidity Flow

The 133 cm core (GC1) on the slope adjacent to the Upper Slope Slide presents a near surface layer of coarse, bioclastic, shelly sand (91%) with silt (8%), interpreted to be a turbidite deposit or grain flow (Figures 4.4 and 4.9a). This layer was deposited above and below hemipelagic muds, which are common across the entire EACM. A clear age gap of >30 ka of sediment is missing below the turbidite suggesting that it was energetic enough to remove a significant thickness of material accumulated at this site. Sedimentation rates could not be estimated for the hemipelagic mud unit below the turbidite in GC1 as the samples dated immediately below the turbidite and further down at 45 and 82 cm respectively were radiocarbon dead (Table 4.2 and Figure 4.10). The chaotic and coarse-grained nature of these facies also suggests that the material was deposited rapidly through a high-energy gravity-driven event (Hjelstuen and Brendryen 2014). Turbidite sands appear to be a common form of mass movement in southern QLD with several cores taken within the Wide Bay Canyon Complex on the SS2013/V01 voyage also presenting turbidite sequences (Hubble et al. 2013); sands that cascade downslope just north of the Fraser Canyon Complex were described by Boyd et al. (2008) (Figure 2.6, Chapter 2); and widespread turbidite deposits have been identified off the Great Barrier Reef in northern QLD by Webster et al. (2012) and Puga-Bernabeu et al. (2014). The cause, or triggering mechanisms of these turbidites is suggested to be earthquake-induced shaking that is sufficiently strong enough to cause cohesionless shelf sands to collapse or liquefy and move downslope. However, the turbidite in GC1 is not necessarily earthquake triggered. Another possibility is that the strong southward moving EAC is driving ‘waves’ of shelf sands through the head of the Fraser Canyon where it then flows downslope. This process is consistent with the multibeam bathymetry presented in Chapter 3 that shows numerous linear rills incised into most of the upper slope of the southern QLD margin (top-down incision; see Figure 3.5, Chapter 3). While an earthquake could have helped to initiate movement, the narrowness of the shelf edge between Fraser Island and the continental slope particularly during glacial maximum which is when this turbidite was deposited, is suggested to cause the EAC to funnel along the shelf, accelerating the flow, and delivering sand to be shed down the continental slope (c.f. Harris et al. 1996b).
It is interesting to note that some sand has stopped and been deposited on the upper part of the slope and that this material has not travelled down to the abyssal plain as might be expected. GC1 was taken at ~1000 m below sea level and with the turbidite event occurring around 15 ka BP when sea level was almost at low stand (~105 m lower than it is today; Waelbroeck et al. 2002), suggests a possible delta or beach collapse. The abrupt rise in sea level was primarily produced by the onset of deglaciation and the subsequent melting of the west Antarctic ice sheet ~14.5 ka BP (Clark et al. 2009). Lowered sea level is known to increase the likelihood of sliding due to increased seismicity (isostatic adjustment), erosion and/or sedimentation as the shelf edge migrates closer to the shoreline (Lee et al. 2009; Brothers et al. 2013; Hunt et al. 2013; Smith et al. 2013). Another credible finding is that the 15 ka BP turbidite event is the fourth observed slide or erosional date along the EACM contemporaneous with the glacial maximum. Further south in NSW, Clarke et al. (2012) identified three slide plane boundaries with radiocarbon ages of 15.8, 20.1, and 20.7 ka BP taken directly above such boundary surfaces (see Figure 2.9, Chapter 2). This suggests a common cause or process for these factors.

### 4.4.3.2 Erosional Unconformities

Biostratigraphic dates show the slope deposits to be very thin or entirely absent, suggesting that both the smooth slope surfaces present at the upper (GC1) and middle (GC4) slope sites are effectively erosional unconformities with distinct hiatuses of >2 Ma and >6 Ma between the deposition of the slope sediments and their current state. A plausible explanation for this is that strong Pleistocene currents have either removed material and abraded the slope or prevented sediment deposition on the slope (Bohm et al. 2015).

A well-defined boundary surface was identified within GC1 on the upper slope where the gravity core terminated in compacted hemipelagic mud of lower Pleistocene age at 123 cm from the surface (Figure 4.9b). This boundary surface is emphasised by a distinct colour change, from light grey to dark grey; a change in sediment composition from sandy, clay-bearing silts to silty sands (Figure 4.5); and a remarkably well constrained age gap of ~2 Ma between the two
contacts (Tables 4.3 and 4.4, Figure 4.8). Biostratigraphy showed the above boundary unit to present an age of 0.44-0.45 Ma BP while the below boundary is constrained to 1.93-2.58 Ma BP which marks the start of the Quaternary Glaciation ~2.6 Ma BP (Jansen and Sjoholm 1991; Zachos et al. 2001; Barker and Thomas 2004; Lyle et al. 2008). At this time period the northern hemisphere ice sheets expanded and global currents intensified (Jansen and Sjoholm 1991). Barker and Thomas (2004) also suggest that a hiatus in sediment deposition can indicate strong bottom currents that prevent deposition of any kind. It is thought that this lower unit represents the underlying basement seafloor of the EACM and highlights the youth of the Fraser Canyon slope. The morphology of the upper slope is lower Pleistocene (< 2 Ma BP) in age, however further investigations through the use of seismic profiling would help to constrain this model (Locat and Lee 2002; Engen et al. 2009). Nonetheless, a regionally significant erosional unconformity of ~2 Ma BP is apparently present on the upper slope which signifies the maximum age of the slope.

For the case of GC4, located on the adjacent slopes of the Middle Slope Slide, this core is short (43 cm), presents a very thin layer of young Holocene and Pleistocene sediment at the surface, but terminates quickly into upper Miocene material (Figures 4.8). Biostratigraphy constrained the surface sediments (40-41.5 cm) to 5.92-8.43 Ma BP showing that there is a definite hiatus or unconformity >6 Ma at the surface where the sediment is constantly being eroded or not accumulating. This erosional unconformity suggests either; a) a cessation of deposition has occurred, or b) the sediments are not sticking to the slopes and are constantly being abraded by currents. A series of geological events have been shown to occur post 8.43 Ma BP that could describe this regional feature and explain why the Wide Bay Plateau has not accumulated any sediment since the late Miocene:

1) The intensification of the Asian monsoon ~8 Ma BP is thought to have caused changes in the physical and chemical weathering of the worlds oceans subsequently leading to a decrease in climate over the Pliocene-Pleistocene Period (Filippelli 1997; Zachos et al. 2001). As a result, global cooling and ice build-up started to commence.
2) Immediately following the Asian monsoon intensification in the late Miocene, ice sheet expansion of east Antarctica into west Antarctica occurred ~6 Ma BP that increased bottom current flows from the south (Zachos et al. 2001; Barker and Thomas 2004; Exon et al. 2004). This expansion created cooler water and hence an increase in currents that could lead to erosion of bottom sediments along the slope (Lyle et al. 2008).

3) At the Miocene/Pliocene boundary, the gateway between North and South America known as the Panama seaway closed (~5.3 Ma BP; Haug and Tiedemann 1998) causing intensification of the global thermohaline circulation (Schneider and Schmittner 2006) and migration of the Antarctic polar front to the north. Final closure occurred at ~2.75 Ma BP which is thought to have led to the subsequent onset of the Northern Hemisphere Glaciation (Bartoli et al. 2005; Lunt et al. 2008).

4) Direct onset of the separation of the EAC over the Wide Bay Plateau during the last glacial period (~110-11 ka), which did not allow any sediment to accumulate during the Pleistocene (Kawagata 2001; Bostock et al. 2006; see section 4.4.1).

It is difficult to determine which event, if any, played the biggest role, but it is thought that these geologic events have all played a part in preventing the accumulation of sediment after the late Pliocene. It is more likely that the key factor for the erosional unconformity on the middle slope is for ongoing erosion rather than for sediment accumulation to have ceased over this long period of time. The age of the middle slope on the Wide Bay Plateau is less than 6-8.5 Ma BP.

### 4.4.3.3 Possible Timing of the Upper Slope Slide

Because GC2 did not successfully reach the slide plane surface of the main event and penetrated as far as the gravity corer could go (<6 m), the timing of the Upper Slope Slide could not be accurately quantified. However, a 33 ka age gap equaling around 0.63 m of sediment missing from the surface (at 19 cm), along with lithological examinations of disturbed bioturbated material immediately above, provides evidence for a small secondary slide that occurred around 8 ka BP within the fill of the main event (Table 4.2, Figures 4.8 and 4.9c). Multibeam bathymetry of the Upper Slope Slide shows around 300 m of sediment was removed.
from the headwall scarp (see Table 3.2b, Chapter 3) that is not shown in this age break. This demonstrates that the sediments within GC2 are only post-slide drape after the main event that was generated. There are four possible reasons for the age break in the surface of GC2 which has been termed a ‘cryptic hiatus’: 1) cessation of deposition; 2) material has been winnowed off and removed by strong currents; 3) a submarine landslide; 4) continuous episodic liquefaction removal as a result of a geologic event/s. Geotechnical tests have been performed to distinguish between these potential causes and to examine the geotechnical stability of the upper slope (Chapter 5).

While the timing of the Upper Slope Slide cannot be accurately determined, core GC2 within the slide can give us the minimum age and core GC1 located on the adjacent slope can give us the maximum age of when the slide occurred. The bases of GC2 at 556 cm and GC1 at 126 cm have biostratigraphic ages of 0-0.45 Ma BP and 1.93-2.58 Ma BP respectively (Table 4.3 and 4.4). This suggests that the Upper Slope Slide was more likely to have occurred in the Pleistocene predating ~0.5 Ma BP, but that it is no older than ~2.5 Ma BP.

4.4.3.4 Possible Timing of the Middle Slope Slide

The base of GC3 within the Middle Slope Slide terminated into stiff darker grey muds with a distinct boundary surface above, thought to represent a slide plane boundary. $^{14}$C ages increased linearly down core towards this boundary feature, providing a fairly accurate timing of this event with the sediments immediately above predicted at ~71 ka BP (Figure 4.8). However, a reliable age of the sediments below this boundary surface and geotechnical investigations of the strength of the soil (see Chapter 5) were unable to provide any evidence as to the amount of sediment that has been removed between this boundary. For this reason, it is hard to determine whether or not this boundary surface represents the main event or is a smaller retrogressive failure within the slide, similar to that presented in GC2. However, GC4 on the slope adjacent to the Middle Slope Slide consists of stiffer coarse sandy silt with minimal clay that is not evident at the base of GC3, which is what we would expect to see below the slide plane failure (Figures 4.4b and 4.5). Furthermore, biostratigraphy shows the sediment
below the boundary surface in GC3 inside the slide to be no older than 0.75 Ma BP (Table 4.3). The main event is estimated to have either occurred at ~71 ka BP or sometime between 71-750 ka and 5.92-8.43 Ma BP (the base of GC4) during the mid Pleistocene and late Miocene. It is most likely to be the latter (71-750 ka BP) as this boundary surface represents similar characteristics to the retrogressive within slide failures shown by Clarke et al. (2012) (e.g., colour and stiffness) as well as slight differences in grainsize (Figure 4.5). Further investigations into the age and strength of the sediment at the base of GC3 needs to be undertaken in order to constrain the timing of failure for the Middle Fraser Island Middle Slope Slide.

4.5 Conclusions

The main findings from this chapter are:

1) Cores taken on the continental slope within both slides are long (upper slope 565 cm, middle slope 364 cm) and present hemipelagic Recent to upper Pleistocene muds. Cores taken adjacent to both slides are short (upper slope 133 cm, middle slope 43 cm) and terminate in stiff muds of lower Pleistocene and upper Miocene age respectively. Muds of this type are ubiquitously present along the entire EACM on the upper continental slope of the west Tasman Sea in NSW and southern QLD.

2) Present day sediment accumulation rates for the surface sediments (top 16 cm) on the Upper Slope offshore Fraser Island is extremely slow around 0.019 mka⁻¹ (1 m per 50 ka) inside the slide (GC2), and 0.011 mka⁻¹ (1 m per 100 ka) on the adjacent slope (GC1). Reliable sedimentation rates could only be accurately quantified within GC3 (inside the Middle Slope Slide) with material accumulating 0.057 mka⁻¹ (1 m every 18 ka).

3) All four cores showed evidence of sediment unconformities with distinct age gaps across boundary surfaces showing that the continental margin is very active. GC1, GC2, and GC3 were the most obvious where they penetrated through boundary surfaces that showed distinct changes in colour above and below each boundary unit.

4) GC1 (133 cm) on the slope adjacent to the Upper Slope Slide presents a near surface layer of coarse, bioclastic, shelly sand interpreted to be a turbidite deposit. This
turbidite was deposited around 14.6 ka BP pene-contemporaneously with slides dated by Clarke et al. (2012) in northern NSW.

5) Both the upper and middle slope surfaces (present as un-failed portions of the slope) are effectively erosional unconformities with their basal sediments dating around 2-2.5 Ma BP (GC1) and 6-8.5 Ma BP (GC4) respectively. These dates are regionally significant as they provide maximum ages for the upper slope preserved adjacent to and within the Fraser Island Complex, and the middle slope surface preserved on the Wide Bay Plateau.

6) The entire continental slope is undergoing constant erosion and very little sediment is accumulating as a result of either: a) sediments being abraded off by turbidites along the shelf, b) Strong Pleistocene currents, namely the EAC and the Australian Circumpolar Current, are eroding sediment from the slope (e.g., the EAC is driving sand along the shelf and sweeping sediment off down the slope consequently eroding it), or c) the slopes are liquefying and sliding downslope by an earthquake or similar geologic event such as sea level low stand.

7) We have possible events occurring along the Fraser Island Canyon Complex and Wide Bay Plateau at approximately 8.4 ka (GC2), 14.6 ka (GC1) and 71 ka (GC3) BP. The age of the Upper and Middle Slope Slides cannot be specifically determined but have been shown to be relatively young and thought to have occurred sometime after the early Pleistocene.
CHAPTER 5

Sediment Geotechnical Properties and Slope Stability Modeling

5.1 Introduction

Two box-shaped, translational submarine landslides were identified offshore Fraser Island onboard the SS2013-V01 cruise (Hubble 2013). Extensive geomorphological (Chapter 3), sedimentological (Chapter 4), and geotechnical investigations (this chapter) have been undertaken in order to assess the stability of the slope offshore Fraser Island and to help constrain the timing, frequency, and potential triggering mechanisms that initiate slope failure along the entire south-east Australian continental margin (EACM).

