Determining the Subsidence Rate of the Cascade Seamount using Strontium Isotope Stratigraphy

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Determining the Subsidence Rate of the Cascade Seamount using Strontium Isotope Stratigraphy

By

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Bachelor of Arts
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Abstract

The Cascade Seamount is a wave-planated feature located on the microcontinent of the East Tasman Plateau (ETP). The minimum subsidence rate of the Seamount and the ETP can be estimated by dividing the present-day depth of the wave-cut surface (640 m) by the age of Cascade Seamount basalts as determined by potassium-argon (K-Ar) dating (33.4 and 36 Ma). This approach yields a subsidence rate of 18 m/Myr. However, a significantly more rapid subsidence rate of the ETP since the Eocene-Oligocene transition has been proposed based on sedimentological and biostratigraphic techniques. The late Eocene paleodepths determined by Stickley et al. (2004) using sedimentological and biostratigraphic techniques, indicate a subsidence rate of 85 m/Myr for the ETP. These two results present a paradox, which implies that the ETP subsided at a rate greater than the seamount itself over the same time interval. It also implies that the seamount formed above sea level. We posit that the subsidence ambiguity may be attributed to the presence of a turbidity current deposit in the sediment core, or uncertainty in the age of the wave-planated surface of the Cascade Seamount. Sr isotope stratigraphy (SIS) was used to measure the $^{87}$Sr/$^{86}$Sr ratios in order to find the ages of the marine carbonate samples recovered from the Cascade Seamount during the August 2016 RV Investigator Voyage (IN2016_E01). The youngest geologically reliable age was reported to be 20.39 Ma, while the oldest age was 27.74 Ma. This gives the ETP a subsidence rate of 23.1 - 31.4 m/Myr. Results from statistical analyses of the published grain size measurements indicated the presence of a turbidity current deposit in ODP Site 1172. Therefore, the calculations put forth by Stickley
et al. (2004) are misinterpretations of the events surrounding the Cascade Seamount.
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Chapter 1

Introduction

1.1 Geologic Background of the Cascade Seamount and East Tasman Plateau

What is the subsidence rate of the Cascade Seamount and why is this important? Determining the subsidence rate of this seamount will allow for a more defined time frame for when the Tasmanian Gateway opened, allowing the Antarctic Circumpolar Current (ACC) to form, and it will help to solve the subsidence paradox presented in the publications by Lanyon et al. (1993), Quilty (1997; 2001), Exon et al. (1997), and Stickley et al. (2004).

The Cascade Seamount is a volcanic structure found off the southeast coast of Tasmania, on the submerged microcontinent block of the East Tasman Plateau (ETP), which is made up of thin continental crust and was once a part of the Tasmanian Land Bridge. The ETP was rifted apart from Tasmania in the late Cretaceous (~95 million years ago (Ma)). A Cretaceous to Miocene section of deep-sea sediments was recovered at Ocean Drilling Program (ODP) Site 1172, which is ~23 kilometers (km) west of the Cascade Seamount on the ETP, as shown in Figure 1.1 (Quilty, 1997) and Figure 1.2 (Hill and Exon, 2004a). The source of the volcanic edifice of the Cascade Seamount is related to the Balleny hotspot in the Pacific (Hill and Exon, 2004a) that began to influence the crust 45 Ma. This event coincides with an increased spreading rate of Australia as it moved northward, away from Antarctica (Exon et al., 1997).
At its shallowest, the Cascade Seamount rests ~640 meters (m) below sea level, measures 10 km in diameter at its peak and 20 km at its base, and is about 2 km in height (Lanyon et al., 1993; Exon et al., 1997; Quilty, 1997). The seamount has been planated (is flat-topped), and is thus classified as a guyot, which suggests that it was eroded due to wave action when its peak was near sea level. This was confirmed by dredge samples collected during the August 2016 RV Investigator Voyage (IN2016_E01). In addition, the bathymetry of the guyot was explored during the voyage using a multibeam swath system. In particular, two terraces were discovered close to the top of the guyot. The lower terrace is located ~830 m below sea level and surrounds the guyot, while the upper terrace is located ~700 m below sea level. A steep scarp of 60 m separates the two terraces (Figure 1.3). Recovery of cemented beach rocks with large rounded basalt and carbonate clasts strongly suggests that the terraces represent wave-cut erosional features. Based on published ages, the terraces could have formed from a drop in eustatic sea level resulting from glaciation at the Eocene-Oligocene boundary (Null Hypothesis) or from the tectonic subsidence of the guyot itself (Alternate Hypothesis).

1.2 Significance of the Subsidence of the East Tasman Plateau to Gateway Events and Global Climate

The events surrounding the deepening of the Cascade Seamount are related to the tectonic movements that resulted in the opening of the Tasmanian Gateway, which enabled the ACC. In the presence of an open Drake Passage, the subsidence of the Tasmanian Gateway created an opening between Antarctica and Australia, which allowed for the
establishment and progression of the ACC after 30 Ma (Scher et al., 2015), which is shown in Figure 1.4 (adapted from Exon et al., 2004).

The establishment of the ACC led to the thermal isolation of Antarctica from equatorial and low latitude warm waters that were once allowed to circulate in this polar region. The causation of the opening of the Tasmanian Gateway leading to onset glaciation of Antarctica is known as the tectonic gateway hypothesis (Kennett, 1977). However, the validity of the tectonic gateway hypothesis has been questioned as Antarctic glaciation appears to predate the tectonic gateway events in the Southern Ocean (Stickley et al., 2004). The Eocene-Oligocene transition is marked by increasing δ18O values which occurred at 34 Ma, two million years (Myr) prior to the opening of the Tasmanian Gateway (Shackleton and Kennett, 1975; Miller et al., 1991; Zachos et al., 1994; Exon et al., 2004; Stickley et al., 2004). The continental blocks that make up the ETP are similar to those at the Tasmanian Gateway. Therefore, a more robust subsidence rate for the ETP can be applied to the Tasmanian Gateway in order to pinpoint a more defined timeline in which the Gateway sank and the ACC prevailed.

Continual rifting that occurred between the Tasmanian Gateway and Antarctica around 33.7 Ma (Lawver et al., 1992; Exon et al., 2001) allowed for the establishment of the ACC. This new current was extremely fast and narrow, due to the small channel forming between the two land masses. It is hypothesized that this event, as well as the eustatic drop in sea level due to glaciation at the Eocene-Oligocene boundary (Haq et al., 1987; Miller et al., 1985), gave rise to a massive non-depositional event that occurred in the southwest Pacific basin known as the Marshall Paraconformity (Watkins and Kennett, 1971; Carter, R.M., and Landis, 1972; Pfuhl and McCave, 2003).
The Marshall Paraconformity was first discovered via the lack of late Eocene to early Oligocene section in shallow marine sections of sediment from the New Zealand plateau (Carter, R.M. and Landis, 1972; Carter, R.M., 1985; Fulthorpe et al., 1996) that extended from a few tens of meters in shallow water, to the abyssal plains by several thousands of meters (Carter. R.M. et al., 2004). This event affected the entire region containing the Tasmanian Gateway, which is seen as a sediment lag in deep sea sediment cores throughout the region (Kennett et al., 1975; Kennett and von der Borch, 1986; Carter, R.M., et al., 1999, 2004; Carter, L. et al., 1999; Exon, et al., 2001). Non-deposition in the South Pacific starts in the early to late Oligocene (Lever, 2007), between about 32.5 and 29 Ma in shallow water (Fulthorpe et al., 1996), and between 33.5 and 33 Ma in deeper marine environments (McGonigal and Di Stefano, 2002; Carter, R.M., et al., 2004). Meanwhile, ~23 km from the Cascade Seamount at ODP Site 1172, the youngest sediments deposited offshore after the Marshall Paraconformity were found to be ~33 Ma (Exon et al., 2001), which is depicted in Figure 1.5 (adapted from Carter, R.M. et al., 2004).