The Middle Slope Slide (11 km² in area and 100-150 m thick) is located on the Wide Bay Plateau, and the Upper Slope Slide (25 km² in area and 200-300 m thick) is located at the northern end of the Fraser Canyon Complex (Figure 5.1). Four gravity cores (GC) were collected; one within each slide and a reference core in the slope adjacent to each landslide site. The within slide cores were long, close to the maximum possible 6 m recovery (Middle Slope, GC3 = 3.64 m; Upper Slope, GC2 = 5.65 m), compared to the short gravity cores taken on their adjacent slopes (Middle Slope, GC4 = 0.43 m; Upper Slope, GC1 = 1.33 m). A detailed description on the sedimentology of the four cores is presented in Chapter 4, but in summary, sediments comprised mainly of hemipelagic Recent to upper Pleistocene muds that terminated into stiff muds of lower Pleistocene to upper Miocene age. Three of the four gravity cores penetrated through four boundary surfaces identified by a distinct break in the sediment material through changes in colour and age (Figure 5.2; see Figure 4.8, Chapter 4 for full core length photographs). AMS $^{14}$C isotopic dates and biostratigraphy above and below each boundary surface showed a younger unit overlying an older unit of sediment with distinct differences in age. A reliable
sedimentation rate down core GC3 from 0-239 cm (inside the Middle Slope Slide) was determined with material accumulating at a rate of 0.057 mka\(^{-1}\) (or \(~1\) m every 18 ka). This suggests that the surface sediments within GC3 should be normally consolidated and that significant removal of sediment has not occurred within this upper unit (see section 5.2.3). The geotechnical investigations presented here will confirm this assertion. Sedimentation rates could not be determined for the underlying mud layers below each boundary surface because their contained foraminifera are radiocarbon dead. The age of the reference core sediment indicate that the seafloor slope surfaces are effectively erosional unconformities with their basal sediments dating \(~2-2.5\) Ma BP on the upper slope (GC1) and \(~6-8.5\) Ma BP on the middle slope (GC4) (Figure 5.2b and e). This chapter presents the results from geotechnical tests undertaken on the gravity cores collected inside and adjacent to these two submarine landslide scars in order to: 1) identify changes in sediment properties (e.g. bulk density, void ratio, water content, shear strength), and 2) evaluate shear strength, compressibility, and the stress history of the sediments both between cores and with increasing depth below seafloor. The following objectives are addressed:

1. Determine the composition and stress level of the sediment and evaluate how increasing stress influences sediment behaviour.
2. Compare the geotechnical response of “disturbed” sediment collected from within a submarine landslide scar (cores GC2 and GC3) to “undisturbed” sediment collected from the adjacent slope (cores GC1 and GC4).
3. Determine if boundary surfaces identified within three of the four gravity cores are slide plane surfaces (Figure 5.2).
4. Evaluate the frictional stability of the continental slope and the potential for further slope collapse (i.e. the activation/reactivation of submarine landsliding).

The main geotechnical tests conducted were the determination of Atterberg limits, mini-vane shear tests, oedometer compression tests, and two triaxial tests from core GC3. Slope stability modeling was also investigated to assess possible failure scenarios based on the friction angle (\(\phi\)), cohesion (\(c'\)), and slope angle (\(^\circ\)) of material recovered from the two submarine landslides. The basic concepts of soil
mechanics with key definitions relevant to sediment behaviour and slope stability are first discussed in section 5.2 below.

Figure 5.1. The southern QLD EACM (Australia inset top left) showing the locations of a) the Upper Slope Slide and b) the Middle Slope Slide. Core locations within and adjacent to each slide are shown in plan view below. VE = Vertical exaggeration = horizontal scale/vertical scale.
5.2 Investigating Submarine Slope Failure: Basic Concepts of Soil Mechanics

5.2.1 Soil Composition and Behaviour

In order to accurately access the processes that contribute to causing submarine landslides in any setting, it is critical to understand how marine sediments (or “soils” in the geotechnical sense and used interchangeably throughout chapter 5) behave and their potential to fail. Soils vary in type, grainsize, mineralogy, and organic constituents, which determines overall strength and behaviour. Coarser-grained, granular soils are generally higher in strength and contain silicate minerals and rock fragments. Finer-grained cohesive soils are dominantly composed of clay minerals

Figure 5.2. Close-up images of the four boundary surfaces (dashed lines) with $^{14}$C and biostratigraphy (marked *) ages identified within the gravity cores offshore Fraser Island; a) turbidite within GC1, b) erosional unconformity at the base of GC1, c) possible slide event at the top of GC2, d) possible slide event at the base of GC3 and, e) erosional unconformity at the surface of GC4. Ma = million years before present, ka = thousand years before present, and RCD= radiocarbon dead. See Figure 5.1 for core locations.
such as kaolinite, illite, and montmorillonite (Mitchell and Soga 2005; Lancellotta 2009). Additionally, clays are relatively compressible, drain poorly, and exhibit plastic behaviours. Silts (composed of quartz and feldspar minerals) and sands exhibit dilatancy, are free draining, and have a greater capability to hold water; but these granular materials are prone to liquefaction if subjected to oscillatory loading (Einsele 1989; Weimer et al. 2012).

Soil is often considered to be a three-phase material comprising solids, water, and air (Figure 5.3). The spaces between soil particles (solids) in the soil mechanics context are known as voids or pores.

![Figure 5.3. Soil components (Adapted from Cornforth 2005).](image)

In a marine setting, the void space is usually entirely occupied by water and the material is fully saturated. The volume of voids is also influenced by the size, shape, and mineralogy of the soil, and described in engineering practice by the term void ratio ($e$) which is defined in equation 5.1:

$$ e = \frac{\text{volume of voids}}{\text{volume of solids}} \quad (\text{Eq.5.1}) $$

A plot by Polito and Martin (2001) of the maximum and minimum void ratios versus silt content for Monterey sand mixtures in California is presented in Figure 5.4. Mitchell and Soga (2005) also described this plot for sand and silts generally, stating
that an increase in silt content causes sand to ‘float’ within the silt matrix and generates an increase in void ratio. At low silt contents, the silt particles occupy the void between the larger sand particles and the void ratio is low.

![Graph showing maximum and minimum void ratios with varying sand and silt mixtures](image)

**Figure 5.4.** Maximum and minimum void ratios with varying sand and silt mixtures (from Polito and Martin 2001).

### 5.2.2 Atterberg Limits

The natural water content above which sediment behaves like a liquid and flows is known as the liquid limit (LL). At the opposite end, the water content at which sediment becomes brittle and cannot be moulded is known as the plastic limit (PL). If the water content is between these two limits the sediment will behave as a plastic material. These measures of critical water contents are known as the Atterberg Limits (Powrie 2004) with the difference between the two limits called the plasticity index (PI) (Equation 5.2):

\[
PI = LL - PL
\]

Plasticity describes the unrecoverable deformation sediment can experience without cracking or crumbling. The water contents at which the transitions between the four states occur (liquid to plastic to semi-solid to solid) differ between sediments and the range of plasticity in relation to liquid limit is summarised in Table 5.1 (Craig 2004). Clays and silts are known to react with water, expanding and contracting at
different moisture contents that change the sediments volume and shear strength. Calcareous silt-sized sediments are also known to exhibit abnormally high water contents in comparison to siliclastic sediments. This is thought to be due to the presence of intra-particle water in the hollow structure of nannofossils (Riggins 1992).

Table 5.1. Liquid limit ranges used to define the level of plasticity for a soil (from Craig 2004).

<table>
<thead>
<tr>
<th>Level of Plasticity</th>
<th>Liquid Limit Range (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Low</td>
<td>&lt;35</td>
</tr>
<tr>
<td>Intermediate</td>
<td>35-50</td>
</tr>
<tr>
<td>High</td>
<td>50-70</td>
</tr>
<tr>
<td>Very high</td>
<td>70-90</td>
</tr>
<tr>
<td>Extreme</td>
<td>&gt;90</td>
</tr>
</tbody>
</table>

5.2.3 Consolidation

In this context, the coefficient of consolidation \( C_v \), in square metres per year, is a measure of the rate at which the soil consolidates or settles when subject to an increase in pressure. It is an important parameter that is a useful indicator of the likely behaviour of a particular soil and can be defined using equation 5.3:

\[
C_v = \frac{0.848d^2}{t_{90}} \quad (Eq.5.3)
\]

Where, \( d \) is the maximum drainage path, and \( t_{90} \) is square root time at 90% consolidation. Settlement (also referred to as consolidation) occurs when a soil is compressed (e.g., during burial) and releases its water as excess pore pressure diminishes from high to low values with a simultaneous decrease in volume (Craig 2004). The main factors that influence \( C_v \) are the magnitude of the applied stress or load, and the type of soil. It should also be noted that compression does not usually occur instantaneously in saturated soils. The rate of compression will depend on the permeability of the soil which controls the time required for the excess pore water to drain away (Lee et al. 2007). For example, if the sedimentation rate is high and \( C_v \) is low, then large excess pore pressures are likely to develop within the sediment.
This is because the load on the sediment is increasing faster than the water is able to drain from the compressing void spaces, which leads to an increase in pore water pressure within the soil. This is the case in the Mississippi Delta where slope failures have arisen in delta front muds due to high pore pressures in the soil from rapid sedimentation (Coleman and Prior 1988). When a vertical load is applied, the rate of consolidation can be measured over time using the Taylor’s square root time method (Figure 5.5).

![Figure 5.5. Calculating the coefficient of consolidation using Taylor’s square root time method (from Craig 2004).](image)

Calculating $t_{90}$ involves drawing a straight line (shown as line D) through the curve square root time versus dial gauge reading (e.g., oedometer test) followed by another line (DE) that has an abscissae 1.15 times greater than line D (Craig 2004). The point on the curve where the line DE crosses gives the square root of time at 90% consolidation (Craig 2004; Holtz et al. 2011; see Figure 5.5).
Another important factor influencing soil strength is their stress history, which can be described in three ways: 1) normally consolidated; 2) over consolidated, and 3) under consolidated. *Normally consolidated* soils are those when the current effective stresses ($\sigma'$), which is the stress actively influencing the soil, are the same as the maximum stresses the soil has been subjected to in the past (called the pre-consolidation stress, $\sigma'_{pc}$ or $pc'$). These soils are usually a result of long and steady accumulation rates over-time. *Over-consolidated* soils are when the maximum stresses the soil has been subjected to in the past ($pc'$) are greater than present effective stresses (Head and Epps 2011). These are typical in soils that have undergone a geological change resulting in unloading of the soil such as glacial melt during an ice age, a submarine landslide, creep, or erosive removal of the overlying sediment, for example, by bottom currents (Knappett and Craig 2012). Over-consolidated soils are generally considered to be stronger than normally consolidated soils (once they are re-loaded) and tend to be much stiffer and experience less settlement than normally consolidated soils. Soil can also be described as being *under-consolidated* which is a state that exists when soils have only recently been deposited and are still consolidating under their own weight and such that excess pore pressures have not had time to dissipate (e.g., geologically recent submarine landslides; Holtz et al. 2011).

The pre-consolidation stress ($pc'$), known as the maximum effective vertical stress that a soil has been subjected to in the past (Craig 2004; Holtz et al. 2011), is a useful parameter in geotechnical investigations. $pc'$ cannot be measured directly but can be estimated theoretically using the Casagrande method from an e-log $\sigma'$ curve of over-consolidated soils (Craig 2004; Holtz et al. 2011; see Figure 5.6). The steps for estimating $pc'$ are as follows:

1. Draw back the straight line at BC of the curve.
2. Determine the maximum point of curvature (D) for the recompression part (AB) of the curve and draw a horizontal line.
3. Draw the tangent to the curve through D and bisect the angle between the tangent and the horizontal.
4. Extend a vertical line where the bisector meets line CB. The point of intersection at x is the pre-consolidation stress.

Once the pre-consolidation stress has been determined, the consolidation state of the soil can be evaluated numerically by determining the over-consolidation ratio (OCR) of the soil:

\[
OCR = \frac{\sigma'_{pc}}{\sigma'}
\]  

(Eq.5.4)

Where, \(\sigma'\) is the current effective stress, calculated from the total stress (\(\sigma\)) and pore water pressure (\(u\)) defined in equation 5.5:

\[
\sigma' = \sigma - u
\]  

(Eq.5.5)

In the case of submarine landslides, if the overlying sediment has been removed from the above sample (i.e. a slide has taken place), the OCR should be >1 and the sediment is considered to be over-consolidated. If a landslide did not take place, the sediment above the sample will present continuous sedimentation showing no sign of sediment removal. In this case, the OCR should equal 1 and the sediment would be considered normally consolidated.

---

**Figure 5.6.** Calculating pre-consolidation pressure using the Casagrande method (from Craig 2004).
5.2.4 Assessing the Slope Stability of Submarine Landslides

A variety of methods exist to calculate the stability of a slope and potential slip surfaces within the slope but it must be noted that this form only applies to drained failures where no excess pore pressure is generated during shearing and the water is able to flow out (Thiebes 2012). Figure 5.7 depicts the stress vectors within a slope where a mass \( m \) is subject to acceleration of gravity \( g \), which can be differentiated into a downslope stress component \( \tau \) and a force acting perpendicular to the slope surface \( \sigma \). The distribution of stresses depends on the slope angle \( \beta \) and the downslope force increases with higher slope angles.

![Stress vectors within a slope](image)

Figure 5.7. Stress vectors within a slope (Adapted from Thiebes 2012).

The stability of a slope can be assessed by calculating the Factor of Safety (FoS), which is a modification of the Mohr-Coulomb failure criterion and the ratio of the resisting and driving forces within a slope (Cornforth 2005; Holtz et al. 2011). The FoS defines the factor by which the shear strength of a soil or material load must be reduced in order to bring the mass of the soil into a state of limiting equilibrium (i.e., not moving; Krahn 2004) and is shown in Equation 5.6:

\[
FoS = \frac{\text{shear strength}}{\text{shear stress}} = \frac{S_u}{\tau}
\]  
(Eq.5.6)

Where, \( S_u \) is the shear strength, and \( \tau \) is the shear stress. A slope is stable when the FoS is \( >1 \) and slope movements commence if the FoS is \( \leq 1 \) (Krahn 2004). An example of the application of this method to investigating submarine landslides is given in Hubble et al. (2012), where the program GEOSLOPE/W was used to model the
stability of a failed slope on the southern Queensland (QLD) EACM. The slope’s pre-failure geometry was reconstructed and using the values for known physical properties (e.g., cohesion, friction angle, saturated weight), its FoS was assessed. Results showed the slope to be inherently stable at slope of ~8° with a FoS of 6.7 (FoS>1; Figure 5.8). In order for a slope to fail, some form of triggering mechanism that leads to an increase in the stress or a decrease in the shear strength must occur to actively shift the slope from a state of stability to an unstable form (Thiebes 2012). In this case, the shear strength must be reduced by one eighth in order for the slope to fail (c.f. Hubble et al. 2012; Clarke et al. 2012; Clarke 2014).

![Figure 5.8](image)

*Figure 5.8. Geomechanical modeling of a slope on the southern QLD continental margin using Bishop’s Method determined by GEOSLOPE/W indicating that the slope is inherently very stable (from Hubble et al. 2012).*

It is important to note that unlike many terrestrial landslides which result from erosional steepening due to uplift and incision, submarine mass movements are not usually a consequence of over-steepened slopes (Masson et al. 2006). Many slides are assumed to have been triggered by earthquakes because the slopes they occur on typically have gradients less than 5° and are thought to be stable unless unusually weak sediments are involved (McAdoo et al. 2000; Locat et al. 2014). Indeed, some of the world’s largest submarine slope failures occur on gradients of just 2°, for example, the Cap Blanc and Dakar Slides on the NW African continental margin (Krustel et al. 2012). It is thought that in these cases, as well as many others, high rates of sedimentation can be a controlling factor for failure as this is thought to generate high excess pore water pressures and produce low effective stresses (Umbaub et al. 2012). It has been suggested that this can result when there is prolonged accumulation of sediments over time. If the load (input of sediment) being deposited is too great and the permeability of the materials too low to allow
dewatering, then the trapped pore water develops a pressure equal to that of the lithostatic load. As a consequence, the strength of the soil will be exceeded and failure ensues.