1.3 Significance of the Subsidence of the East Tasman Plateau to Gateway Events Regional Tectonic Events

In order to truly understand the subsidence rate of the Cascade Seamount, it is important to fill in the gaps of the tectonic history of this region. As previously mentioned, major rifting of the ETP from Tasmania began in the late Cretaceous, between ~95 Ma (Veevers, 1986; Royer and Rollet, 1997) and ~83 Ma (Sayers et al., 2001). Reconstruction of the tectonics in this region can be seen in Figure 1.6 (Exon et al., 2004). This rifting event continued at steady rate until the middle Eocene, when it began to increase (Royer
and Rollet, 1997). Many tectonic events took place during this ~60 Myr gap, which have been recovered through sediment core analyses. At ~75 Ma, Australia and New Zealand began to drift from each other due to sea floor spreading (Cande and Stock, 2004), which eventually resulted in the final breakup of northeast Australia, thus forming the Tasman Sea ~60 Ma (Gaina et al., 1999). The expansion of the Tasman Sea allowed for newly forming ocean currents to circulate around the developing eastern coastlines of Australia and Tasmania. The South Tasman Rise, the microcontinent south of the ETP, broke away from Antarctica at ~55 Ma. Once Australia and Antarctica were almost completely separated by the mid-Eocene (~43 Ma), their divergent movement decreased. The energy from this movement was then transferred to the north-south transform fault along the Tasman Fracture Zone on the western South Tasman Rise. This movement ended by the late Eocene (~33.5 Ma), causing the collapse of continental margins, including the ETP, around Tasmania. This collapse marked the separation of the South Tasman Rise from Antarctica, as well as the beginning of rapid subsidence of the ETP at the Eocene-Oligocene boundary (Exon et al., 2004).

It is paramount to note that Exon et al. (2004) does not provide a plausible geological mechanism for the rapid subsidence of the ETP in the late Eocene. This is noteworthy because an alternative theory put forth by Hill and Exon (2004b) and Exon et al. (2004) states that instead of the suggested rapid subsidence of the ETP at the Eocene-Oligocene boundary, there was a considerable decline in sedimentation caused by a deepening of the South Pacific seaways, starting ~37 Ma. All former Tasmanian bridge masses had fully subsided below sea level by the Late Oligocene, allowing for full ACC establishment at all water depths, thus eroding older sediments (see Marshall
Paraconformity for more information). This event would have significantly reduced land mass exposure, thereby decreasing the amount of sediment deposited in the Tasmanian region (Exon et al., 2004). This newly submerged landmass would no longer able to supply the continental shelf with siliciclastic sediment, as it had done since the early Cretaceous. Sediment core analyses from ODP Leg 189 indicate that once sedimentation began to decrease (~33.5 Ma), south Pacific core sites shifted from siliciclastic sedimentation, indicating a calm, poorly-oxygenated, warm, shallow marine environment, to biogenic sedimentation, indicating a dynamic, well-oxygenated, cool pelagic environment. This decrease in sedimentation could also be explained by a cooling climate, which is known to have occurred at the Eocene-Oligocene transition. This climate change could have caused decreased rainfall, thereby reducing weathering and erosion of the microcontinents, and thus inhibiting siliciclastic deposition onto the continental shelf (Exon et al., 2004).

There are some alternative theories as to when rapid subsidence of the Tasman land bridges occurred. As previously mentioned, Australia and Antarctica were almost completely rifted apart in the middle Eocene (~43 Ma). Exon et al. (2004) hypothesizes that this tectonic event could have been the catalyst for the rapid subsidence of the regional microcontinents. The reason for the drastic sedimentological change 9.5 Myr later is the slowing and eventual ceasing of siliciclastic sediment, as previously explained. It was only in the early Oligocene that carbonate sedimentation began the dominant source of sediment in the eastern portion of ODP Leg 189, including Site 1172. Therefore, these changes could also be linked with global position, sedimentation rates, and oceanic conditions.
1.4. Paradoxical Subsidence Estimates for the East Tasman Plateau

1.4.1 Subsidence History from the Cascade Seamount

As seamounts sink, they incorporate the conditions of the seawater as well as nearby fossils into their sediment, which can be collected through dredging (Quilty, 1997). There have been previous studies using biostratigraphy and chemostratigraphy in order to constrain the age of the Cascade Seamount. However, the published age of the seamount is questionable. This is because the Potassium-Argon (K-Ar) dates from Lanyon et al. (1993), Quilty (1997), and (2001) were obtained from rock samples opportunistically provided by fishing trawlers in the 1970’s. The original data showing how these dates were determined were never published, only cited as personal communication. Nonetheless, analysis of microfossils within the dredged samples from the top of the seamount (~640 m below sea level) by Lanyon et al. (1993) was consistent with late Eocene sedimentation from 33.4 and 36 Ma. Another study by Quilty (1997) took dredged basalt fragments that were found to be from the mid-Oligocene, ranging from 33.4 ± 0.3 Ma and 31.5 ± 0.5 Ma based on K-Ar dating. Exon et al. (1997) agreed with this time frame and stated that the seamount was formed between the late Eocene and early Oligocene, and subsided below sea level in the late Oligocene. This age, when combined with the present depth suggests an average subsidence rate of 18 m/Myr since the late Eocene.

1.4.2 Subsidence History from ODP Site 1172

Analysis of a sediment core 39X, ~23 km from the base of the seamount from ODP Site 1172 by Stickley et al. (2004), using sedimentological and biostratigraphic techniques, reported shallow marine sediments of late Eocene age at depths at 2,922 m below sea level
on the ETP. These results suggest that the ETP subsided at a rate of 85 m/Myr. Stickley et al. (2004) projected that the seamount subsided slowly at first, and then once in shallow waters, subsided rapidly, which is reflected in the subsidence rate calculated. This very high subsidence rate suggests the geological improbability that the ETP subsided nearly five times faster than the Cascade Seamount. It is also incompatible with the time at which rifting that led to the formation the ETP. This in turn implies that the phase of rapid subsidence as well as sediment loading of the guyot was well over by the Eocene.

In order to validate the exceedingly rapid, and geologically implausible subsidence rate from Stickley et al. (2004), Hill and Exon (2004a) hypothesized that peak subsidence would have had to occur across the Eocene-Oligocene boundary, with water depths deepening from 50-150 m in the middle and early Eocene, to 500 m in the late Eocene, and to 3,000 m in the early Oligocene. This would imply that the ETP subsided at a rate greater than the Cascade Seamount itself, subsiding almost 2,000 m more than the seamount did over the same time interval, and would suggest that the seamount was established above sea level. Since there is no evidence of any vertical offset in the seismic profiles (Hill and Exon 2004a), the ETP and the Cascade Guyot would have subsided at the same rate. Moreover, small parasitic cones were found on the flanks and terraces around the Cascade Seamount (Exon et al., 1997), as depicted in Figure 1.7. These cones would have been eroded through wave action if they formed in surface waters. Therefore, this feature demonstrates that the seamount formed below sea level, which would deem the Stickley et al. (2004) subsidence rate invalid.

It is clear that there are discrepancies in the literature regarding the rate at which the Cascade Seamount subsided. As previously mentioned, Lanyon et al. (1993) and Quilty
(1997; 2001) found the seamount to have subsided 18 m/Myr, while Stickley et al. (2004) found the subsidence to be a rate of 85 m/Myr. The depths at which both rates were calculated are shown in Figure 1.8 (Scher et al., 2015). Therefore, in order to resolve the paradox surrounding the subsidence rate of the Cascade Seamount, samples from the August 2016 RV Investigator Voyage will be analyzed in order to calculated a vertical sinking rate. These samples were dredged from depths ranging from 650 m below sea level to 1,850 m below sea level.

1.5 Strontium Isotope Stratigraphy

Strontium (Sr) Isotope Stratigraphy (SIS) is a chemostratigraphic technique that allows for the age-correlation of marine sediments using a global reference curve for seawater $^{87}\text{Sr}$ and $^{86}\text{Sr}$ isotopes through time. SIS is performed under the assumption that past, present, and future oceans have had and will continue to have homogenous $^{87}\text{Sr}/^{86}\text{Sr}$ isotopic ratios. Homogeneity of Sr isotopes is maintained in the present ocean since the residence time of Sr (~2.5 Myr) is longer than the mixing time of the oceans (1,500 years). This makes Sr a conservative trace metal in seawater (Vollstaedt et al., 2014; Hodell et al., 1990).

Calcium carbonate contains high concentrations of Sr. The geochemical similarity of calcium (Ca) and Sr allows for Sr to easily substitute for Ca in the calcium carbonate structure. This substitution can occur because Ca and Sr are both found within Group 2 on the periodic table. Therefore, the major sink of marine Sr is found in the formation of calcite and aragonite, two polymorphs of calcium carbonate minerals (Milliman and Droxler, 1996).
SIS is reliant upon the type of carbonate samples analyzed. Dredged carbonate rock samples from the top of the Cascade Seamount contain both biogenic material from skeletal foraminifera and the inorganic bulk carbonate matrix in which it is preserved. While both forms of calcite can be used in SIS, the matrix may have gone through diagenesis (specifically the recrystallization of the less stable aragonite to its more stable form, calcite). During diagenesis, the enriched carbonate structure exchanges Sr with the depleted interstitial waters (Gieskes et al., 1986) until equilibrium is reached. This exchange of Sr results in a new diagenetically altered carbonate that contains the equilibrated interstitial water Sr signal, thereby changing the original $^{87}\text{Sr}/^{86}\text{Sr}$ ratio (Brand and Veizer, 1980; Veizer, 1989; Banner and Hanson, 1990; Vollstaedt et al. 2014).

Bulk carbonates may be analyzed for their respective $^{87}\text{Sr}/^{86}\text{Sr}$ ratios in order to study the degree to which they were diagenetically altered. In particular, micrite samples will be analyzed for their $^{87}\text{Sr}/^{86}\text{Sr}$ signal. Micrite is a fine-grained carbonate that has low porosity and permeability. This decreases the possibility of recrystallization, lowers the concentration of Sr expelled into the interstitial waters of the carbonate rock, and minimizes the likelihood of the initial $^{87}\text{Sr}/^{86}\text{Sr}$ signal of the seawater to be lost (Edwards et al., 2015).

Samples analyzed using SIS can be easily and accurately dated by applying the $^{87}\text{Sr}/^{86}\text{Sr}$ signature of seawater to the widely accepted LOWESS (LOcally WEighted Scatterplot Smoother) Curve. This curve, as shown in Figure 1.9 from McArthur et al. (2012), was originally developed by J.M. McArthur and then updated by McArthur and Howarth (2004) using a total of 4,119 data points from well dated sedimentary rock sections found globally that were converted to the most recent time scale, the 2012
Geological Time Scale (McArthur et al., 2012). Many methods including biostratigraphy, magnetostratigraphy, astrochronology, and sedimentation rates were of extreme importance in aiding in the generation of the LOWESS Curve (McArthur et al., 2012). This curve shows the $^{87}\text{Sr}/^{86}\text{Sr}$ ratio using a best fit line in order to keep the data continuous, as a function of time. Continuity was optimized by using numerous overlapping segments to create one fitted curve between different time periods, chron, epochs etc. It can accurately date samples within a 95% confidence interval from the Paleozoic, Mesozoic, and Cenozoic eras.

The LOWESS Curve can be particularly accurate in constraining the ages of samples when there is a drastic increase in the slope of the $^{87}\text{Sr}/^{86}\text{Sr}$ slope over a short period of time. A change such as this occurs after ~40 Ma, which is demonstrated in the enhanced view of the LOWESS Curve showing the late Cenozoic era (Figure 1.10). This increased steepness of the $^{87}\text{Sr}/^{86}\text{Sr}$ slope reflects the tectonic shifts as well as the dramatic oscillations in climate that occurred during this time. The first appearance of ice-sheets on Antarctica during the Oligocene caused global changes in precipitation patterns, a drastic eustatic sea level decline, and increased global weathering rates. Moreover, the uplift of the Tibetan Plateau and Himalaya, following the collision of India with Asia in the middle Eocene also increased continental weathering rates on both a regional and global scale (DePaolo and Ingram, 1985; Zachos et al., 1999). Increased continental weathering allowed for an influx of enriched continental Sr input into the oceans, which led to the initial rise of the $^{87}\text{Sr}/^{86}\text{Sr}$ signature (Koepnick et al., 1985; Zachos et al., 1999), thus changing the global oceanic $^{87}\text{Sr}/^{86}\text{Sr}$ signal and slope on the LOWESS Curve.
1.6 Statistical Analyses

It is possible that there was a turbidity current present in the core 39X that was analyzed by Stickley et al. (2004). Turbidity currents are problematic to paleoceanographers when determining the accuracy of age models of sediments because unlike normal deep-sea sediment deposits, turbidity currents cause major slumping of sediments in one area. This slumping causes the sediment to settle out in a size-dependent formation, where larger, coarse-grained sediment settles on the bottom of the debris, while smaller, fine-grained sediment settles at the top of the debris. This causes the sediment to settle in a fining-upward, graded deposit, thus altering the in-situ location of sediment and creating error in the interpretation of the paleodepth stratigraphy. This pattern would be apparent in that there would be an increase of grain size (µm) with increasing depth (m). This can cause errors in the calculated subsidence rate. If sediment from this core shows evidence of a turbidity current, the paleodepth estimate to determine the timing of the deepening of the Tasmanian Gateway published in Stickley et al. (2004) must be revisited.

Three statistical analyses will aid in showing whether the hypothesis that a turbidity current is present in core 39X holds true. A correlation will be used to estimate the degree to which grain size and depth vary together. A standard linear regression will be applied in order to explain a possible causation or variation of changes in grain size by changes in depth. A Single Factor Analysis of Variance (ANOVA) will be implemented to explain if grain size differs significantly with depths binned in 1 m increments from the core.

If the outcome of these statistical analyses show that there is a significant correlation and significant relationship between grain size and depth (correlation and linear regression, respectively), as well as a significant difference in mean grain size with
increasing depth (ANOVA), then it can be concluded that a turbidity current occurred in core 39X at Site 1172.

Samples for the statistical analyses were separated into evolutionary phases delineated by Stickley et al. (2004) in Table 1.1, which are in descending order of core depth. These phases can also be seen in Figure 1.11 (adapted from Stickley et al., 2004), which shows the corresponding measurements of grain size with depth.
Figure 1.1 Location of the Cascade Seamount on the East Tasman Plateau in relation to Tasmania (Quilty, 1997).
Figure 1.2 Location of the Cascade Seamount on the East Tasman Plateau in relation to ODP Site 1172 and Tasmania (Hill and Exon, 2004a).
Figure 1.3 Profile of terraces found on the Cascade Guyot surveyed by the August 2016 RV Investigator Voyage.
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Figure 1.7 Distribution of slopes on the Cascade Guyot. Note that the parasitic cones on the outermost parts of the guyot have a very steep relief, indicating wave erosion did not take place.
The rate calculated by Lanyon et al., 1993, Quilty, 1997, and 2001 taken from basalt fragments found on the Cascade Guyot to yield a subsidence rate of 18 m/Myr. The rate calculated by Stickley et al., 2004 taken from sediment cores on the East Tasman Plateau to yield a subsidence rate of 85 m/Myr (Scher et al., 2015).
Figure 1.9 LOWESS Curve depicting variations of $^{87}\text{Sr}/^{86}\text{Sr}$ ratio through time (McArthur et al., 2012).
Figure 1.10 Enhanced LOWESS Curve depicting variations of $^{87}{\text{Sr}}/^{86}{\text{Sr}}$ ratio during the late Cenozoic era.
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<table>
<thead>
<tr>
<th>Evolutionary Phase</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>D1</td>
<td>30.2Ma, end major erosion; start of siliceous-rich carbonate ooze deposition with cosmopolitan phytoplankton</td>
</tr>
<tr>
<td>C2</td>
<td>32 Ma, end “endemics”; hiatus, followed by inception of oceanic, oligotrophic, warm-temperate conditions</td>
</tr>
<tr>
<td>C1</td>
<td>33.5 Ma, further deepening; intensification of energetic bottom currents; end palynology</td>
</tr>
<tr>
<td>B3</td>
<td>34.5 Ma, FO <em>S. kakanuiensis</em>; first west-to-east surface water connection between AAG and Pacific sites (same water mass)</td>
</tr>
<tr>
<td>B2</td>
<td>35.2 Ma, FAO <em>Brigantedinium</em> sp.; end first erosional event; installment of oceanic upwelling</td>
</tr>
<tr>
<td>B1</td>
<td>35.5 Ma, first deepening step; inception of energetic bottom currents; brief palynology break</td>
</tr>
<tr>
<td>A2</td>
<td>Brief return to moderate sedimentation rates during Subchron C16n.1n</td>
</tr>
<tr>
<td>A1</td>
<td>Initial moderate deepening during Chron C17n</td>
</tr>
</tbody>
</table>
Figure 1.11 Average grain with depth from sediment core 39X from ODP Site 1172 broken up by evolutionary phases (adapted from Stickley et al., 2004).
Chapter 2

Methods

2.1 Samples Shipped from Tasmania

Samples were dredged from depths ranging from 650 to 1,850 m below sea level. For this analysis, these samples were cut into thin sections. Specific areas of each thin section, particularly where foraminifera and micrite were present, were isolated using a microdrill. This resulted in 12 fine powdered samples.