5.3 Methodology

5.3.1 Determination of Atterberg Limits

Atterberg limits are used to measure the critical water contents of fine-grained sediment. Both LL and PL tests were undertaken to determine the upper and lower limits respectively of the range of water content at which the sediment exhibits liquid and plastic behaviour (Craig 2004). From these values the PI was determined, enabling the sediment to be characterised using the Unified Soil Classification System (USCS) according to the ASTM D 2487 standard procedure. Atterberg limits of seven representative samples from the four cores were tested using the Australian Standard (AS) 1289.3.9.1 and AS 1289.3.2.1 standard procedures for LL and PL respectively. Around 10-15 cm of sediment was extracted from the gravity cores for each sample and stored in airtight bags for both LL and PL analysis.

The mini-cone penetration test was used to determine the LL of the core samples. This is based on the depth of penetration into the sediment of a standardised cone of specific mass (80 g) (Craig 2004). In this method the LL is determined from the water content of a sample at 20 mm of cone penetration. A large sub-sample of the sediment was mixed with seawater (to simulate in-situ conditions) to form a homogenous paste and placed in a cylindrical cup making sure all voids were emitted or uniformly distributed in the sample. The cone was dropped onto the sample and the depth of penetration measured five seconds after the release of the cone. The test was repeated to get an average of between three to five values within 0.3 mm of each other and an overall range no more than 1 mm. A subsample of about 10 g was then weighed and oven dried to determine water content (see Section 5.3.2). The entire test procedure was repeated five times using the same sediment sample, increasing the amount of water in the sediment with each repetition. Penetration
ranged from approximately 10-25 mm to encompass a range of water content values. The cone penetration was then plotted against water content with a line of best fit. The LL is defined as the percentage of the water content at a cone penetration of 20 mm (Craig 2004).

The PL of the sediment was determined by continuous rolling of a small sub-sample of the sediment into a thread 3 mm in diameter until the point where the sample would crack or crumble. This involved moulding the sample into the palm of the hand to remove excess moisture and dry the sediment out followed by rolling a small portion of the sample over a glass plate to produce a thread. Once cracks start to appear, the sample was weighed and oven dried to determine the water content (see Section 5.3.2). This test was repeated four times for each sample with the average recorded as the PL.

**5.3.2 Water Content Testing**

Water content (w) readings were taken in the same location as each mini-vane shear test (see section 5.3.3) to minimise disturbance to the core in accordance with AS 1289.2.1.1. A small sample of sediment was weighed, oven dried, and weighed again to calculate the ratio of the mass of water ($M_w$) to the mass of solids ($M_s$) shown in equation 5.7 (Craig 2004):

$$w = \frac{M_w}{M_s} \quad (Eq. 5.7)$$

**5.3.3 Mini-Vane Shear Testing**

A laboratory mini-vane shear apparatus was used in accordance with British Standards (BS) 1377: Part 7: 1990: Clause 3 (Head and Epps 2011) using a vane made up of four blades measuring 12.7 mm wide and 12.7 mm long and using a torsion spring 0.92391 Nmm/per degree of rotation (K; Figure 5.9). The test measured the undrained residual shear strength ($S_{ur}$), remolded shear strength ($S_{ur}$) and sensitivity ($S_s$) of the sediment within each gravity core at regular intervals (top, centre, and base of each 1 m core). Measurements were also taken above and below boundary
surfaces, e.g. the turbidite in GC1. The vane was lowered into the sediment and the torque (rotation) electronically applied at a rate of 6-12° per minute until the sediment failed in shear due to the vane’s rotation (Craig 2004). The vane shear strength of the sediment ($S_u$) was calculated using equation 5.8:

$$S_u = \frac{M}{4.29} \text{ kN/m}^2 \quad (Eq.5.8)$$

Where, $M$ is the applied torque (N mm) and is equal to $C_s \times \theta_f$, where $C_s$ is the calibration factor (N mm/degree) for the torque spring used and $\theta_f$ (degrees) is the relative angular deflection of the ends of the spring at failure (Head and Epps 2011). Typical strength values for undrained clays are provided in Table 5.2.

![Figure 5.9. Photographic image showing mini-vane shear testing on GC2/6A.](image)

Table 5.2. Undrained strength classification (Adapted from Craig 2004, and Head and Epps 2011).

<table>
<thead>
<tr>
<th>Stiffness State</th>
<th>Undrained Shear Strength ($S_u$) (kPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Very Soft</td>
<td>&lt;20</td>
</tr>
<tr>
<td>Soft</td>
<td>20-40</td>
</tr>
<tr>
<td>Firm</td>
<td>40-75</td>
</tr>
<tr>
<td>Stiff</td>
<td>75-150</td>
</tr>
<tr>
<td>Hard</td>
<td>150-300</td>
</tr>
<tr>
<td>Very Hard</td>
<td>&gt;300</td>
</tr>
</tbody>
</table>
The remoulded shear strength was measured by rapidly manually rotating the vane for two revolutions. The sensitivity of the sediment can be calculated using equation 5.9:

\[ S_t = \frac{S_u}{S_{ur}} \]  
\text{(Eq.5.9)}

### 5.3.4 Oedometer Testing

Both low and high stress path oedometer tests were carried out on all cores at various depths to measure the amount and rate (time) by which the sediment will compress one-dimensionally when loaded, swell and consolidate, and settle (Head and Epps 2011; Powrie 2004). Because the high stress path oedometer (maximum load around 6.6 MPa) starts with an initial pressure of around 120 kPa and the samples are very soft, low stress path oedometer tests were also conducted using lighter weights to fill in the consolidation before this time (0-576 kPa). Both devices were front-loading, which involved manually loading and unloading weight increments to create a compression/recompression curve. For the high stress path oedometer, the change in thickness of the sample against time was measured automatically via a computer. The low stress path oedometer was operated manually which requires the user to read and record the gauge height at timed intervals (minutes) at each increment of weight load (i.e. 00:10, 00:20, 00:30, 01:00, 01:30, 02:00, 03:00, 04:00, 06:00, 09:00, 12:00, 15:00, 25:00). Samples for the high and low stress path tests were taken as close to each other as possible from within the core to minimise differences in consolidation and to generate comparable results. For both stress paths, the sediment sample was enclosed in a metal ring measuring 34.3 mm in diameter and 12.3 mm in height, which is placed between two porous stone “end-plates” to allow two-way drainage to occur during the test. The sample was then mounted into the consolidation cell, covered with seawater (to simulate in-situ conditions) to keep the material saturated, and loaded into the unit. Two separate tests for the high stress oedometer were carried out simultaneously using the two available, self-loading oedometer machines and sets of weights (labeled set A and set B; Figure 5.10, Table 5.3). Low stress oedometer tests were
undertaken individually due to the need for manual recording of the height gauge readings at short time intervals (Table 5.4).

The results from the consolidation tests were graphed by plotting void ratio (e) against the corresponding effective stress (kPa) at the equilibrium of each weight load. The compression index (C_c) and recompression index (C_r) of the sediment was then determined from the plotted results using the slope of the normally consolidated compression and recompression lines respectively. Empirical calculations were used to estimate the coefficient of consolidation (C_v) to determine the rate at which the sediments consolidate using the root time method (Equation 5.3; Figure 5.5) and the pre-consolidation stress (pc’) to determine the maximum vertical overburden stress sustained in the past using the Casagrande method (Figure 5.6). The maximum depth the sediment has been buried (z) at a particular point down a sample can be measured from the pc’ using equation 5.10, where γ_{sat} is the saturated unit weight of water, and γ_{water} is the unit weight of water (10.1 kN m^{-3} for sea water):

\[ z = \frac{pc'}{\gamma_{sat} - \gamma_{water}} \]  

*Figure 5.10. Photographic image showing the two high stress path oedometer apparatus’s.*
Table 5.3. High stress path oedometer kPa values for each increment of weight load and unload for oedometer one (set A) and oedometer two (set B).

<table>
<thead>
<tr>
<th>Set A – Oedometer One</th>
<th>Set B – Oedometer Two</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Weight Number</strong></td>
<td><strong>kPa</strong></td>
</tr>
<tr>
<td>0</td>
<td>0.001</td>
</tr>
<tr>
<td>1</td>
<td>119.92</td>
</tr>
<tr>
<td>2</td>
<td>301.25</td>
</tr>
<tr>
<td>3</td>
<td>539.11</td>
</tr>
<tr>
<td>4</td>
<td>1023.51</td>
</tr>
<tr>
<td>5</td>
<td>1751.38</td>
</tr>
<tr>
<td>6</td>
<td>2721.56</td>
</tr>
<tr>
<td>7</td>
<td>4175.18</td>
</tr>
<tr>
<td>8</td>
<td>6575.69</td>
</tr>
<tr>
<td>Unload 8</td>
<td>4175.18</td>
</tr>
<tr>
<td>Unload 7-6</td>
<td>1751.38</td>
</tr>
<tr>
<td>Unload 5-3</td>
<td>301.25</td>
</tr>
<tr>
<td>Unload 2</td>
<td>119.92</td>
</tr>
</tbody>
</table>

Table 5.4. Low stress path oedometer kPa values for each increment of weight load and unload.

<table>
<thead>
<tr>
<th><strong>Weight Number</strong></th>
<th><strong>kPa</strong></th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0.001</td>
</tr>
<tr>
<td>1</td>
<td>18</td>
</tr>
<tr>
<td>2</td>
<td>36</td>
</tr>
<tr>
<td>3</td>
<td>72</td>
</tr>
<tr>
<td>4</td>
<td>144</td>
</tr>
<tr>
<td>5</td>
<td>288</td>
</tr>
<tr>
<td>6</td>
<td>576</td>
</tr>
<tr>
<td>Unload 6-5</td>
<td>144</td>
</tr>
<tr>
<td>Unload 4-2</td>
<td>18</td>
</tr>
</tbody>
</table>

5.3.5 Triaxial Testing

Two small core sections 20 cm long from GC3 (within the Middle Slope Slide) were left un-split for undrained-consolidated triaxial testing. Core sections were taken at the top (GC3/5B/24-44cm) and bottom (GC3/1F/344-364cm) of GC3 to compare the behaviour of the sediment with depth and consolidation (Figure 4.8, Chapter 4). During core splitting, a boundary surface was found within GC3/1F/344-364cm at
357 cm (Figure 5.2d). Testing could still be conducted just above this surface as only a small thickness of material was recovered from below the boundary surface (~1-2 cm). Triaxial data for the study was limited to just one core (GC3) due to the number of samples required for the other sedimentological and geotechnical tests, and the limited amount of sediment available (11.05 m of core in total, GC1-GC4).

A cylindrical specimen 12.5 cm in length and 5.4 cm in diameter was taken from each core and placed on the central pedestal sealed inside a rubber membrane with porous discs and O-rings above and below the sample to allow for drainage to occur. A watertight Perspex cylinder encased the body of the cell (Figure 5.11). Once fitted, the samples were consolidated to around 15 kPa (in-situ conditions) and the backpressure raised to reach 200 kPa prior to shearing. A 1-D stress state was estimated by assuming the 1-D coefficient of consolidation ($K_0$) to be 0.4 and stresses were increased to a mean effective stress of 100 kPa. The rate of loading was determined by the coefficient of consolidation, $C_v$, to follow the 1-D consolidation (see Craig 2004) and to keep the stress rate low enough to prevent excess pore pressures exceeding 30 kPa. The samples were then subjected to shear by increasing the axial stresses and gradually bringing the specimens to failure. The test is fully computer controlled and the changes in effective stress, pore pressure, deviator load, axial displacement, and volume were measured throughout the test. Internal friction angle ($\phi'$) and undrained strength ($S_u$) were also quantified to calculate a pre-failure strength of the sediment. The water content of the specimen offcuts was taken before the test and the water content of the entire specimen were recorded after to check the consistency of void ratio calculations (see Section 5.3.2). Specific gravity ($G_s$) tests in accordance with AS 1289.3.5.2 were undertaken for GC3/5B/22-42cm and GC3/1F/344-364cm for the post-calculation of the triaxial tests. The methodology and results for the determination of $G_s$ is presented in Appendix 1.
5.3.6 Slope Stability Modeling

Geotechnical modeling using GEOSLOPE/W software (http://www.geoslope.com/products/slopecs.aspx) was undertaken to assess how the physical properties of the sediment such as effective unit weight (γ), effective cohesion (c’), and friction angle (ϕ) influenced the slope stability of both the submarine landslides examined in this study. As the sediment within the gravity cores represent the overburden muds post-slide (sediment drape), and were deposited after the main landslide events, it is probable that the physical properties of these sediments are not representative of the stiff slope muds that failed. Instead, the input parameters determined by Yu (2010) to assess mass failure of sediments along the EACM between Noosa Heads in southern QLD and Cape Byron in northern NSW were used (Table 5.5). These values by Yu (2010) were determined from an average of six dredge samples on the mid-slopes and represents the stiffer material that comprises the slope at the Upper and Middle Slope Slide locations (e.g. the sediment at the base of GC1 and within GC4, see Figure 5.2b and e).
The geometry of the slope was calculated by bathymetric cross-sectional profiles of the adjacent un-failed slopes obtained using *Fledermaus* (v7.3.3b) visualisation software (http://www.qps.nl). Data was analysed in GEOSLOPE/W and factor of safety (FoS) limits quantified. FoS is the ratio of the driving forces to the resisting forces within a slope (stable slope, FoS>1, unstable slope, FoS<1; see Section 5.2.4). The output value that showed the best fit relative to the failed geometry of the slope was used.

Both the Upper and Middle Slope Slides were modeled using a similar approach to Clarke et al. (2012) and Yu (2010). The slides were first analysed to determine the static FoS of the slope at pre-failure using input parameters from Yu (2010) (Table 5.5). The output values will indicate the stability of both slopes at the time of failure. Back analysis was then undertaken to determine what values of $c'$ and $\phi$ apparently apply during slope failure. This is achieved by incrementally reducing $c'$ and $\phi$ by a factor of 2 until failure is induced. The range of scenarios is as follows:

1. Fixed peak $c'$ at 22 kPa, decreasing $\phi$ by a factor of 2 starting at 30° (i.e. 30°, 15°, 7.5°, 3.75°).
2. Fixed residual $c'$ at 0 kPa, decreasing $\phi$ by a factor of 2 starting at 30° (i.e. 30°, 15°, 7.5°, 3.75°).
3. Fixed peak $\phi$ at 30°, decreasing $c'$ by a factor of 2 starting at 22° (i.e. 22 kPa, 11 kPa, 5.5 kPa, 2.75 kPa, 1.375 kPa).

**Table 5.5.** Input parameters taken from mid-slope dredge sediments from Yu (2010) used for slope stability modeling with GEO-SLOPE/W software.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Units</th>
<th>Input Parameter from Yu 2010</th>
<th>Scenario Input Range</th>
</tr>
</thead>
<tbody>
<tr>
<td>Unit Weight, $\gamma$</td>
<td>kN/m$^3$</td>
<td>10</td>
<td>0-10</td>
</tr>
<tr>
<td>Apparent Cohesion, $c'$</td>
<td>kPa</td>
<td>22</td>
<td>0-22</td>
</tr>
<tr>
<td>Friction Angle, $\phi$</td>
<td>°</td>
<td>30</td>
<td>3.75-30</td>
</tr>
</tbody>
</table>
5.4 Results

5.4.1 Atterberg Limits and Water Content
The Atterberg limits and PI are summarised in Figure 5.12 and Table 5.6, where the ‘U’ line represents the upper limit for natural sediment, and the ‘A’ line separates the clay-like materials from the silty-materials (Holtz et al. 2011). The sediment was classified as high plasticity silts (MH; Figure 5.12) ranging between high (GC1, GC2, and GC3) to extremely high (GC4) plasticity (Table 5.1). PI ranged between 16-34% and decreased with depth down-core. The sediments were highly compressible (LL>50%) with water contents ranging between 44-93% (average = 71%), resulting in the sediments being very brittle (Figure 5.13). When compressed, the water is pushed out of the voids creating a volume change and ultimately disturbance to the sediment (Kim et al. 2013). The water content in all cores except GC4 was higher than their LL indicating some degree of sensitivity (Figure 5.14; Mitchell and Soga 2005). In this case, GC4 was considered an outlier as it is a stiff, old mud, only penetrating close to the surface (43 cm) and has a small sample size (n=2). The water content of the sediment in GC1 decreased significantly below the turbidite layer (19-42 cm) from 86% above to 56% below (Figure 5.14a). The water contents for GC2, GC3 and GC4 are all similar, 73% ± 9% and fall within the typical natural range for marine sediments (Figure 5.13).

It should be noted that water content was calculated by the AS 1289.2.1.1 and did not allow for the natural marine salt. When the marine soil is dried, the water evaporates but the dissolved salt remains with the soil solids. As a result, soil physical properties such as void ratio, water content and specific gravity are slightly over or under estimated (Noorany 1984).
Figure 5.12. Plasticity chart for cores GC1 (green), GC2 (purple), GC3 (blue), and GC4 (red). Light coloured circles represent the top of the core, and dark coloured squares represent the base of the core. See Table 5.6 for LL and PL values and Table 4.5 (Chapter 4) for the USCS.
Table 5.6. Atterberg properties for the four gravity cores.

<table>
<thead>
<tr>
<th>Core</th>
<th>Section</th>
<th>Depth (cm)</th>
<th>Soil Classification</th>
<th>Liquid Limit (LL) (%)</th>
<th>Plastic Limit (PL) (%)</th>
<th>Plasticity Index (PI) (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>GC1</td>
<td>2A</td>
<td>0-16</td>
<td>MH</td>
<td>67.8</td>
<td>42.5</td>
<td>25.3</td>
</tr>
<tr>
<td></td>
<td>1B</td>
<td>67-82</td>
<td>MH</td>
<td>55.2</td>
<td>39.2</td>
<td>16.0</td>
</tr>
<tr>
<td>GC2</td>
<td>6A</td>
<td>35-50</td>
<td>MH</td>
<td>68.0</td>
<td>44.1</td>
<td>23.9</td>
</tr>
<tr>
<td></td>
<td>1F</td>
<td>521-536</td>
<td>MH</td>
<td>58.5</td>
<td>41.1</td>
<td>17.4</td>
</tr>
<tr>
<td>GC3</td>
<td>6A</td>
<td>5-20</td>
<td>MH</td>
<td>73.4</td>
<td>40.9</td>
<td>32.5</td>
</tr>
<tr>
<td></td>
<td>2E</td>
<td>313-328</td>
<td>MH</td>
<td>63.1</td>
<td>41.6</td>
<td>21.6</td>
</tr>
<tr>
<td>GC4</td>
<td>1A</td>
<td>9-25</td>
<td>MH</td>
<td>106.4</td>
<td>72.4</td>
<td>34.1</td>
</tr>
</tbody>
</table>

Figure 5.13. Water contents with depth for GC1 (green), GC2 (purple), GC3 (blue) and GC4 (red).

5.4.2 Mini-Vane Shear Test Results

Undrained mini-vane shear tests were conducted on all four cores with depth. Result averages are presented in Table 5.7 with the entire data set presented in Appendix 2. Laboratory vane shear testing is generally only suitable for fine-grained sediments (Richards 1988; Craig 2004; Fratta et al. 2007; Head and Epps 2011). Vane shear testing within the sandy turbidite layer in GC1 were either not conducted or if they were, the sediment failed immediately because the sand was coarse grained and cohesionless (indicated by dotted lines in Figures 5.15a and 5.16). Testing at the base
Figure 5.14. Liquid (square) and plastic (triangle) limits for a) GC1, b) GC2, c) GC3 and d) GC4 displayed alongside their water contents (lines). See Table 5.6 for Atterberg limit results. N.B. the different scales on the y-axis.
of GC1 below the boundary surface into the hard silts was also not conducted, as the sediment had been greatly disturbed upon retrieval.

**Table 5.7.** Average mini-vane shear results for each core. Note, GC1 excludes turbidite and GC3 was tested on board the RV *Southern Surveyor* (SS2013-V01) where the average time to failure was not recorded.

<table>
<thead>
<tr>
<th>Core</th>
<th>Average Peak Undrained Strength, S_u, kPa</th>
<th>Average Remoulded Undrained Strength, S_ur, kPa</th>
<th>Min. Peak Strength, kPa</th>
<th>Max. Peak Strength, kPa</th>
<th>Average Undrained Strength Ratio</th>
<th>Average Angular Strain at failure (°)</th>
<th>Average Time to failure, (min)</th>
</tr>
</thead>
<tbody>
<tr>
<td>GC1</td>
<td>7.82</td>
<td>2.11</td>
<td>3.34</td>
<td>18.09</td>
<td>4.35</td>
<td>36</td>
<td>8</td>
</tr>
<tr>
<td>GC2</td>
<td>11.77</td>
<td>2.98</td>
<td>5.06</td>
<td>19.38</td>
<td>1.46</td>
<td>55</td>
<td>8</td>
</tr>
<tr>
<td>GC3</td>
<td>5.24</td>
<td>1.81</td>
<td>3.12</td>
<td>8.83</td>
<td>1.10</td>
<td>24</td>
<td>-</td>
</tr>
<tr>
<td>GC4</td>
<td>18.57</td>
<td>3.55</td>
<td>7.32</td>
<td>29.83</td>
<td>21.26</td>
<td>86</td>
<td>11</td>
</tr>
</tbody>
</table>

The sediment in all cores displayed soft (GC4; 7-30 kPa) to very soft (GC1, GC2, and GC3; 3-19 kPa) strength values (Table 5.2, 5.7 and Figure 5.15). Sediment from GC2 within the Upper Slope Slide appears to be slightly stronger than sediment from GC3 within the Middle Slope Slide averaging 12 kPa and 5 kPa respectively (Figure 5.16a), possibly due to differences in sediment composition. GC2 contains more clay (~15%) than GC3 (~7%), and is dominantly comprised of silt (55%) and sand (29%), while GC3 presents a mixture of sands (45%) and silts (47%; Figures 4.4-4.6, Chapter 4). Clays are more cohesive (hence stronger) than silts, which tend to lack particle cohesion (Shephard et al. 1987; Leroueil and Hight 2003; Grabowski et al. 2011). In general, the vane shear tests show no convincing variations with depth, between slides, or between slide sediment and adjacent slope sediment.

High differences in strength above and below interfaces can represent compaction and a significant removal of sediment (Clarke et al. 2012; L’Heureux et al. 2012).
Figure 5.15. Mini-vane shear results showing the undrained peak (dark colours) and remoulded/residual (light colours) strengths for a) GC1, b) GC2, c) GC3 and d) GC4. N.B. The different scales on both the x and y-axes.
Vane shear tests were conducted above and below two identified boundary surfaces, the turbidite in GC1, and the boundary surface in GC2 to see if a significant amount of sediment had been removed (Figure 5.2a and c). Sediment above the turbidite in GC1 had a very low strength of ~5 kPa and high water content of ~86%. Immediately below this feature the sediment strength increased to 18 kPa and water content decreased to ~60% (Figures 5.14a and 5.15a). Despite these distinct property changes above and below the turbidite, the strength below the boundary surface appears to be relatively similar to those recorded for GC2, the within slide core on the upper slope (average 12 kPa). This suggests that the sediment that had been removed between the two interfaces in GC1 at the time of the turbidite event was minimal (Figure 5.16a). Sediment strength was seen to subsequently drop with depth to the base of this mud unit to ~6 kPa (water content 56%) as the clay content reduces to ~13%. Likewise, no significant difference in strength was observed across the boundary surface in GC2 (5 vs. 6 kPa above and below the boundary at 19 cm) indicating that it is unlikely that this surface represents the main Upper Slope Slide failure. Instead, this surface is most likely to represent a smaller failure or removal of sediment that occurred subsequent to the main event and a significant thickness of overburden has not been removed. Strengths increased thereafter possibly owing to the slight increase in clay content (7 to 16%) below this boundary, and remained fairly consistent down the rest of the core fluctuating between 10-20 kPa (Figure 5.15b; Figure 4.5, Chapter 4).

Clays are known to increase cohesion yet GC4 contains little to no clay (2%) and has a much higher strength (~30 kPa) than the other cores (Figures 5.15d and 5.16a). Two possibilities are thought to describe the higher strengths determined for GC4. Firstly, the higher sediment strength is consistent with the removal of overlying sediment (e.g. slide) and therefore greater compaction of the remaining sediment due to past burial (Barazza et al. 1990). Secondly, biological activity such as bioturbation or bio-cementation is likely where both of these processes are known to create structure within the sediment that can increase strength (Shephard et al 1987; Mitchell and Soga 2005). However, given that the core is short due to the underlying harder sediment, the sample size is therefore small and only two vane shear strength values
could be determined for GC4 (Figure 5.15d). The small amount of core penetration at the GC4 site is however consistent with its greater strength and it is considered that this form of sampling has disturbed and weakened this GC4 material.

Figure 5.16. Mini-vane shear results showing, a) undrained shear strength, and b) sensitivity with depth for GC1 (green), GC2 (purple), GC3 (blue) and GC4 (red).
Sensitivities ranged between 1.5-13.6, which is slightly to highly sensitive (Mitchell and Soga 2005), but values averaged around 4 with a few outliers (Figure 5.16b). Sensitivity is slightly higher in GC2 (2.7-13.6) than in GC3 (1.5-4.6) possibly due to differences in constituents, with GC2 having a greater difference in re-moulded strength relative to undrained strength (Figures 5.15b and c).  

### 5.4.3 Oedometer Test Results

The results for both the high and low-stress path oedometer tests are presented in Table 5.8 and Figures 5.17 and 5.18. Wet unit weights from the high-stress path oedometer were high and ranged between 17.73 and 19.31 kN/m³, making them relatively compacted (Fratta et al. 2007; Table 5.8). Current effective stresses (σ’) increased with depth and ranged between 2-46 kPa inside the Upper Slope Slide and 5-26 kPa inside the Middle Slope Slide. Reasonably high compressibility was shown with compression index values (Cc) calculated from the slope of their normal compression lines ranging from 0.19-1.20 (Table 5.8, Figure 5.17a). These values suggest that the pre-consolidation stresses of the sediments are less than 200 kPa indicating a maximum burial depth of ~25 m. Recompression values (Cr) ranged from 0.03 to 0.19. Void ratios were much higher than typical sand-silt mixtures with initial void ratios between 1.4 and 3.85 (Figure 5.4, Table 5.8).

Based on the headwall height of the landslide scars from the bathymetry, the two slides showed to have a maximum range of 200-300 m, and 100-150 m of sediment shed from the Upper and Middle Slope Slides respectively (see Table 3.2, Chapter 3). Pre-consolidation pressures (pc’) would had to have reached around 1000 kPa and the undrained strengths around 200 kPa to be consistent with burial depths over 100 m in order to be representative of the base of the landslide scars. This is clearly not the case, where pc’ stress values averaged ~29 kPa for all samples and showed no significant relationship with depth (Table 5.8, Figure 5.18). Burial depths were less than 6 m, with the sediment shown to be slightly over-consolidated at the surface (OCR>1) but nearing to around normally consolidated with depth (OCR ~1; Table 5.8). However, based on the sedimentation rate of around 0.057 mka⁻¹ (or 1 m every
18 ka) determined for GC3, this core should be normally consolidated at the surface with the pc' = σ'. This is however not the case. A similar finding is also found in the triaxial tests where both specimens analysed within the Middle Slope Slide (GC3) appeared to be normally consolidated based on their position relative to the normal compression line but yield pc' stresses showed the surface sediments to be over-consolidated (see section 5.4.4; Table 5.9 and Figure 5.20a). This high OCR at the surface is thought to be a result of a local surface effect such as bioturbation or possibly bio-cementation. Nevertheless, both the oedometer sample GC3/2E/310.75cm and the triaxial sample GC3/1F/344-364cm near the boundary surface at the base of core GC3, showed to normally consolidated (OCR = 1) with burial depths (3-3.57 m) fairly consistent with present day sedimentation rates (0.057 mka⁻¹). This suggests that the sediments sampled within the Middle Slope Slide scar has not been buried very deeply (if at all), and is young infill that has been deposited within the scar since the main landsliding event.

From the high-stress path oedometer, GC4 showed a high initial void ratio of 3.85 and an extremely high C_v value of 1.2 (Table 5.8; Figure 5.17a). A high void ratio is typical in sediment that experiences high LL, which is the case with GC4, which displayed a LL of 106% (Holtz et al. 2011; Table 5.6). The voids in GC4 were an order of ~4 times higher than the maximum expected void ratio for a silt (60%), sand (38%) mixture with these properties (void ratio ~1.0). This could be explained through the presence of a high percentage of microfossils in particular foraminifera, which are highly porous by nature, resulting in high initial void-ratios (Lee et al. 2011). However, investigations into the microstructure and mineral composition, e.g. via XRD (x-ray diffraction) and SEM (scanning electron microscope) of the gravity core sediments were beyond the resources available to this study; and it is not possible to ascertain the specific reason why the void ratio is high.

The rate of consolidation was determined by calculating the coefficient of consolidation (C_v) at a vertical stress of ~500 kPa. C_v values ranged between 3-45 m² yr⁻¹, which are low for silty materials (Head and Epps 2011; Table 5.8). The C_v of GC4 estimated to be between 3.1-8.7 m² yr⁻¹, typical in high plasticity clays (Head and
Epps 2011). However, grainsize analyses showed GC4 to contain very little to no clay content (<2%); nevertheless it is a highly plastic material (PI = 34%; Figures 4.4 and 4.5 in Chapter 4, Figure 5.18). Again the reason for this is unclear but thought to be a result of the sediment undergoing some form of disturbance due to sediment reworking and inter-particle bonding due to microbial activity (Lee et al. 2011).