2.2 Weighing Samples

The Sr/Ca ratio of Cenozoic benthic foraminiferal ranges from 1.2-2.0 mmol Sr/mol Ca (Lear et al., 2003). Using this range, the following calculations can be used in order to determine how many grams of calcite are needed for SIS:

1. \((1.2 \text{ mmol Sr/1 mol CaCO}_3) \times (87.62 \text{ g/mol Sr}) \times (1 \text{ mol/100.09 g}) = 1.05 \text{ mg Sr in 1 g CaCO}_3 = \sim 1000 \text{ ppm}\)

2. \((2 \text{ mmol Sr/1 mol CaCO}_3) \times (87.62 \text{ g/mol Sr}) \times (1 \text{ mol/100.09 g}) = 1.75 \text{ mg Sr in 1 g CaCO}_3 = \sim 1750 \text{ ppm}\)

Therefore, the mass of each sample can be as small as 1.05 mg.
2.3 Sample Preparation for Sr Columns

Individual microcentrifuge tubes (1.5 mL) were weighed as is. Once the sample was isolated, each was added to a respective tube and weighed. From here, the weight of each sample was recorded by subtracting the weight of the tube from the weight of both the sample and tube.

In order to dissolve the samples from their solid state, 250 µL of 50% acetic acid (CH$_3$COOH) was added to each tube containing the samples. Using this dilute acid prevents non-carbonate mineral phases (e.g., silicates) from dissolving, which could introduce non-seawater derived Sr to the supernatant. Then each sample was sonicated for 2 – 3 minutes to facilitate breaking up the solid samples. After, another 250 µL of CH$_3$COOH was added to each tube and sonicated for 10 minutes. The samples were spun down in the centrifuge for 5 minutes at 13,200 revolutions per minute (rpm). Then, the liquid samples were separated from the supernatant via pipette into a Teflon vial. Then, each sample was put on dry heat (50°C – 60°C) overnight. This allowed each sample to completely dry.

The next day, samples were taken off the heat and inspected to see if they had all fully dissolved. The presence of extraneous sediment in the sample could cause some samples to not dissolve fully. If this was the case, 200 µL of 0.25M hydrochloric acid (HCl) was added to these samples in order to dissolve everything in the vial. Samples were then placed on dry heat (50°C – 60°C) again for a few hours.

The weight of each Teflon vial was recorded before and after the dried sample was added. To get the weight of the sample only, the weight of the vial only was subtracted from the weight of the sample and vial. Then, each of the dried samples was reconstituted
in 100 µL of 8M nitric acid (HNO₃). All samples in the Teflon vials were weighed again, and then sonicated for 5 minutes in order to make sure the entirety of the sample was resuspended. After, samples were transferred to 1.5 mL microcentrifuge tubes and spun down in the centrifuge at 13,200 rpm for 5 minutes. The samples were then ready for the Teflon columns.

2.4 Teflon Column Preparation

To build the Teflon columns, super Q H₂O was added to the stem of the column until it was completely filled and void of any air bubbles in the stem. Then, about 500 µL of SrSpec resin (Eichrom Inc., Omaha, NE) was added to the mouth of each column so that it settled into the stem. This step was repeated in order to ensure there was enough resin to fill the entire stem and replace the super Q. The resin settled into the column, with any extra resin pipetted out of the column. The end goal was to have resin level off at the mouth of the column.

2.5 Column Protocol

600 µL of 0.001M HNO₃ was added to each column so that the columns would be clean of any Sr that was left on the resin from previous usage. Next, 200 µL of 8M HNO₃ was added to the columns, which allowed the resin to be conditioned and acidified at the correct pH. Then, an aliquot of 100 µL of each sample was introduced to its respective column. After, three rounds of 50 µL of 8M HNO₃ were run through the columns in order to make sure the sample washed through the entirety of the column. From here, 1 mL of 8M HNO₃ was rinsed through the column followed by 700 µL of 8M HNO₃. These two
steps guaranteed that all other major elements and contaminants were removed from the sample, while only Sr remained on the resin. Finally, 1 mL of 0.001 HNO₃ was washed through the columns in order to remove the Sr from the resin, and collect it for analysis. 4 mL omni vials were used for collection.

2.6 NEPTUNE Mass Spec Preparation

Sr isotope ratios were analyzed using the NEPTUNE Plus Multicollector Spectrometer (ICP-MS) in order to obtain the $^{87}\text{Sr}/^{86}\text{Sr}$ ratio for each sample. The Sr isotope analysis used at the University of South Carolina is outlined in detail in Scher et al. (2014), and accounts for isobaric corrections for rubidium (Rb) and krypton (Kr, which is present in the Ar sample gas).

The NEPTUNE (ICP-MS) measures isotopes according to their mass. It cannot distinguish between different isotopes that have the same mass. In the case of measuring the $^{87}\text{Sr}/^{86}\text{Sr}$ ratio, $^{87}\text{Rb}$ can cause interference since $^{87}\text{Sr}$ and $^{87}\text{Rb}$ are of the same mass. Therefore, it was necessary to show that there is no $^{87}\text{Rb}$ interference. Since there is no way to decipher $^{87}\text{Rb}$ from $^{87}\text{Sr}$, another Rb isotope, $^{85}\text{Rb}$ was examined by looking at the $^{85}\text{Rb}/^{88}\text{Sr}$ ratio. Since it is known that the NIST-SRM987 standard does not contain any Rb isotopes, the ratio observed from these samples was the target ratio for all unknown samples. Since the standards ran a bit higher than expected, the $^{85}\text{Rb}/^{88}\text{Sr}$ ratio was in turn, higher than expected. The range for the standard $^{85}\text{Rb}/^{88}\text{Sr}$ ratio was between 0.000021 and 0.000036. The ratios found from the samples was a bit larger, ranging from 0.000021 to 0.000115. This did not show a significant amount of Rb in the samples, indicating no Rb interference with the corrected $^{87}\text{Sr}/^{86}\text{Sr}$ values.
Dip check dilutions of the collected samples were made using 50 µL of the sample combined with 950 µL of 2% HNO₃, where the acid was added first. This resulted in a 20% dilution of the sample. These samples were then put through a dip check in the NEPTUNE (ICP-MS) in order to make sure that adequate Sr levels were measured, which was shown through the voltage and concentration. Adjustments were made if these dilutions were not satisfactory. After this adjustment, all samples, as well as the standards, were measured for their $^{87}\text{Sr}/^{86}\text{Sr}$ ratio. Instrumental mass fractionation of the $^{87}\text{Sr}/^{86}\text{Sr}$ ratio was corrected by normalizing all measured ratios to the natural ratio of $^{86}\text{Sr}/^{88}\text{Sr} = 0.1194$ using an exponential log. The $^{87}\text{Sr}/^{86}\text{Sr}$ ratio was then corrected by using the accepted NIST-SRM987 standard, whose long-term uncertainty is $2.3 \times 10^{-6}$. Each individual NIST-SRM987 value was corrected to the accepted value of 0.710248 by dividing the average of these standard values and multiplying this by 0.710248. This factor is known as the normalization factor. An E+A standard was run as an unknown in order to validate the normalization factor. In addition, two standard deviations from the NIST-SRM987 mean were found by taking the standard deviation of the individual mean values of each NIST-SRM987 value and multiplying them by two. These newly rectified $^{87}\text{Sr}/^{86}\text{Sr}$ ratios were compared to values from the LOWESS Curve (McArthur, 2012), shown in Figure 1.9, in order to assign each sample an appropriate minimum, average, and maximum age range, as well as to calculate a subsidence rate for the Cascade Guyot.