5.4.3.1 Errors and Uncertainties

The low-stress path oedometer tests accord reasonably well with the high-stress path oedometer tests aside from the few usual discrepancies that are expected in natural materials (Figure 5.18). Low-stress path $C_c$ values were slightly lower (0.19-0.67) than the high-stress path $C_c$ values (0.39-1.2). Errors were affected by sample handling and small sample size, which can lead to higher sample disturbance and disruption of the testing apparatus during the testing procedure. Of particular interest are the low-stress path samples GC2/3D/287.75cm and GC2/1F/543.75cm whose normal compression curves show a slight kink in them as a result of human error upon loading of a new weight (Figure 5.18b). It should also be noted that because samples were taken from a core, tests could not be duplicated at the same depth within the core. Samples were taken as close to each other as possible but this generally involves slight changes in sediment composition and water contents. Small oedometer samples around 10 cm$^3$ were used for both the high and low-stress path apparatuses and must be considered when interpreting the results. In general, the high-stress oedometer produces more reliable data due to better computational capabilities and a secure loading frame.

The results from the low-stress path oedometer are somewhat questionable and the high-stress path oedometer results did not show a maximum point of curvature as the first weight applied was too heavy (equivalent to a stress of ~120 kPa, i.e. $p_c'$ was below 120 kPa). A reliable $p_c'$ stress was therefore unable to be determined accurately using the Casagrande method and should be used as a guide only. Smaller weight increments should be considered in further investigations to obtain a more reliable result.
Table 5.8. High and low stress path oedometer test results for all gravity cores with depth: bsf= below seafloor, $X_I$= Initial values, $X_F$= Final values, $C_v=$ coefficient of consolidation, $\sigma'_{pc}=$ preconsolidation stress, OCR= overconsolidation ratio.

<table>
<thead>
<tr>
<th>Core #</th>
<th>Depth bsf, cm</th>
<th>Initial Void Ratio, $e_i$</th>
<th>Final Void Ratio, $e_f$</th>
<th>Compression Index, $C_c$</th>
<th>Recompression Index, $C_r$</th>
<th>Initial Water Content, $W_i$, %</th>
<th>Final Water Content, $W_f$, %</th>
<th>$C_v$, m$^2$/yr at 500kPa</th>
<th>$\sigma'_{pc}$, kPa</th>
<th>Dry Density, $\gamma'$, kg/m$^3$</th>
<th>Effective Unit Weight, $\gamma$, kN/m$^3$</th>
<th>Current Effective Stress, $\sigma'$, kPa</th>
<th>OCR</th>
</tr>
</thead>
<tbody>
<tr>
<td>GC1/1B</td>
<td>50.5</td>
<td>2.02</td>
<td>0.93</td>
<td>0.51</td>
<td>0.09</td>
<td>62</td>
<td>35</td>
<td>6.4</td>
<td>-</td>
<td>1365.2</td>
<td>-</td>
<td>18.11</td>
<td>8.01</td>
</tr>
<tr>
<td>GC1/1B</td>
<td>107.25</td>
<td>2.21</td>
<td>0.86</td>
<td>0.39</td>
<td>0.07</td>
<td>55</td>
<td>32</td>
<td>24.9</td>
<td>-</td>
<td>1422.4</td>
<td>-</td>
<td>18.46</td>
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</tr>
<tr>
<td>GC2/6A</td>
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<td>72</td>
<td>38</td>
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<td>75</td>
<td>39</td>
<td>16.0</td>
<td>-</td>
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<td>-</td>
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<td>7.63</td>
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<td>66</td>
<td>33</td>
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<td>-</td>
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<td>-</td>
<td>18.45</td>
<td>8.35</td>
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<td>0.10</td>
<td>81</td>
<td>33</td>
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<td>-</td>
<td>1401.8</td>
<td>-</td>
<td>18.33</td>
<td>8.23</td>
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<td>-</td>
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<td>9.21</td>
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<td>70</td>
<td>37</td>
<td>44.7</td>
<td>-</td>
<td>1332.8</td>
<td>-</td>
<td>17.91</td>
<td>7.81</td>
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<td>36</td>
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<td>-</td>
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<td>8.16</td>
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<td>45</td>
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<td>60</td>
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<td>1.56</td>
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<td>74</td>
<td>59</td>
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<td>17.73</td>
<td>7.63</td>
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<td>16.9</td>
<td>6.8</td>
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</tr>
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<td>70</td>
<td>51</td>
<td>7.5</td>
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<td>1176.8</td>
<td>3.0</td>
<td>17.39</td>
<td>7.29</td>
</tr>
<tr>
<td>GC4/1A</td>
<td>28.25</td>
<td>2.50</td>
<td>1.97</td>
<td>0.67</td>
<td>0.19</td>
<td>78%</td>
<td>75%</td>
<td>8.7</td>
<td>56</td>
<td>1117.3</td>
<td>6.2</td>
<td>19.13</td>
<td>9.03</td>
</tr>
<tr>
<td>GC4/1A</td>
<td>28.25</td>
<td>2.50</td>
<td>1.97</td>
<td>0.67</td>
<td>0.19</td>
<td>78%</td>
<td>75%</td>
<td>8.7</td>
<td>56</td>
<td>1117.3</td>
<td>6.2</td>
<td>19.13</td>
<td>9.03</td>
</tr>
</tbody>
</table>

5-33
Figure 5.17. Void ratio (e) vs. effective vertical stress (kPa) relationships from a) high stress-path oedometer and b) low stress path oedometer tests. N.B. the logarithmic and different scales of both x-axes.
Figure 5.18. Void ratio (e) vs. effective vertical stress (kPa) relationships for all cores (a-d) for high stress-path oedometer (dashed lines) and low stress path oedometer (solid lines) tests. N.B. the logarithmic scales of both x-axes.
5.4.4 Triaxial Test Results

Two triaxial tests were carried out on core GC3 at the top (GC3/5B/22-42cm) and the bottom (GC3/1F/344-364cm) of the core. Both tests were run to fail at the same stress level (100 kPa). Both samples are hemipelagic sandy silts (MH) but varied in grainsize with the top of the core (GC3/5B) presenting less clay (5%) and silt (39%) and coarser fine-grained sands (56%) when compared with the bottom of the core (GC3/1F), which consisted of more clay (14%) and silt (48%), and less sand (37%; Figure 5.19). The specific gravity of the sediments is 2.72 and 2.66 for the top and base of core GC3 respectively and is described in further detail in Appendix 1. Based on the nearest Atterberg limit tests presented in Table 5.6, GC3/5B had a LL and PL of around 73 and 33 respectively, while GC3/1F had a LL and PL of 63 and 22 respectively. Significantly different initial water contents were also evident between the two samples with 94% water content in GC3/5B and 68% in GC3/1F (Table 5.9). This is most likely due to grading of the sediment where GC3/5B presents more void space allowing for additional water as a result of its higher grainsize (Figure 5.19). Depth could also play a minor factor where GC3/1F has experienced greater compression and the water has been pushed out of the voids.

A summary of the results from the two triaxial tests is provided in Table 5.9, and suggests that failure is more likely to occur along the surface than with depth. Of the two samples tested, GC3/5B showed indications of instability under undrained conditions through decreasing shear stress upon failure, higher compressibility and axial strain, as well as displaying contractive behaviour (Figure 5.20).

Figure 5.20a shows the relationship between void ratio and the mean effective stress for the two samples. At the surface, GC3/5B started off with a higher initial void ratio and has a higher compressibility than GC3/1F, as would be expected due to differences in water content and grainsize. Higher clay content is present in GC3/1F (14% as opposed to 5% in GC3/5B), which lowers the void ratio. Both samples were normally consolidated based on their position relative to the normal compression line with $C_c$ values of 0.49 in GC3/5B and 0.16 in GC3/1F. However, $P_c'$ stresses for the top and bottom of GC3 were calculated to 6 and 20 kPa, giving burial depths
of 1.58 and 3.57 m respectively. This shows the surface sediments to be apparently over consolidated but the deeper sediments are fairly consistent with that of present day normally consolidated sediments as discussed in section 5.4.3.

Figure 5.19. Cumulative grainsize volume against particle diameter plotted on a log scale for the two triaxial samples at the top (GC3/5B/22-42cm; black) and base (GC3/1F/344-364cm; grey) of GC3.

Figure 5.20c shows the stress path for the deviator stress \( q \) against mean effective stress \( p' \). The effective shearing paths move left towards an ultimate frictional failure line with a slight initial increase in deviator stress occurring once undrained shearing commences before decreasing again. Samples reached an ultimate frictional resistance \( \phi' \) of 37° in GC2/5B and 39° GC3/1F, corresponding to a \( q/p' \) ratio (M) of 1.5 and 1.6 respectively (Table 5.9). The final stress in GC3/5B is lower than its initial stress, compared to GC3/1F where the final and initial stresses are equal or decrease only slightly (Figure 5.20c). For both samples, the triaxial compression tests show contractive behaviour due to a reduction in the mean effective stress and increase in pore pressure. For contractive sediments, the sediment is more likely to mobilise into a flow than one that is denser (dilative sediment), with the increase in pore pressures reducing sediment strength (Lee et al. 2007).
Table 5.9. Summary of triaxial test data.

<table>
<thead>
<tr>
<th></th>
<th>GC3/5B/22-42 cm</th>
<th>GC3/1F/344-364 cm</th>
</tr>
</thead>
<tbody>
<tr>
<td>Water Content, w, %</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Initial</td>
<td>94.21</td>
<td>68.11</td>
</tr>
<tr>
<td>Final</td>
<td>68.63</td>
<td>57.53</td>
</tr>
<tr>
<td>Axial Effective Stress at Start of Shear, σ'v, kPa</td>
<td>156.1</td>
<td>158.4</td>
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<tr>
<td>Undrained Strength, S_u, kPa</td>
<td>51.2</td>
<td>52.5</td>
</tr>
<tr>
<td>Normalised Undrained Stress, (s_u/σ'v)</td>
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<td>0.33</td>
</tr>
<tr>
<td>Critical State Line (slope), M</td>
<td>1.5</td>
<td>1.6</td>
</tr>
<tr>
<td>Ultimate Frictional Resistance, Φ, (°)</td>
<td>37</td>
<td>39</td>
</tr>
<tr>
<td>Specific Gravity, G_s</td>
<td>2.72</td>
<td>2.66</td>
</tr>
<tr>
<td>Unit Weight (Wet), kN/m³</td>
<td>13.9</td>
<td>15.7</td>
</tr>
<tr>
<td>Recompression Index, C_c</td>
<td>0.49</td>
<td>0.16</td>
</tr>
<tr>
<td>Compression Index, C_r</td>
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<td>0.002</td>
</tr>
<tr>
<td>C_v (initial), mm²/yr</td>
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<td>-</td>
</tr>
<tr>
<td>Current Effective Stress, σ', kPa</td>
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<td>19.82</td>
</tr>
<tr>
<td>Preconsolidation Stress, pc', kPa</td>
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<td>20</td>
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<tr>
<td>Burial Depth, m</td>
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<tr>
<td>Over-consolidation Ratio, OCR</td>
<td>4.93</td>
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</table>
Figure 5.20. Triaxial test results for GC3/5B/22-42cm (black; top of core) and GC3/1F/344-364cm (grey; base of core): a) void ratio (e) vs. effective stress (kPa) relationships with the x-axis plotted on a log scale; b) effective radial stress (kPa) vs. effective vertical stress (kPa); c) effective stress paths showing deviator stress (kPa) vs. mean effective stress (kPa). Critical State Line= M; d) deviator stress (kPa) vs. axial strain.
Deviator stress versus axial strain plots showed GC3/5B to have a higher axial (horizontal) strain with the sediments increasing in shear stress up to 102 kPa at about 0.2 axial strain, which is the maximum stress of the sample. The shear stress then decreased to about 80 kPa at 0.3 axial strain (Figure 5.20d). Deviator stress versus axial strain plots showed GC3/1F to have a lower axial strain with the sediments increasing in shear stress up to 105 kPa at about 0.09 axial strain, which is the maximum stress of the sample. The shear stress then stayed relatively constant with 105 kPa at 0.12 axial strain (Figure 5.20d).

5.4.5 Slope Stability Modeling

Static modeling of the slope immediately surrounding the two landslides presented in this study showed both the upper slope and middle slopes to be inherently stable (terminology follows Hubble 2010) under present day conditions (Figure 5.21, Table 5.10). Analyses predicted the upper slope to have a FoS >4 using parameters from measured values (c’= 22, φ= 30°; Table 5.5) with a slope angle of 7.6° (Figure 5.21a; see Table 3.2, in Chapter 3). The middle slope predicted a higher FoS value of >7 using the same parameters with a slope angle of 5.2° (Figure 5.21b; see Table 3.2, in Chapter 3).

Back-analysis modeling used to determine the parameters needed to facilitate slope failure is summarised in Table 5.10. Results showed that for failure to occur, the φ would need to drop as low as 3.75° on the upper slope with a peak c’ (i.e. 22 kPa), or 7.5° with a residual c’ (i.e. 0 kPa). The slope appears to be effectively stable with a peak φ (i.e. 30°) and is not affected by a decrease in c’.

For failure to occur on the middle slope, the φ would need to drop as low as 3.75° with a residual c’ (i.e. 0 kPa). The slope appears to be effectively stable both with a peak φ (i.e. 30°) decreasing c’ or a peak c’ (i.e. 22 kPa) decreasing φ.
Figure 5.21. Factor of Safety (FoS) values determined by GEOSLOPE/W for a) the Upper Slope Slide, and b) the Middle Slope Slide \((c' = 22, \phi = 30^\circ)\). N.B. the vertical exaggeration of the images = horizontal scale/vertical scale.
Table 5.10. Back analysis outputs from GEOSLOPE/W showing the Factor of Safety (FoS) for the initial failure of the Upper and Middle Slope Slides, firstly using the results from the slope sediments analysed by Yu (2010)*, then with decreasing friction angle and cohesion shown in Table 5.5. Critical FoS <1 are underlined (Input scenarios taken from Clarke et al. 2012).

<table>
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<tr>
<th>Location</th>
<th>Scenario</th>
<th>Cohesion, $c'$ (kPa)</th>
<th>Friction Angle, $\phi$ (°)</th>
<th>FoS</th>
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<td>3.75</td>
<td>0.611</td>
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<td></td>
<td>Peak friction angle, Decreasing cohesion</td>
<td>11</td>
<td>30</td>
<td>6.201</td>
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<td>2.75</td>
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<td>1.375</td>
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5.5 Synthesis of Sediment Geotechnical Properties and Slope Stability Modeling

This chapter describes the geotechnical properties of four gravity cores taken within and adjacent to the Middle and Upper Slope Slides located offshore Fraser Island. The longer within slide gravity cores (Middle Slope Slide, GC3= 3.65 m; Upper Slope Slide, GC2= 5.65 m) were compared with the shorter gravity cores taken on their adjacent slopes (Middle Slope, GC4= 0.43 m; Upper Slope, GC1= 1.33 m) and tested for differences in sediment composition and stress history, as well as the frictional stability of the two slopes. The sediment offshore Fraser Island is generally comprised of homogenous sandy (30-55%), silts (47-58%) with low clay contents (4-15%; Figure 4.4, in Chapter 4). A reliable average sedimentation rate during Pleistocene to Recent times of around 0.057 mka\(^{-1}\) (or 1 m every 18 ka) for the within slide
sediments on the southern QLD continental margin, determined from GC3 in Chapter 4, suggests normally consolidated sediments, with their adjacent slopes effectively presenting erosional unconformities. Geotechnical analysis along the EACM is a new approach and has only recently been reported in Glenn et al. (2008), Clarke et al. (2012), Hubble et al. (2012) and Clarke (2014). Aside from a few differences in responses, the sediments along the entire EACM are strikingly similar.

5.5.1 The Effect of Microfossils and Bioturbation on Physical and Geotechnical Properties
The presence of microfossils such as diatoms, radiolarians, and foraminifera is known to have a profound effect on the behaviour of sediment. As a result, unusual geotechnical properties arise within the sediments such as high porosity, plasticity, water content, unusual compressibility’s ($C_v$), high void ratio, and high friction angles (Einsele 1989; Tanaka and Locat 1999; Mitchell and Soga 2005; Lee et al. 2011). The sediments offshore Fraser Island were relatively uniform across all cores, distinguished by unusually high plasticity silts, low clay content, high void ratios, and brittle behaviour, similar to Clarke (2014) on the northern NSW and southern QLD slope. Overall, the sediments appear to be relatively soft with high liquid limits (55-106%; Table 5.6) and low strengths (3-30 kPa; Table 5.7), which can be found in surface sediments rich in microfossil and/or organic matter (Tanaka and Locat 1999; Lee et al. 2011; Rajesekaran 2006). GC4, taken on the adjacent slope of the Middle Slope Slide, showed to be stiffer, with strength values of ~30 kPa, and displayed a large compressibility ($C_v$ = 0.67-1.2; Table 5.8) despite having little to no clay content (~2%). This high compressibility is thought to reflect changes in inter-particle structure as a result of microfossil crushing and particle rearrangement. Furthermore, diatoms can determine particle size distribution as they approach silt-size (Rajasekaran 2006) hence there is a need for SEM imaging and XRD to determine the microstructure and mineral composition of the slope sediments. However, due to time constraints SEM and XRD were beyond the scope of this study but should be considered in further investigations.
All cores were apparently over-consolidated at the surface (top 100 cm) with the OCR decreasing with depth to around normally consolidated, and this was consistently seen in oedometer and triaxial testing (Tables 5.8 and 5.9). However, for cores GC3 and GC4 taken on the Wide Bay Plateau, no geological evidence from erosion was found to suggest the sediment should be anything but normally consolidated. The sediment in GC3 is entirely homogenous down core to 3.57 m, confirmed through its well-correlated $^{14}$C age-depth plot shown in Figure 4.7 (in Chapter 4) where age increases linearly with depth. Triaxial tests also showed the base of GC3 just above the boundary surface to be normally consolidated, with a burial depth the same as present day (~3.57 m). It is thought that the sediments are in fact normally consolidated but a local surface effect such as bioturbation has caused such a high apparent OCR at the surface. Animal burrowing (bioturbation), inter-particle bonding, creep, or secondary compression (ageing) are all shown to be factors for slight over-consolidation (Lee and Edwards 1986; Mitchell and Soga 2005; Lee et al. 2007) and is believed to be the case with the EACM sediments (Clarke et al. 2014).

High OCR values can also suggest a loss of sediment, e.g. erosion of part of the sediment load that previously existed (Barazza et al. 1990; Lee et al. 2007; O'Regan et al. 2010). Furthermore, short gravity cores that present evidence of slow sedimentation as well as having a large difference in the age of the deposits can indicate the presence of bioturbation. This can lead to an increase in sediment structural strength (cohesion) due to increased inter-particle bonding from cementation of the micro-organisms and a resultant high OCR (Hamilton 1971). GC4 is a short core (43 cm long) located on the middle slope of the Wide Bay Plateau and displays unusually high strength, compressibility, and LL for sediment that has very little to no clay content (<2%). Oedometer tests showed the sediment to be highly over-consolidated which resulted in abnormally high values of shear strength for its depth (25-35 cm; Figures 5.16a and 5.18d, Table 5.8; Wilson et al. 2004). Despite no visual sign of an unconformity, biostratigraphy dating has shown a significant amount of sediment to be missing (>1 Ma in just 43 cm of sediment; Figure 5.2e), which has been eroded and wiped clean from the surface. This makes the high OCR in GC4 somewhat more convincing as the core is short, has high strengths, and
presents extremely slow rates of sedimentation consistent with sediment re-working, inter-particle bonding and sediment removal. However, oedometer tests for GC4 showed high compressibility (Cc) and a high void ratio, which does not support a high OCR (Figure 5.17). Geotechnical testing of the middle slope sediments therefore needs more consideration.

5.5.2 Comparison of Within Slide Slope Sediments vs. Adjacent Reference Slope Material

Small differences in water content and shear strength were seen within cores from the two landslide scars. The Upper Slope Slide displayed slightly lower water content and higher shear strength than the Middle Slope Slide (Figures 5.14 and 5.16a). However these differences were only subtle and not large enough to draw anything conclusive from the results. Likewise, no significant differences were found between sediments on the slopes adjacent to each landslide. The adjacent slide cores (GC1 and GC4) were short compared to the within slide cores (GC2 and GC3); and in the case of GC1, it presented two boundary surfaces within the core deeming it highly disturbed and difficult to use as comparative adjacent slope core material. More samples with a higher core retrieval success rate are required to be collected on the adjacent slopes of the Upper and Middle Slope Slides to compare differences in strength and sediment composition.

5.5.3 Boundary Surfaces

Four distinct sediment boundaries were identified within three of the four gravity cores (GC1, GC2 and GC3; Figure 5.2). All are clearly distinguishable visually through changes in colour and sedimentology, where a younger unit overlies an older unit of sediment shown by $^{14}$C and biostratigraphy dating. Geotechnical tests were conducted where possible above and below these surfaces in an attempt to further ascertain whether or not they can be identified as slide plane surfaces through differences in strength, water content, compression, and depth of burial. In all cases, these boundaries were interpreted to represent mass movements down the east Australian continental slope in various forms.
5.5.3.1 Turbidite within GC1

Geotechnical tests above and below the turbidite in GC1 identified an obvious change in strength (increase from 5 to 18 kPa) and water content (decrease from 86% to 60%) within the two mud contacts (Figures 5.13a and 5.15a). Despite the obvious visual aspects showing a discrete unit of coarse-grained sand within two mud units dated at ~15 ka BP and radiocarbon dead (conventional age >48 ka BP) above and below the turbidite respectively (Figure 5.2a), the higher strength (and therefore higher compaction) of the sediment immediately below the turbidite deposit (18 kPa) suggests that sediment has been removed either prior to the deposition of the turbidite or by the processes that created the turbidite (Puga-Bernabeu et al. 2014). However, given that the shear strength below the turbidite (18 kPa) is nearly the same as strength values from the within slide core, GC2 (average 12 kPa), the idea of stress relating to sediment removal is insufficient (Figure 5.16a). A greater cohesion due to higher clay content (from 6-13%; Grabowski et al. 2011) below this feature is thought to more likely be the reason for the differences in strength and water content, suggesting that removal of sediment between the two interfaces is likely but minimal.

5.5.3.2 Boundary Surface within GC2

Compression testing (via oedometer tests) was undertaken below the boundary surface in GC2 and showed the material to be slightly over-consolidated (Table 5.8; Figure 5.17). However, significant removal of the overlying (missing) sediment has not occurred as the sediment has been buried no deeper than 25 m of the seafloor, well short of the Upper Slope Slide’s headwall height of 200-300 m depicted from the bathymetry (Table 3.2, Chapter 3). This can be further constrained given that: 1) the sediment below the boundary is older than the overlying unit (8.4 ka vs. 41.8 ka; Figure 5.2c) likening to around 2 m of sediment removal; and 2) the differences in strength between the two units is not evident (5 kPa vs. 6 kPa; Figure 5.15b). While there is an obvious change in colour and a significant age gap, the geotechnical tests were unable to identify a deep-seated failure plane near the surface of GC2. If this was the case, tests would have shown obvious differences in strength, over consolidation, and burial depths >100 m (i.e. pre-consolidation stresses >1000 kPa). The upper boundary surface at 19 cm from the seafloor...
is therefore most likely to be a small retrogressive failure of the infill that has been deposited after the main Upper Slope Slide event as a result of liquefaction (section 5.5.5). The Upper Slope Slide is thought to have occurred beyond the reach of the gravity corer >5.65 m below the seafloor.

5.5.3.3 Missing Investigations

Because the gravity corer within GC1 terminated into a boundary surface of hard silty sands, only 10 cm of this material was exposed limiting the extent of testing (Figure 5.2b). The structural composition of these sediments was also compromised, where the sediment was fragmented upon retrieval onboard the SS2013-V01. Strength and compression tests were therefore abandoned inside this feature. A similar situation occurred in GC3 where the corer terminated into a boundary surface suspected to be a slide plane failure with only 7 cm of the older unit exposed beneath (Figure 5.2d). However, the fact that in both cases the gravity corers (GC1 and GC3) stopped as a result of harder material below is evidence itself of a change in sediment composition and strength. The gravity corers are designed to penetrate up to 6 m into the seafloor, leaving 4.67 m and 2.36 m of core barrel still available for GC1 and GC3 to penetrate through to respectively. Should geotechnical investigations such as vane shear and oedometer tests have been able to be undertaken above and below these boundary features, a sounder conclusion could have been made into the nature of these boundaries; i.e., their burial depth, strength differences, and subsequently confirmation of a submarine landslide or retrogressive failure.

5.5.4 Submarine Landslide Slope Stability Offshore Fraser Island

Contrary to the bathymetry which identifies an abundance of mass wasting features and incipient outcrops offshore Fraser Island (see Chapter 3), slope stability modeling showed both the Upper and Middle Slope Slides to be inherently stable under present day conditions with FoS values >4 (Figure 5.21; Table 5.10; Hubble 2010). A slight difference in stability was seen between slopes with the Upper Slope Slide displaying a slightly lower FoS value than the Middle Slope Slide (FoS >4 vs. FoS >7). The difference in slope angle (Upper Slope canyon wall = 7.6°;
Middle Slope plateau = 5.2°) is considered to be the primary factor in this model as the same parameters were used between the two slopes. A similar finding was discovered by Ai et al. (2014) whereby the slope stability of two small landslides (named the Northern Twin Slides) on the slopes of the Gela Basin in the central Mediterranean were analysed. Slope angles were shown to have a larger influence on the FoS than the depth of the failure plane (shown by the headwall height). Ai et al. (2014) showed the FoS to decrease with increasing slope angle possibly due to sediment accumulation during sea-level low stand, or bottom currents that lead to net erosion and undercutting the toe of the slope. These processes are also thought to be key triggers along the EACM and appear to be present offshore Fraser Island (Clarke et al. 2012; Hubble et al. 2012; see section 4.4.1, Chapter 4). Back analysis modeling of both slides further illiterates the inherent stability of these slopes with friction angles needing to drop as low as 7.5° with a cohesion of zero in order for failure to occur (Table 5.10). This is well below the measured strength (i.e. φ 30°, c’ 22; Yu 2010) of the underlying sediments, and is highly unrealistic given the slopes gradient and the physical properties of the sediment. Slope stability models have previously been undertaken on the EACM within a slide just south of the Barwon Canyon on the middle slopes (slope angle ~8°; Figure 5.8; Hubble et al. 2012), within the Coolangatta 1 and Cudgen Slides on the Nerang Plateau (slope angle <3°), and within the Byron Slide on the upper slopes offshore Byron Bay (slope angle 3-7°; Figure 2.7, in Chapter 2; Clarke et al. 2012). Like the Upper and Middle Slope Slides, these slopes all showed to be inherently stable with FoS >6-14, suggesting that an external trigger such as an earthquake or intensive bottom-water currents must be the primary cause in generating slope failure along the entire EACM.

5.5.5 Liquefaction Induced Sliding
Liquefaction is a term used to describe sediment that can behave like a liquid, subsequently losing strength and stiffness, and in the context of submarine landslides, slide downslope. This is a result of excess pore pressures that are unable to escape fast enough due to short, sharp ground movements (e.g. earthquakes) in loose, cohesionless sediment (Mulder and Cochonat 1996; Andrews and Martin 2000; Seed et al. 2001; Wright and Rathje 2003; Sultan et al. 2004;
Lee et al. 2007). Liquefaction-induced sliding is a type of process in which earthquakes can occur (as opposed to accelerated-induced sliding; Wright and Rathje 2003), and is thought to be responsible for the failure of many of the slides along the southern QLD continental margin and possibly further south in northern NSW. There is often much confusion over the liquefaction potential of silty sediments, with silts classified between sand and clay, but often labeled as ‘fines’ that also includes clay (Andrews and Martin 2000; Seed et al. 2001). Clays however, tend to exhibit a higher plasticity than silts and sands (Andrews and Martin 2000), are cohesive sediments, and under earthquake loading, would show signs of ‘cyclic softening,’ whereas sands are cohesionless sediments and would show signs of ‘liquefaction’ (Boulanger and Idriss 2006). Like sands, silts are relatively cohesionless and would drain more easily than clay due to having a larger pore spaces.

There is sufficient evidence within the literature that shows that silty sediments can be susceptible to liquefaction if clay contents are less than 10% (grainsize <2 µm; Andrews and Martin 2000; Seed et al. 2001; Weimer et al. 2012). Weimer et al. (2012) had a slightly higher range showing material with low clay content (<20%) to be less stable under cyclic (e.g. earthquakes) loading than under static (e.g. sedimentation) loading with an example being in the Nankai Trough in Japan. Furthermore, oscillations/shakes via an earthquake lasting >1 minute are likely to cause liquefaction (Andrews and Martin 2000; Weimer et al. 2012). Einsele (1989) also states that a high liquefaction potential can arise when the water content is in excess of, or close to LL, which is the case for all cores except GC4 (Figure 5.14). The Middle and Upper Slope Slides are both stable under static conditions but with the high water content and low clay content in both slides (Middle Slope Slide, GC3, ~7% clay; Upper Slope Slide, GC2, ~15% clay) and with an external trigger such as an earthquake, the chance of slope failure by liquefaction is high. It should also be noted that liquefaction is generally confined to the upper surface layers of the seafloor where water contents are high, causing a decrease in sediment strength and the sediment to swell (Steedman and Sharp 2001). The surface boundary in GC2 (19 cm from the seafloor) within the Upper Slope Slide was most likely a result of liquefaction-induced sliding. This is based on its high water content (86%), low clay content (~9%), and a loss
of ~2 m of sediment from the slope, all of which are indicative of a flow. Surface failure due to liquefaction can also be shown in the triaxial tests, where slope failures along the surface (<1 m) is more vulnerable than at depth (>300 cm). The sediment tested near the surface inside the Middle Slope Slide (GC3/5B) presented a near saturated sample (w= 94%) and was highly compressible (brittle) with the final stress lower that the initial stress making it sensitive to collapse (Table 5.7; Figure 5.20). The sediment tested at depth (GC3/1F) had a lower water content (w= 69%) and low void ratio, with the final stress equal to the initial stress (Table 5.7; Figure 5.20). Both samples showed contractive behaviour, which is known to mobilise sediments into a liquefied flow rather than a denser slump or slide (Lee et al. 2007). Further investigation on the effect of the continental slopes offshore Fraser Island in relation to cyclic and static earthquake loading is warranted.