2.7 ELEMENT Mass Spec Preparation

The Thermo ELEMENT 2 High Resolution Inductively Coupled Plasma Mass Spectrometer (HR-ICP-MS) was used to screen the samples for silicate contamination
using trace metal ratios (Mg/Ca, Sr/Ca, and Ti/Ca). The weight of each bulk powder sample was obtained from the 1.5 mL microcentrifuge tubes in the same protocol as previously mentioned. In addition, samples were dissolved using the aforementioned protocol from that of the Sample Preparation for Sr Columns. Then, 5 mL of 2% HNO₃ with Indium (In) spike was added to each of the dried samples. Samples were weighed one last time in the Teflon vial, sonicated for 5 minutes in order to make sure the entirety of the sample was resuspended, and then transferred to 4mL omni vials. Samples were then ready for ELEMENT (HR-ICP-MS) analysis.

Standards were run alongside the samples on the ELEMENT in order to correct for deviations within sample runs. A B/Ca standard and BHVO-2 with 1ppb In were both used was used in order to normalize samples relative to the accepted Geological and Environmental Reference Material (GeoReM) values. From here, known GeoReM values of Ca, Mg, Sr, and Ti were used against the BHVO-2 values in order to find a relative sensitivity factor (RSF) value for the standard to compare to each element. This RSF value was then used to normalize the elemental concentrations for each of the samples.
Chapter 3

Results

3.1 Cascade Seamount Results

3.1.1 SIS Results

Age ranges and respective dredge depths, as well as other characteristics of the 12 samples are shown in Table 3.1. The age determined for the only sample from dredge 1 (1,750 m – 1,850 m) was 18.04 Ma. The average age for samples from dredge 2 (950 m – 1,500 m) was 19.77 Ma. Dredge 3 (650 m – 700 m) samples were found to be on average 24.27 Ma. There was only one sample fourth dredge (725 m – 750 m), which was found to be 26.32 Ma. The dredge 5 samples (825 m – 850 m) had an average age of 16.63 Ma. Finally, the sole sample from dredge 6 (900 m – 925 m) was found to be 20.12 Ma. Figure 3.1 shows how these ages fit onto the LOWESS Curve.

3.1.2 Trace Metal Results

Ratios of Mg/Ca, Sr/Ca, and Ti/Ca were calculated using concentrations obtained from the ELEMENT (HR-ICP-MS). These elemental ratios range between 17.97 – 63.10 µmol Mg/mol Ca, 0.26 - 2.49 µmol Sr/mol Ca, and 0.00094 – 0.048 µmol Ti/mol Ca. The results are shown in the Table 3.2 and Figure 3.2.
3.2 Statistical Analysis of ODP Site 1172 Results

The results of the Pearson’s Product-moment correlation analysis, as shown in Figure 3.3, revealed a significant correlation between depth and increasing grain size for evolutionary phase C2 (r = 0.528, n = 21, p = 0.014, p < 0.05). All other evolutionary phases did not show a significant correlation.

A Model I least-squares linear regression analysis of the samples from C2 indicated a significant linear relationship in which grain size increases with depth (n = 21, adj $R^2=0.240$, p = 0.014, < 0.05). Figure 3.4 shows the relationship of grain size with depth, the fitted line obtained from the regression equation, and 95% confidence intervals. The equation for the relationship is: Grain Size = (18.40*Depth) - 6568.17.

The results of the single factor ANOVA indicated that increasing depth had a significant effect on grain size ($F_{7,101} = 7.83$, p < 0.05), demonstrating that grain size did change significantly with increasing depth. A Dunnett’s T3 post hoc analysis test identified four significantly different depth-interval groups (p < 0.05) of increasing grain size. The first group contained the shallower depths (phases B2, B3, C1, C2, and D1) with smaller, fine-grain sizes ranging from 10.02 µm to 16.68 µm. The second group represented deeper depths (phases A1, B3, C1, C2, and D1) with averages grain sizes ranging from 13.17 µm to 22.95 µm. The third group contained the two deepest depths (phases A1 and A2), with average grain sizes of 22.95 µm and 31.64 µm. The fourth and final group contained (phases A2 and B1) with the largest average grain sizes of 31.64 µm and 36.79 µm. The distribution of these groups can be seen in Table 3.3.
Table 3.1 Depth range, description, image in rock form and thin section (if available), $^{87}\text{Sr}/^{86}\text{Sr}$ ratio, 2 standard mean error (SEM), as well as minimum, average, and maximum age range for each sample from the Cascade Seamount.

<table>
<thead>
<tr>
<th>Sample Name</th>
<th>Depth Range of Dredge (m)</th>
<th>Sample Description and Picture/Thin Section</th>
<th>$^{87}\text{Sr}/^{86}\text{Sr}$</th>
<th>2SEM</th>
<th>Min Age (Ma)</th>
<th>Ave. Age (Ma)</th>
<th>Max Age (Ma)</th>
</tr>
</thead>
<tbody>
<tr>
<td>D1-I-05</td>
<td>1750 - 1850</td>
<td>Micrite cement bounding altered basaltic clasts with interspersed bioclast fragments</td>
<td>0.708571</td>
<td>0.000010</td>
<td>17.97</td>
<td>18.04</td>
<td>18.11</td>
</tr>
<tr>
<td>D2-E-04 CEM</td>
<td>950 - 1500</td>
<td>Conglomerate with biowacke matrix, minor biogeic material (&lt;5%), and has ~5-10% calcite cement. Clast supported. Clasts are highly altered basalt (varying degrees)</td>
<td>0.708410</td>
<td>0.000010</td>
<td>20.05</td>
<td>20.21</td>
<td>20.39</td>
</tr>
<tr>
<td>D2-E-04 CLA</td>
<td>950 - 1500</td>
<td></td>
<td>0.708463</td>
<td>0.000010</td>
<td>19.22</td>
<td>19.33</td>
<td>19.45</td>
</tr>
<tr>
<td></td>
<td>Description</td>
<td></td>
<td></td>
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<td></td>
</tr>
<tr>
<td>D3-B-03</td>
<td>Micrite cement supported, polymict conglomerate</td>
<td>650 - 700</td>
<td>0.708165</td>
<td>0.000007</td>
<td>24.53</td>
<td></td>
<td></td>
</tr>
<tr>
<td>D3-C-05</td>
<td>Micrite cement supported, polymict conglomerate</td>
<td>650 - 700</td>
<td>0.708049</td>
<td>0.000011</td>
<td>27.53</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Description</td>
<td></td>
<td></td>
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<td>-----</td>
<td>------------------------------------------------------------------------------</td>
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<td></td>
<td></td>
</tr>
<tr>
<td><strong>D3-L-02</strong></td>
<td>650 - 700 Calcite cemented. Calcite forming radiating outwards from clasts (biogenic and secondary, e.g. on volcanic clasts)</td>
<td>0.708400</td>
<td>0.000011</td>
<td>20.22</td>
<td>20.39</td>
<td>20.57</td>
<td></td>
</tr>
<tr>
<td><strong>D4-A-06</strong></td>
<td>725 - 750 Mud matrix with lots of carbonate. Clasts and zones of micrite in matrix</td>
<td>0.708097</td>
<td>0.000020</td>
<td>26.09</td>
<td>26.32</td>
<td>26.56</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Description</td>
<td>D5-D-05</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>----</td>
<td>----</td>
<td>------------------------------------------------------------------------------</td>
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<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Graded, mud/micrite matrix, lots of variable biogenic material</td>
<td>825 - 850</td>
<td>0.708936</td>
<td>0.000021</td>
<td>7.43</td>
<td>7.69</td>
</tr>
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<td></td>
<td></td>
<td></td>
<td><img src="image1.png" alt="Image" /></td>
<td><img src="image2.png" alt="Image" /></td>
<td><img src="image3.png" alt="Image" /></td>
<td></td>
<td></td>
</tr>
<tr>
<td>D5-E-06</td>
<td>825 - 850</td>
<td>Porous, little matrix and cement, micrite-clast rich, moderately calcite cemented, bioclast poor, calcite forming on boundaries of bioclastic material</td>
<td>0.708101</td>
<td>0.000012</td>
<td>25.98</td>
<td>26.21</td>
<td>26.44</td>
</tr>
<tr>
<td>D5-G-01</td>
<td>825 - 850</td>
<td>Conglomerate composed of polymictic clasts within a matrix composed primarily of biogenic material and mudstone</td>
<td>0.708651</td>
<td>0.000010</td>
<td>16.66</td>
<td>17.02</td>
<td>17.08</td>
</tr>
<tr>
<td>---------</td>
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<td>-------------------------------------------------------------------------------------------------</td>
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<td>------</td>
</tr>
<tr>
<td>D5-G-02</td>
<td>825 - 850</td>
<td></td>
<td>0.708751</td>
<td>0.000011</td>
<td>15.55</td>
<td>15.60</td>
<td>15.66</td>
</tr>
<tr>
<td>D6-C-02</td>
<td>Micrite-matrix, minor bioclasts (too fine to drill)</td>
<td>0.708415</td>
<td>0.000011</td>
<td>19.96</td>
<td>20.12</td>
<td>20.30</td>
<td></td>
</tr>
<tr>
<td>---------</td>
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</tr>
</tbody>
</table>

39
Figure 3.1 Average age of each sample from the Cascade Seamount superimposed onto the LOWESS Curve.
Table 3.2 Elemental concentrations and ratios of samples from the Cascade Seamount.

<table>
<thead>
<tr>
<th>Sample Name</th>
<th>[Ca] (mol)</th>
<th>[Mg] (µmol)</th>
<th>[Sr] (µmol)</th>
<th>[Ti] (µmol)</th>
<th>Mg/Ca</th>
<th>Sr/Ca</th>
<th>Ti/Ca</th>
</tr>
</thead>
<tbody>
<tr>
<td>D1-I-05</td>
<td>0.00896</td>
<td>0.56554</td>
<td>0.00342</td>
<td>0.00043</td>
<td>63.10276</td>
<td>0.38181</td>
<td>0.04768</td>
</tr>
<tr>
<td>D2-E-04 CEM</td>
<td>0.01409</td>
<td>0.33092</td>
<td>0.01874</td>
<td>0.00007</td>
<td>23.48083</td>
<td>1.32980</td>
<td>0.00496</td>
</tr>
<tr>
<td>D2-E-04 CLA</td>
<td>0.01525</td>
<td>0.35665</td>
<td>0.02867</td>
<td>0.00003</td>
<td>23.38685</td>
<td>1.88023</td>
<td>0.00181</td>
</tr>
<tr>
<td>D3-B-03</td>
<td>0.00830</td>
<td>0.34844</td>
<td>0.02067</td>
<td>0.00006</td>
<td>41.99151</td>
<td>2.49154</td>
<td>0.00689</td>
</tr>
<tr>
<td>D3-C-05</td>
<td>0.04916</td>
<td>1.81456</td>
<td>0.01284</td>
<td>0.00025</td>
<td>36.91026</td>
<td>0.26126</td>
<td>0.00506</td>
</tr>
<tr>
<td>D3-L-02</td>
<td>0.03197</td>
<td>0.73641</td>
<td>0.03836</td>
<td>0.00012</td>
<td>23.03118</td>
<td>1.19975</td>
<td>0.00382</td>
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<tr>
<td>D4-A-06</td>
<td>0.05291</td>
<td>1.54417</td>
<td>0.06244</td>
<td>0.00070</td>
<td>29.18267</td>
<td>1.18010</td>
<td>0.01318</td>
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<tr>
<td>D5-D-05</td>
<td>0.02049</td>
<td>0.41899</td>
<td>0.02951</td>
<td>0.00002</td>
<td>20.44535</td>
<td>1.44002</td>
<td>0.00094</td>
</tr>
<tr>
<td>D5-E-06</td>
<td>0.05877</td>
<td>1.51282</td>
<td>0.02797</td>
<td>0.00074</td>
<td>25.74111</td>
<td>0.47586</td>
<td>0.01265</td>
</tr>
<tr>
<td>D5-G-01</td>
<td>0.06039</td>
<td>1.08531</td>
<td>0.04847</td>
<td>0.00044</td>
<td>17.97293</td>
<td>0.80271</td>
<td>0.00736</td>
</tr>
<tr>
<td>D5-G-02</td>
<td>0.00871</td>
<td>0.16693</td>
<td>0.01061</td>
<td>0.00009</td>
<td>19.16830</td>
<td>1.21868</td>
<td>0.01042</td>
</tr>
<tr>
<td>D6-C-02</td>
<td>0.01555</td>
<td>0.63922</td>
<td>0.03335</td>
<td>0.00003</td>
<td>41.11326</td>
<td>2.14477</td>
<td>0.00166</td>
</tr>
</tbody>
</table>
Figure 3.2 Isotopic ratios of samples from the Cascade Seamount with error bars: (A) Mg/Ca ratios, (B) Sr/Ca ratios, (C) Ti/Ca ratios.
Figure 3.3 The significant correlation between depth and increasing grain size for evolutionary phase C2 ($r = 0.528$, $n = 21$, $p = 0.014$, $p < 0.05$). No other evolutionary phases show a significant correlation.
Figure 3.4 The results of a Model I least-squares linear regression from evolutionary phase C2 (n = 21, adj $R^2=0.240$, $p = 0.014$, < 0.05), which indicate a significant relationship between increasing grain size and increasing depth, as shown by the equation Grain Size = (18.40*Depth) – 6568.17. No other evolutionary phases show a significant regression.
Table 3.3 Dunnett’s T3 post hoc analysis test reveals four significantly different groups that show different depth intervals (p < 0.05) with increasing grain size. The groups indicated below are in descending order of depth, showing that grain size does increase with depth.

<table>
<thead>
<tr>
<th>Group</th>
<th>Evolutionary Phases</th>
<th>Depth Range (m)</th>
<th>Minimum Grain Size (µm)</th>
<th>Maximum Grain Size (µm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>B2, B3, C1, C2, D1</td>
<td>356.11 - 360.01</td>
<td>10.02</td>
<td>16.68</td>
</tr>
<tr>
<td>2</td>
<td>A1, B3, C1, C2, D1</td>
<td>356.11 - 362.05</td>
<td>13.17</td>
<td>22.95</td>
</tr>
<tr>
<td>3</td>
<td>A1, B1</td>
<td>360.07 – 362.05</td>
<td>22.95</td>
<td>31.64</td>
</tr>
<tr>
<td>4</td>
<td>A2, B1</td>
<td>360.07 - 360.97</td>
<td>31.64</td>
<td>36.79</td>
</tr>
</tbody>
</table>
Chapter 4
Discussion

4.1 Cascade Seamount

The subsidence rate of the Cascade Seamount is relevant to the large scale tectonics that resulted in the opening of the Tasmanian Gateway. The ages determined from the $^{87}$Sr/$^{86}$Sr isotope ratios indicate that the 12 samples from the Cascade Seamount are younger than the Eocene-Oligocene transition (~34 Ma). Therefore, the null hypothesis stating that the beach terraces on the seamount were the result of a drop in eustatic sea level due to Antarctic glaciation during the Eocene-Oligocene transition can be rejected. The alternate hypothesis, which stated that beach terraces, located ~700 and ~830 m below sea level were the result of tectonic subsidence of the Cascade Guyot can therefore fail to be rejected. The results from Stickley et al. (2004) indicate a period of rapid subsidence after rifting occurred in the late Eocene to early Oligocene, which is reflected in their calculated subsidence rate. As previously mentioned in Exon et al. (2004), however, there is no mechanism for this rapid subsidence. The SIS and Argon-Argon (Ar-Ar) analyses suggest that rather than rapid subsidence, the Cascade Seamount remained shallow for at least 16 Myr after the initial volcanic eruption that formed the seamount, at 36 Ma (J. Halpin, Personal Communication, 2018, see Section 4.1.3).

In order to calculate a subsidence rate for the Cascade Seamount and by extension, the ETP and Tasmanian Gateway, two important assumptions need to be addressed. These
assumptions are that 1) the carbonate samples being analyzed were deposited in a shallow marine environment and 2) the $^{87}\text{Sr}/^{86}\text{Sr}$ isotopic values reflect the seawater Sr isotopic signature at the time of deposition.