5.6 Conclusions

The geotechnical properties of the sediment collected from the upper and middle slopes offshore Fraser Island have been analysed, interpreted, and discussed to improve our understanding on the behaviour of the sediment along the EACM, and the implications of sediment behaviour in relation to slope stability. The significant findings from this chapter include:

1) Unusual properties are seen in the sediments both within and adjacent to the submarine landslides particularly at the surface, and are suspected to be a result of the presence of microfossils and bioturbation. The sediments display high void ratios, water content, plasticity, and are highly compressible. This is indicative of sediment reworking, inter-particle bonding, and microfossil crushing that has resulted in an apparent over-consolidation of the surface sediments that have led to bias in the geotechnical properties of the sediment. Scanning electron microscope imaging (SEM) and x-ray diffraction (XRD) are needed to further our understanding on the microstructure and mineral composition of the continental slope sediments.

2) The sediments are normally consolidated >1 m of the seafloor within both slide scars (GC2 and GC3), and have burial depths consistent with present day sedimentation.
Asides from a small retrogressive failure within GC2, the main sedimentary units within the two landslides are thought to be young infill that have been deposited since the main landsliding events which have occurred at depth beyond the reach of the gravity corers.

3) Significant differences in physical properties (i.e., strength, plasticity, and water content) are not evident between the two submarine landslides and on their adjacent slopes.

4) Slope stability modeling shows both the upper and middle slopes to be inherently stable (FoS >4) under present day conditions. An external trigger such as an earthquake or strong bottom water currents is the most likely causal mechanism that induced the major submarine mass failures of the Upper and Middle Slope Slides. This inherent stability appears to be widespread along the entire EACM.

5) The brittle nature of the surface sediments within the submarine landslide scars are shown to be susceptible to small retrogressive failures as a result of liquefaction induced by earthquakes. For example, the slide plane boundary surface found in GC2 within the Upper Slope Slide.
CHAPTER 6

Overall Synthesis and Thesis Conclusions

6.1 Chapter Outline

This study has been undertaken to enhance our knowledge and understanding of the triggering mechanisms and factors that contribute to submarine landsliding on the eastern Australian seaboard of southern Queensland (QLD). Detailed site investigations during the SS2013/01 voyage has provided geomorphological, sedimentological, and geotechnical data that has been interpreted in the context of previous work. This thesis has presented an investigation into submarine landsliding by first providing the background context of submarine landslides globally in Chapter 1, outlining their distribution, reoccurrence, the types of landslides, and triggering mechanisms involved; followed by previous studies of submarine landslides along the east Australian continental margin (EACM) in Chapter 2. The new research data are presented in Chapters 3 to 5. Chapter 3 describes and depicts the bathymetry of the southeast QLD EACM and identifies a range of previously undiscovered features including marginal plateaus, linear rills, ridges and gullies, canyon systems, as well as slides and slumps. Four gravity cores were collected from within and adjacent to two submarine landslides identified on the upper and middle slopes of the continental slope near Fraser Island. Chapters 4 and 5 examine the nature of these sediments and the probable causes of failure of the two submarine landslides from which these samples were taken, through the use of sedimentological and geotechnical investigations of the material in the gravity cores. Six specific sedimentological and geotechnical objectives for the gravity cores were set for this study and have been achieved. Section 6.2 below briefly reiterates these objectives and their respective findings. Section 6.3 presents a conceptual model that synthesises and integrates these findings (Figure 6.1), and identifies the processes that have played a major role in the geologic evolution of the EACM offshore Fraser Island in southern QLD. This conceptual model is the culmination of this thesis. Finally, a number of areas for further investigations that would build on this work and improve our understanding of submarine landslides in this study area are suggested in in section 6.4.
6.2 Thesis Overview: Research Objectives and Conclusions

This thesis has contributed to the wider study of submarine landsliding along east Australia’s continental slope since slope failures were first discovered by Jenkins and Keene (1992), providing a better understanding of the age, size, and extent of mass wasting in this region. Three explorations on RV Southern Surveyor (SS) have been undertaken with works pertaining to this study including the SS2006-V10 voyage studied by Glenn et al. (2008), as well as the SS2008-V12 voyage studied by Boyd et al. (2010), Clarke et al. (2012; 2014), Hubble et al. (2012) and Clarke (2014). This section briefly discusses the achievements of the main objectives for this thesis given in section 2.2, Chapter 2 from the most recent SS2013-V01 voyage:

**Objective One:** “To determine the physical and geotechnical properties of sediment taken from the four gravity cores collected.”

The first main objective of this thesis has been achieved and the physical and geotechnical properties of the study area’s sediments are presented in detail (Chapters 4 and 5). The sediments are bioturbated, homogenous, Holocene, Pleistocene, Pliocene, and Miocene hemipelagic muds. They are comprised of siliclastic sandy muds, which also contain an abundance of microfossils including skeletal, pelagic foraminifers, and nannofossils. These muddy sediments were mostly sandy (30-55%), silts (47-58%) with generally low clay content (4-15%). Three of the four cores penetrated through boundary surfaces that are identified by distinct, sharply defined boundary surfaces that separate sediments of different composition, colour, and age. Radiocarbon (AMS \(^{14}\)C) and biostratigraphic dating above and below each boundary surface showed a younger unit overlying an older unit of sediment.

The sediments in all cores present unusual geotechnical properties. They are high plasticity silts (MH) with high liquid limits (55-106%), void ratios (1.4 and 3.85), and low strengths (3-30 kPa) that are highly compressible. Triaxial compression tests of post-failure sediments indicate that the recent sediment drapes that have accumulated within the slide scars are very brittle and susceptible to retrogressive failure (Lee et al. 2007). All cores were
apparently over-consolidated at the surface, but the surficial sediments of core GC3 on the Wide Bay Plateau showed no obvious geological evidence of erosion and removal of overlying material, which means that this material should be normally consolidated. It is thought that sediment re-working, inter-particle bonding or bio-cementation is responsible for the presence of these unusual properties.

Objective Two: “To compare the morphology, sediment, and geotechnical properties of the box slide on the upper slope with the box slide on the middle slope of the continental margin and their adjacent slopes.”

The second main objective of this thesis was dealt with in Chapters 3-5, in which the submarine landslide on the upper slope was compared with the submarine landslide on the middle slope, as well as their adjacent slope sediments. Both of these features are box-shaped, translational slide scars from which rectangular slabs of material have been shed.

The Upper Slope Slide is situated at a water depth of approximately 750 m at the northern end of the Fraser Canyon Complex. The head of this slide has apparently detached from a structural surface comprised of a Miocene reef complex located beneath the continental shelf edge. This slide is estimated to be 25 km² in area and an average of 200-300 m thick.

The Middle Slope Slide is situated in 1500 m of water at the southern end of the Fraser Canyon Complex on the Wide Bay Plateau. It is estimated to be 12 km² in area and ~100-150 m thick. Cores taken within both slides were relatively long (upper slope, GC2 = 5.65 m, middle slope, GC3 = 3.64 m) and were dominantly comprised of Pleistocene to Recent hemipelagic muds. Cores taken adjacent to both slides were short (upper slope, GC1 = 1.33m, middle slope, GC4 = 0.43m) and terminated in stiff muds of upper Pliocene to lower Pleistocene (GC1), and upper Miocene to lower Pliocene age (GC4). This unique pattern shows that the sediment is being accumulated and protected inside the slide hollows but removed on the exposed adjacent slopes, and it is most likely that the sediment is being removed by abrasion. Accumulation is either extremely slow or non-existent. It is suggested that the southward flow of the East Australian Current (EAC) has been concentrated on the upper and middle slope during the Pleistocene’s many glacial low-stands. Additionally, a 1.33 m core on the slope adjacent to the Upper Slope Slide (GC1) presented a near surface layer of well-sorted, coarse, bioclastic, shelly sand interpreted to be a grain flow or turbidite
sand. This turbiditic feature along with the large number of linear rills within several amphitheater failures evident in the bathymetry (Chapter 3), suggests that the Fraser Canyon Complex is a highly energetic and active system during the recent geologic past (Pleistocene), and has experienced top-down incision and failure. The Upper Slope Slide is larger and steeper than the Middle Slope Slide with its more sharply defined morphology, and the absence of rills suggests that the slab has been removed relatively recently and probably during the last 500 ka. In contrast, the smaller Middle Slope Slide is situated on a marginal plateau (Wide Bay Plateau) and presents smoother more subdued morphology and is suspected to be older.

Slope stability modeling using standard geotechnical methods has shown both slopes to be comprised of relatively strong and inherently stable materials. This suggests that an external trigger and unusual conditions are responsible for failure. It is not the inclination of the slope or the frictional properties of the sediments that leads to failure. An increase in the effects of oceanic currents at various times during the Pleistocene is suggested be a major contributing factor that has led to destabilising the EACM by causing widespread and probably ongoing erosion. There are no significant differences in the geotechnical properties of the material present in the two slides or on their adjacent slopes to suggest a difference in stability between the two slopes.

**Objective Three:** “To determine a reliable average sedimentation rate for this section of the margin.”

The determination of a reliable rate for accumulation of sediment on the Fraser Island section of the EACM is important as it enables comparisons to be made to other sites on the margin, and provides data with which the effects of current activity and other sedimentary processes can be evaluated. A reliable sedimentation rate could only be determined for core GC3 inside the Middle Slope Slide on the Wide Bay Plateau with material accumulating \( \sim 0.057 \text{ mka}^{-1} \) or 1 m every 18 ka. This rate gives us an average estimate of sediment accumulating in a protected area on the Middle Slope. It was not possible to calculate sedimentation rates for core GC4 on the slope adjacent to the Middle Slope Slide, as there is no recent sediment accumulated there. Instead, the exposure of upper Miocene sediment
at the surface (40-41.5 cm from top) indicates that the smooth slope exposed at this site is an erosional unconformity surface of significant antiquity. Several hiatus surfaces within cores GC1 and GC2 presented clear ages gaps of >30 ka (GC1) and 33 ka (GC2) based on AMS $^{14}$C dating, making the determination of the rate of sedimentation difficult. Sedimentation rates are extremely slow $\sim 0.011$ m ka$^{-1}$ (1 m per 100 ka) in core GC1, and $\sim 0.019$ m ka$^{-1}$ (1 m per 50 ka) for core GC2 inside the Upper Slope Slide. The presence of these hiatus surfaces just below the seafloor at both of these two sites indicates that sediment was removed by scour and/or ‘turbidite-related’ abrasion from the continental slope. These results are inconsistent with pene-contemporaneous long-term sediment accumulation, and indicate that erosion of the slope is on-going and the slope is probably shedding sediment quasi-continuously.

**Objective Four:** “To obtain a detailed $^{14}$C and/or biostratigraphic age record of the gravity cores in order to investigate the age of the box slides and to determine whether or not their occurrence can be related to a specific geologic event such as a change in sea level or major global environmental event.”

The fourth research objective to obtain a detailed $^{14}$C age and event record of the gravity cores was achieved, but additional biostratigraphy dating of the basal sediments was required to determine the age of the basal sediments in the core as these were beyond the range of radiocarbon methods. Based on the newly calculated $^{14}$C age records within the gravity cores, three possible sediment removal events (slides or scour events) along the Fraser Island Canyon Complex and the Wide Bay Plateau were uncovered. These events occurred at 8.4 ka BP for GC2, 14.6 ka BP for GC1, and approximately 71 ka BP for GC3. It was not possible to determine an age for the Upper and Middle Slope Slide events because the cores did not penetrate to their main slide planes. Nevertheless, these features are suspected to be relatively young with the Upper Slope Slide probably older than 0.45 Ma BP in the lower Pleistocene, and the Middle Slope Slide is suspected to be a post-Pliocene feature.
The biostratigraphic ages determined for the basal material also demonstrates that the seafloor surface of both slopes are effectively erosional unconformities and the maximum age at which these slopes formed can be determined. The basal, stiff sediments within GC1 (~1.27 m) on the upper slope were dated at ~2-2.5 Ma BP, and this material was scoured and then buried 0.45 Ma BP. Sediments within GC4 (~0.41 m) on the middle slope dated ~6-8.5 Ma BP. This indicates that the smooth upper slope morphology is at most mid-Pleistocene, while the middle slope is a post-Pliocene feature. It is thought that a series of geological events from the Pliocene-Pleistocene Period has caused significant changes in current intensity both relating to the southward EAC and the northward Antarctic Circumpolar Current (ACC) that has led to either cessation of sediment, or constant erosion re-sculpting of the slope geometry by deposition (see section 6.4).

**Objective Five:** “To compare the morphology, sediment, and geotechnical properties of the slope around Fraser Island with existing studies such as Clarke et al. (2012) and Hubble et al. (2012) further south, to be able to better determine the timing and frequency of the slides and the potential triggers that initiate slope failure along the entire south eastern Australian continental margin (EACM).”

The composition and texture of the sediments found that comprise the four Fraser Island cores is very similar to the sediments recovered from other sites on the EACM. These sediment characteristics are ubiquitously present along the entire EACM both in southern, central and northern NSW, as well as in southern QLD. These materials are hemipelagic, sandy, muds (Hubble and Jenkins 1984a and b; Jenkins and Keene 1992; Troedson and Davies 2001; Glenn et al. 2008; Clarke et al. 2012; Hubble et al. 2012; Clarke 2014). The one distinguishing sediment characteristic between the northern and southern end of the east Australian margin is the presence of turbidite sand in the north (GC1) (this study; Hubble et al. *in press*). The presence of this turbidite sand, as well as others from the Wide Bay Canyon (Pers. Comm., T. Hubble, 20 February 2015) indicates that this part of the EACM appears to be undergoing very active erosion with the southeast QLD margin experiencing top-down abrasion and incision that is responsible for generating the morphology of the continental margin, including its large, extensively riled submarine canyons. Submarine landslides are a
common process along the entire EACM. Previous work and this study has demonstrated slides tending to be more common in northern NSW, while riled systems being the dominant feature north of the margin in southeast QLD (Boyd et al. 2008).

The turbiditic sand identified within GC1 contains bioclastic sand (33 ka BP) but this material was probably deposited on the continental slope at around 15 ka BP. This event is the fourth report of an EACM mass movement that occurred during the glacial maximum. Clarke et al. (2012) and Clarke (2014) has identified three slide plane boundaries with AMS $^{14}$C ages of 15.8, 20.1, and 20.7 ka BP for submarine landslides in northern NSW. This suggests that these events are in some way, related to the glacial sea level low stand that occurred between 20 ka and 14 ka BP.