Section 4.1.1 Assumption 1: Shallow Deposition of Carbonate Samples

The assumption that the carbonate samples were deposited in a shallow marine environment is necessary to track the full subsidence history of the Cascade Seamount and ETP. There are many observations that suggest the carbonates samples from the Cascade Seamount were deposited at a shallow depth. These observations are a way to constrain the ages of the samples as well as the subsidence rate. Calcareous algae that can only form in the photic zone (within ~50 m below sea level) were found on samples pulled from dredge 3 (P. Quilty, Personal Communication, 2018). This indicates that this dredge was once located at a shallow depth. A closer look at the samples from dredge 3 (D3-B-03, D3-C-05, and D3-L-02) reveals characteristics specific to cemented beach rocks, including rounded clasts of basalt and carbonate, which indicate their exposure to wave action, and thus deposition in shallow waters. The ages of these samples range from 20.39 - 27.74 Ma, which is on the older end of the age spectrum of the sample set. This older range indicates a more complete history of the subsidence event. Therefore, the samples in dredge 3 provide a high degree of confidence that deposition occurred in a shallow marine environment. The ages of the dredge 3 samples will thus give the most reliable rate at which the seamount subsided. That being said, the present depth of the seamount was found to be ~640 m below sea level. Therefore, the minimum inferred subsidence rate of the Cascade Seamount can be calculated by using the age of the oldest sample — D3-C-05 with an
$^{87}\text{Sr}/^{86}\text{Sr}$ age of 27.74 Ma — which is determined to be 23.1 m/Myr. The maximum inferred subsidence rate comes from using the age of the youngest sample from this dredge — D3-L-02 with an $^{87}\text{Sr}/^{86}\text{Sr}$ age of 20.39 Ma — which is 31.4 m/Myr. This rate is in agreement with the work of Lanyon et al. (1993) and Quilty (1997; 2001).

The cement and clast samples recovered from D2-E-04 in dredge 2 contain minor biogenic material in a calcite matrix. The sample recovered from dredge 4, D4-A-06, is breccia, which contains calcareous shell fragments embedded into the matrix as well as calcareous algae limited to the photic zone (P. Quilty, Personal Communication, 2018). The presence of biogenic matter in dredge 2 as well as shell fragments and algae in dredge 4 show some degree of confidence that deposition occurred in a shallow marine environment. These observations, however, are not as compelling as those from dredge 3. Samples from dredges 2 and 4, therefore, should not be as heavily influential in determining the subsidence rate as compared to samples from dredge 3 since the confidence level at which this assumption is met is not as strong.

Dredge 5 samples, D5-D-05, D5-E-06, D5-G-01, and D5-G-02, are classified as having shell and bioclastic fragments held together in a cement matrix with few calcareous algae (P. Quilty, Personal Communication, 2018). It is possible that the shell fragments were formed earlier than the cement, and thus were cemented together with the algae at a later date. In particular, sample D5-D-05 resembles a rip-up clast, especially since it is composed of a mudstone matrix. Rip-up clasts are not formed at the site of deposition and are unlikely to represent an in-situ deposit. This is supported by the location of this dredge, 825 – 850 m below sea level, upon the lower terrace. It is possible that material from the upper terrace (~700 m below sea level, dredges 3 and 4) was transported through a turbidity.
current or debris flow to the lower terrace. This could explain the large spread of ages (7.69 – 25.98 Ma) from this dredge. There would be no way for the aforementioned physical processes to occur if this dredge was in a shallow marine environment, which further supports the notion that this dredge does not adhere to the shallow deposition assumption. Therefore, there is low confidence that samples from dredge 5 were deposited in a shallow marine environment at this time. This eliminates dredge 5 from subsidence calculations.

The samples recovered from dredges 1, D1-I-05, and 6, D6-C-02, are composed of basaltic clasts. This characteristic is not indicative of shallow marine deposition and would therefore contradict the assumption at hand. Thus, these two samples have a low degree of confidence in inferring the subsidence of the seamount and by extension, the ETP.

The observations from the carbonate samples can therefore be ranked in terms of confidence of deposition in a shallow marine environment, as well as determining the subsidence rate of the Cascade Seamount, which is shown in Figure 4.1. Dredge 3 has the highest confidence in determining the most accurate seamount subsidence history. Dredges 2 and 4 can also be taken into consideration to determine the subsidence rate, however, they do not show as high of a level of confidence as dredge 3. Samples from dredge 5 resemble rip-up clasts as well as cements that could have formed after they had been deposited. These samples do not represent shallow marine deposition and therefore show low confidence in determining the rate of subsidence. Lastly, dredges 1 and 6 are made of basaltic clasts, which indicate low confidence of deposition in a shallow marine environment.
Section 4.1.2 Assumption 2: \(^{87}\text{Sr}/^{86}\text{Sr}\) Signature to Reflect Time of Deposition

As previously mentioned, since Sr has a residence time that is longer than the mixing time of the oceans, Sr isotopes are uniform throughout the present-day oceans and in ancient marine carbonates with equivalent age. However, diagenesis can modify the isotopic ratio of Sr, thus making some samples unreliable for the \(^{87}\text{Sr}/^{86}\text{Sr}\) isotope age determinations. The underlying assumption when determining the rate of subsidence of the Cascade Seamount is that the samples have not undergone diagenesis, nor were they exposed to contamination from non-carbonate phases such as basalt during microdrilling, essentially assuming their respective \(^{87}\text{Sr}/^{86}\text{Sr}\) ratios representative of the seawater during the time in which they were deposited. Elemental ratios of Mg/Ca were analyzed in order to determine the source of carbonate for each sample. Sr/Ca ratios were determined for each sample to help to determine if \(^{87}\text{Sr}/^{86}\text{Sr}\) ratios were altered due to diagenesis. Ti/Ca ratios were analyzed in order to determine if samples were exposed to non-carbonate phases during microdrilling that would alter their \(^{87}\text{Sr}/^{86}\text{Sr}\) ratios.

Inorganic carbonates have Mg/Ca signatures one to two orders of magnitude greater than biogenic carbonates (Barker et al., 2005). According to Oomori et al. (1987), predicted Mg/Ca signals from inorganic precipitated carbonates were between \(~75\) and \(118\) mmol Mg/mol Ca, while Lea et al. (1999) measured organic foraminifera ratios from \(<1\) to \(~17\) mmol Mg/mol Ca. The difference in the Mg/Ca ratios from these studies are depicted in Figure 4.2 (adapted from Barker et al., 2005). The Mg/Ca ratios obtained from these studies can therefore be used in order to help determine sample origin. All Cascade Seamount samples fall between the biogenic and inorganic Mg/Ca ranges, indicating that the samples are in fact, a mix of the skeletal foraminifera and the micrite matrix in which they were
preserved. While micrite can still undergo diagenesis, its low porosity and permeability reduce the possibility of carbonate recrystallization and minimizes the concentration of Sr expelled into the interstitial waters of the carbonate rock (Edwards et al., 2015). These factors lessen the possibility of losing the original $^{87}\text{Sr}/^{86}\text{Sr}$ signal. Edwards et al. (2015) indicates that the change in bulk carbonate during diagenesis is not significant enough to change the $^{87}\text{Sr}/^{86}\text{Sr}$ seawater ratio of the carbonate matrix (Chaudhuri and Clauer, 1986; Veizer, 1989). Therefore, these samples that are of mixed carbonate origin should have $^{87}\text{Sr}/^{86}\text{Sr}$ signatures that reflect the time at which they were deposited.