Sediment accumulation rates of ~0.011-0.057 mka$^{-1}$ offshore Fraser Island measured in this study were slightly lower but consistent with measured rates elsewhere along the EACM. Packham (1983), suggested rates in southern NSW to range between 0.05-0.16 mka$^{-1}$ during Pleistocene to Recent times, and 0.03-0.05 mka$^{-1}$ for Miocene to Pleistocene sediment, while Clarke (2014) calculated Pleistocene to Recent sedimentation rates between 0.02-0.12 mka$^{-1}$ for northern NSW. The sediments offshore Fraser Island are relatively uniform across all cores and are distinguished by unusually high plasticity silts, low clay content, high void ratios, and brittle behaviour, which are similar to Clarke’s (2014) finding for the northern NSW and southern QLD slope. Like the Upper and Middle Slope Slides, these slopes further south are inherently stable with a Factor of Safety (FoS) >6-14, suggesting that an external trigger such as an earthquake must be the primary cause in generating slope failures on this section of the EACM.

**Objective Six:** “To investigate the potential for future landslides in the context of their ability to generate a tsunami.”

Based on the findings of the geomorphological, sedimentological and geotechnical tests reported in this study and elsewhere, it can be demonstrated that the EACM is an active, erosive margin with numerous small to large landslides that had the potential to cause a significant tsunami at the time of their failure. Should a similar landslide occur today, the
The presence of the large population living along the QLD coastline is at a real risk of experiencing the devastating effects of a tsunami, including damage to infrastructure and possible loss of human life. Fortunately, the large landslides evident along the continental slope offshore Fraser Island are separated from the mainland by Fraser Island, which would take direct impact of a potential surge. However, tsunami modeling was undertaken by Clarke (2014) on a number of submarine landslides along the entire EACM including the Upper and Middle Slope Slides. Clarke (2014) showed that with wave velocities of 20 ms$^{-1}$, failure of the two slides could have produced flow depths at the coastline of 7.9 and 5.6 m, inundation distances of around 69 and 68 m, and run-up heights of 7.4 and 5 m from the Upper and Middle Slope Slides respectively. This shows that significant wave heights are capable of being generated and could still propagate onto the surrounding Australian coastline where people live, particularly to the south towards Noosa Heads, Brisbane River, and the Gold Coast. There is a pressing need for further investigation of potential failure sites along the entire EACM (such as those mentioned in section 3.3.6, Chapter 3). Further tsunami modeling and disaster and risk management programs should be undertaken such as tsunami resistant infrastructure, planting and restoration of dense, rough, vegetation, and installation of beach sirens and evacuation plans. However, given the close proximity of the area to the coastline (~30-80 km), little warning for an evacuation can be given.

### 6.3 Major Findings and Key Processes

A conceptual model is presented in Figure 6.1 below which links together key processes that have contributed to the morphologic development and on-going erosion of the continental margin offshore Fraser Island. Figure 6.1 shows the continental margin offshore Fraser Island to be a highly active system with erosion of the slope occurring both top-down and bottom-up. The oceanic currents are thought to have influenced both processes with the southward direct EAC hugging the shelf and travelling along a narrow passageway at the northern end of Fraser Island. Surface flows mobilises the terrestrial sands and transports sediment downslope (Harris et al. 1996b; Bostock et al. 2006; Boyd et al. 2008). The northward flowing, bottom water of the ACC travels near the abyssal plain and has probably removed sediments from the lower slope (c.f. Mata et al. 1998; Barker and Thomas 2004; Keene et al. 2008; Hubble et al. 2012). The upper slope sands utilise the canyon systems...
scouring the slope creating a series of linear rills that is evident along the entire Fraser Island slope. Three probable processes are suggested to explain why the southern QLD slope is experiencing erosion and retreat:

1. The upper continental slope appears to be abraded by turbidites and grain flows like the feature present in core GC1 on the upper slope (Hubble 2013). This particular sand is suggested to be derived from southward-moving shelf sands driven over the shelf-edge during the glacial low-stand by the equivalents of the EAC acting on a much narrower continental shelf. The linear rills in the Fraser Canyon Complex are likely cut by shelf derived sands transported downslope resulting in top-down incision and further slope abrasion.

2. Oceanic currents are probably sweeping the slope’s exposed areas clean of new sediments and abrading them. The east coast of Australia is influenced by two major currents: 1) the southward flowing EAC, and 2) the northward flowing ACC. Both of these flows undergo major changes in intensity during the warming and waning of the ice-sheets, particularly during the Pleistocene (Barker and Thomas 2004; Bostock et al. 2006). These currents probably abrade the slopes and are suspected to have had a profound effect on the morphologic evolution of the EACM, and suppressed the accumulation of slope sediment during the Pleistocene, excavating an erosional moat at the foot of the slope (Keene et al. 2008).

3. Slope sediment is probably being removed downslope as mass movements either due to liquefaction, or as slides moving as a consequence of earthquake ground shake. The geotechnical properties of the sediments have shown the within slide material to display brittle behaviour with high water content and low clay, making the slopes susceptible to failure by liquefaction. Previous failures have been identified within core GC2 inside the Upper Slope Slide and a potential failure by liquefaction within core GC3 inside the Middle Slope Slide.

Two major findings of this study in relation to the formation and activity of the southeast QLD continental margin, offshore Fraser Island are illustrated in the conceptual model (Figure 6.1). They are:
1) The upper continental slope offshore Fraser Island between around 500 and 1200 m water depth is a geologically young, post-Pliocene feature that has not accumulated material during the Quaternary.

The upper Pliocene/lower Pleistocene age determined for the stiff hemipelagic sediments at the base of core GC1 on the upper slope, and the upper Miocene/lower Pliocene sediments at the base of core GC4 on the middle slope indicate that the large-scale submarine landsliding in this area is a geologically recent phenomenon that is at most Plio-Pleistocene in origin.

2) Sediment is not accumulating on the slope and is either being shaken off or abraded away.

The geomorphology and age of the sediments presented in this thesis strongly support this area of the margin to be highly active and erosional. Biostratigraphy ages of the basal material on both the upper and middle slopes showed >2 Ma BP of sediment to be missing from the slopes, and presented erosional unconformities where a long period of erosion or non-deposition has occurred. This section of the margin is steeper than further south, with extensive canyon systems, upper and lower slope rills, and newly formed box slides within the upper slopes. The upper slope turbidite sand identified in GC1, and AMS $^{14}$C ages above and below this feature, strongly indicate ‘continual removal’ of sediment from the slope during the Pleistocene.

6.4 Limitations and Future Research

This study has presented new data on submarine landslides and the geological processes involved in causing failure along the EACM. The results indicate the potential for future failure to be high, given the abundance of the mass wasting features that have been identified in the geomorphology and analysed sediment cores, as well as the presence of large areas of un-failed slope adjacent to the Fraser Canyon Complex and on the Wide Bay Plateau. The need for further investigation of this region and its landslides is obvious. It should include further tsunami hazard assessment that should build on from the detailed catalogue presented by Clarke (2014), which estimates the tsunami flow depth at the
coastline, inundation distances, and run-up heights of a large number of past and potential landslides on the EACM. Of equal importance and to compliment the tsunami modelling, further studies looking into whether or not such submarine landslides events seen in this study and catalogued by Clarke (2014) actually generated tsunamis offshore the EACM and with waves of the magnitudes predicted. Dominey-Howes (2007), Courtney et al. (2012) and Goff and Chague´-Goff (2014) have catalogued prehistoric tsunamis along the NSW coast of SE Australia (see section 2.6, Chapter 2), but assessment of the southern Queensland coastline is minimal and should be looked into more closely. Such research should involve trying to find depositional and erosional features within on-shore deposits for evidence of inundation from large tsunamis (Bryant and Nott 2001; Courtney et al. 2012). Chronological dating of these deposits would also be useful to try and coincide with submarine landslide events.

A total of 39 gravity cores and 24 dredge samples from Yamba in NSW to Fraser Island in southeast QLD were collected on the SS2013/V01. To date, only half of these cores have been split and examined (Pers. Comm., T. Hubble, 20 February 2015). The dredge samples are currently being analysed by Yu (in progress). The analysis of this material will increase the size of the available dataset and enable a better understanding of the formation and geology of the margin, and better constrain the timing and age of these submarine landslides.

This thesis has provided a detailed age record of the sediment within the gravity cores dating up to the Miocene epoch, but a good understanding of the conditions required for failure and the frequency of their occurrence is still to be developed. The use of short-coring techniques for investigating shallow underwater landslides has been the only sampling available to date. However, an investigation into the sediment deposited in the receiving basin using the new deep-water coring facilities on RV Investigator is needed. The gravity coring undertaken so far has provided short cores (<6 m) and has not sampled the major slide detachment surfaces (which has been the case in this study). The new long corer (24 m), may be able to acquire this material and will be required to develop a more accurate understanding of when the failure of the larger landslides occurred (Geoscience Australia 2015).
To complement the high resolution bathymetry data and sediment cores, it would also be useful to have downslope and across-slope sub-bottom profiler or seismic reflection records for the Upper and Middle Slope Slides. Such profiles can identify the geometry of the layers and the presence of bedrock basement. This would enable a more confident characterisation of the margins mass transport deposits, possible weak layers, turbidites and geological sequences. The Kongsberg TOPAS PS 18 Parametric Sub-Bottom Profiler (http://www.km.kongsberg.com) deployed on the SS2013-V01 did not have sufficient power to penetrate the sub-bottom and produce usable profiles. Collection of such profiles must be a priority of future work.
Figure 6.1. Conceptual model of the key processes occurring offshore Fraser Island in southern Queensland with cross-sectional interpretations (not to scale) of (A) the MSS, and (B) the USS. LGM = Last Glacial Maximum, EAC = East Australian Current, ACC = Antarctic Circumpolar Current.
References


Clare, MA, Talling, PJ, Challenor, P, Malgesini, G, Hunt, J (2014). Distal turbidites reveal a common distribution for large (>0.1 km³) submarine landslide recurrence. Geology, 42 (3): 263-266.


Hance, JJ (2003). Development of a Database and Assessment of Seafloor Slope Stability Based on Published Literature (doctoral dissertation, University of Texas at Austin).


on Recent Advances in Geotechnical Earthquake Engineering and Soil Dynamics, San Diego, CA, USA.


Appendix 1. Determination of Specific Gravity

Methodology
Specific gravity ($G_s$) is the ratio of the density of sediment to the density of water (Holtz et al. 2011) and is needed in the post-calculations of the triaxial geotechnical tests in section 5.4.4, Chapter 5. $G_s$ tests in accordance with the AS 1289.3.5.2 were measured for soil particles within the two triaxial cores in GC3 at the top (GC3/5B/22-42cm) and base (GC3/1F/344-364cm) of the core inside the Middle Slope Slide. Around 100 g of sediment from each sample was oven dried and carefully ground into powder using a mortar and pestle and sieved through a 600 µm mesh sieve to remove any remaining large particles or shell material. A 50 ml pycnometer was first calibrated by measuring its mass, followed by the mass of the pycnometer filled with water to the meniscus and temperature recorded. The pycnometer was then emptied and dried. Around 5 g of the sample was then placed into the pycnometer with the sediments mass accurately recorded. The pycnometer was then filled with distilled water to the base of the neck and transferred to a desiccator for around two hours to remove all air from the sample. Once the air had been removed, the pycnometer was filled to 50 ml and the mass of the pycnometer, sample and water was determined. The $G_s$ was calculated by dividing the mass of the solids by the mass of an equal volume of water using Equation A.1).

$$G_s = \frac{K M_S}{M_S + M_{PW}(at\ T_X) - M_{PWS}}$$  
(Eq.A.1)

Where, $K=$ temperature coefficient, $M_S=$ mass of sediment sample, $M_{PW}=$ mass of pycnometer and water, $T_X=$ density of water, $M_{PWS}=$ mass of pycnometer, water and sediment. The density of water and temperature coefficient was determined from Lide (1993-1994). The procedure was repeated in three separate pycnometers and the average recorded.

Results
The $G_s$ at 22-44 cm from the top of the core (section GC3/5B) presented an average of 2.72, typical of the clay mineral illite and the silt mineral feldspar (Fratta et al. 2007). The $G_s$ at 344-364 cm at the base of the core (section GC3/1F), presented an average of 2.66 typical of the clay minerals illite and Kaolinite and the silt mineral feldspar (Fratta et al. 2007).
**Date:** 16-09-2014  
**Core #:** GC3  
**Section #:** 1F (Triaxial sample)

### Calibration of Pycnometer:

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<th>3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mass of pycnometer, ( M_p ) (g) =</td>
<td>33.85</td>
<td>34.18</td>
<td>34.12</td>
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<tr>
<td>Mass of pycnometer + water, ( M_{pw} ) (g) =</td>
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<tr>
<td>Observed temperature of water, ( T_i ) (°C) =</td>
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<td>22.5</td>
<td>22.5</td>
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### Specific Gravity Determination:

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<td>Mass of pycnometer + water + soil, ( M_{pws} ) (g) =</td>
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<td>22.5</td>
<td>22.5</td>
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<tr>
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<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Mass of dish + dried soil (initial), ( M_{dsi} ) (g) =</td>
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<td>75.01</td>
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<td>Density of water at ( T_i ) (g/cm³)=</td>
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<td>( M_{pw} ) (at ( T_x )) = ( \frac{\text{density of water at } T_x}{\text{density of water at } T_i} \left[ M_{pw} (at T_i) - M_p \right] + M_p )</td>
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<td>Mass of solids, ( M_s ) (g) =</td>
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<td>Spec. Gr: ( G_{S@20^\circ C} = \frac{K M_s}{M_s + M_{pw} (at T_x) - M_{pws}} )</td>
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<td><strong>Average Specific Gravity:</strong></td>
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Date: 17-09-2014
Core #: GC3
Section #: 5B (Triaxial sample)

### Calibration of Pycnometer:

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<td>Mass of pycnometer, $M_p$ (g) =</td>
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<tr>
<td>Mass of pycnometer + water, $M_{pw}$ (g) =</td>
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### Specific Gravity Determination:

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<td>Mass of dish + dried soil (initial), $M_{dsi}$ (g) =</td>
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<td>$M_{pw}(at \ T_x) = \frac{\text{density of water at } T_x}{\text{density of water at } T_i} \times [M_{pw}(at \ T_i) - M_p] + M_p$</td>
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<tr>
<td>Spec. Gr: $G_s@20^\circ C = \frac{K \times M_s}{M_s + M_{pw}(at \ T_x) - M_{pws}}$</td>
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## Appendix 2. Mini-Vane Shear Results

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<th>Core</th>
<th>Section</th>
<th>Depth (cm)</th>
<th>Angular Strain at failure (°)</th>
<th>Time to failure (min)</th>
<th>Undrained Strength, $S_u$ (kPa)</th>
<th>Remoulded Strength, $S_{ur}$ (kPa)</th>
<th>Undrained Strength Ratio ($S_u/S_{ur}$)</th>
<th>Sensitivity, $S_t$</th>
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<td>6.14</td>
<td>1.40</td>
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