Samples were analyzed for their Sr/Ca ratios in order to test whether the carbonate samples were preserved or went through diagenesis (Lear et al., 2003). These ratios were compared to accepted foraminiferal ratios from Cenozoic benthic foraminiferal Sr/Ca record, which range from 1.2 to 2.0 mmol Sr/mol Ca (Lear et al., 2003). Six samples have Sr/Ca ratios that do not fall within this range. These samples are D1-I-05 (0.382), D3-B-03 (2.492), D3-C-05 (0.261), D5-E-06 (0.476), D5-G-01 (0.803), and D6-C-02. Although these samples do not fall within this range, the Mg/Ca ratios indicate these samples are due to a mixture of both biogenic and inorganic carbonates, and therefore will vary in their Sr/Ca ratios. As previously stated, samples from dredges 1, 5, and 6 do not have as high of a confidence level in indicating the subsidence rate of the Cascade Seamount as the samples from dredge 3. Therefore, it is important to show that dredge 3 samples were not diagenetically altered. According to Edwards et al. (2015), micrite can still undergo diagenesis, but the $^{87}\text{Sr}/^{86}\text{Sr}$ ratio will remain to reflect the time of deposition (Chaudhuri and Clauer, 1986; Veizer, 1989). Therefore, these samples should still reflect the $^{87}\text{Sr}/^{86}\text{Sr}$ ratios of the seawater at the time of deposition.
Ti/Ca ratios were also of interest in order to determine if Sr signals were contaminated from possible exposure to non-carbonate phases during microdrilling. Faure (1998) determined the percent composition of Ti and Ca in basalt to be 11,400 ppm (1.14%) and 7.2 ppm (0.00072%), respectively, while carbonate rocks were made up of 400 ppm (0.04%) Ti and 30.23 ppm (0.003023%) Ca (Turekian and Wedepohl, 1961; Vinogradov, 1962). The Ti/Ca basalt ratio was found to be 1.583 ([11,400/1x10^6] / [7.2/1,000]), while that of carbonate rocks was 0.0132 ([400/1x10^6] / [30.23/1,000]). All ratios above the carbonate ratio would be considered contaminated with a non-carbonate phase, in this case, basalt. Only sample D1-I-05 had a Ti/Ca ratio of 0.0476751, which is greater than the threshold, indicating the presence of basalt. As previously stated, the sample from dredge 1 was composed of basalt, which would increase the likelihood of contamination. Therefore, the ^87Sr/^86Sr ratio of this sample should be interpreted with caution. Since all other samples had Ti/Ca ratios below this threshold, the samples were not contaminated from exposure to non-carbonate phases during microdrilling, and should represent the ^87Sr/^86Sr ratios of the seawater during their time of formation.

From the elemental ratio analyses, the assumption has been met that the samples have not been diagenetically altered or contaminated, and therefore reflect the ^87Sr/^86Sr ratio of at the time of deposition. The ages obtained from this experiment are in agreement with the hypothesized seamount formation put forth by Exon et al. (1997), stating that the seamount subsided in the late Oligocene until the Miocene, thus identifying the timing of the opening of the Tasmanian Gateway. Therefore, the subsidence rate of 85 m/Ma that was put forth by Stickley et al. (2004) should be disregarded.
Section 4.1.3 Ongoing Work

Ar-Ar analyses are a part of an ongoing collaboration by colleagues in Tasmania to determine the geochronology of basalt recovered from the Cascade Seamount. The ages established from this analysis indicated that the seamount formed 36 Ma (J. Halpin, Personal Communication, 2018). This leaves a 9.5 Myr gap between the time that the seamount formed and the time that calcium carbonate deposits formed on the seamount, which indicate when it began to subside. This lag can be contributed to the Marshall paraconformity, which as mentioned previously, is a lack of sediment deposition in the geological record between the early and late Oligocene (Lever, 2007). As mentioned in Carter, R.M. et al. (2004), all ODP site locations along the Tasmanian Gateway, including Site 1172, have evidence of this paraconformity, as shown in Figure 1.5 (adapted from Carter, R.M. et al., 2004). Since ODP Site 1172 is only ~23 km away from the sampling site, it is safe to assume that the Marshall paraconformity exists on the Cascade Seamount. As shown by the spread of ages found at different dredge depth intervals, there does not seem to be a correlation between depth and age, and therefore, there is a lack of preexisting stratigraphy. This lack of correlation is shown in Figure 4.3. This can be explained by the Ar-Ar analysis, which showed the formation of the seamount at 36 Ma (J. Halpin, Personal Communication, 2018). From that point, sediment was able to accumulate on top of the seamount after it had already formed. In addition to adhering to both assumptions put forth, the oldest age obtained from the samples, 27.74 Ma, is contextually logical in calculating the subsidence rate of the Cascade Seamount. In addition, there may be misinterpretations in the calculated subsidence from Stickley et al. (2004) because of this non-depositional event.
4.2 Statistical Analysis of ODP Site 1172

As previously mentioned, Stickley et al. (2004) used sedimentological, geochemical, paleomagnetic, and biostratigraphic parameters to analyze core 39X from ODP Site 1172 to determine the 85 m/Myr subsidence rate for the Cascade Seamount and by extension, the Tasmanian Gateway. The sedimentological data from this core, grain size, was used for statistical analysis in order to determine the presence of a turbidity current within the core sample.

The results from all three statistical tests indicate that depth has a significant effect on grain size. A Pearson’s Product-moment correlation analysis showed that grain size increases with depth at evolutionary phase C2. A Model I least-squares linear regression analysis showed a significant linear relationship between increasing grain size and depth in C2. The single factor ANOVA indicated that increasing depth had a significant effect on grain size.

The outcome of these statistical analyses indicates that it is very likely that a turbidity current was present in the sediment from evolutionary phase C2. As previously mentioned, turbidity currents are problematic for calculating subsidence rates because they allow for error in the interpretation of the paleodepth stratigraphy. In this case, if a turbidity current was present during the time that sediment was deposited in evolutionary phase C2, the subsidence model created by Stickley et al. (2004) would be inaccurate. Therefore, this invalidates the constraints established by Stickley et al. (2004) that determined the time at which the Tasmanian Gateway deepened.
Figure 4.1 Average age with SEM of each sample from the Cascade Seamount color coded by confidence of deposition in a shallow marine environment, superimposed onto the LOWESS Curve.
Figure 4.2 The Mg/Ca signature of inorganic carbonates (black solid line) appear to be two orders of magnitude higher than that of organic carbonates (black line with white markers and black line with black markers) (adapted from Barker et al., 2005).
Figure 4.3 The $^{87}\text{Sr}/^{86}\text{Sr}$ signature of each sample from the Cascade Seamount plotted with corresponding age and depth. There is no correlation between age and depth.
Chapter 5
Conclusion and Broader Impacts

Determining the rate at which the Tasmanian Gateway subsided is crucial in fully understanding the continental shifts that took place in the Paleogene and early Neogene periods. In the presence of an open Drake Passage, the opening of the Tasmanian Gateway was the final step in enabling the progression of the ACC. This tectonic event is hypothesized to have led to the onset of glaciation on Antarctica (Kennett, 1977). Finding a more robust subsidence rate of the Tasmanian Gateway will help to better understand the controls that tectonic gateways had on the initiation of the ACC.

One way to deduce how the Tasmanian Gateway subsided is by looking at the subsidence of a microcontinent that is similar in structure and composition, the ETP. Here, the Cascade Seamount, which rests on the ETP, is used as a proxy for sea level in order to calculate the subsidence rate for the ETP, and by extension, the Tasmanian Gateway.

Samples dredged from the Cascade Seamount were analyzed using SIS, a chemostratigraphic method that uses the $^{87}$Sr/$^{86}$Sr ratio, in order to determine sediment age. Since none of the samples analyzed were older than the Eocene-Oligocene transition (~34 Ma), it is clear that the beach terraces found on the seamount formed as the result of tectonic subsidence of the seamount itself, and not due to a fall in eustatic sea level from glaciation. The oldest sample that was deemed geologically reliable was dated at 27.74 Ma, giving the Cascade Seamount a new subsidence rate of 23.1 m/Myr. This rate is in agreement with Lanyon et al. (1993) and Quilty (1997; 2001), but not of Stickley et al. (2004). Ar-Ar data
determined the seamount to have formed ~36 Ma, indicating a 9.5 Myr lag between formation and calcium carbonate deposition, which can be attributed to the acceleration of bottom currents throughout the region that resulted in widespread non-deposition known as the Marshall Paraconformity. Therefore, the calculations and results put forth by Stickley et al. (2004) are misrepresentations of the events surrounding the Cascade Seamount.

Statistical analyses performed on the data generated by Stickley et al. (2004) indicate that a turbidity current was present in evolutionary phase C2, which is deduced from the significant results of a correlation, regression, and single factor ANOVA. The outcome of these further debunk the 85 m/Myr subsidence rate.

The data obtained from this study will allow for a more constrained time frame during which the ETP subsided. This can be applied to the subsidence of the Tasmanian Gateway, which led to changes in ocean circulation patterns in the Tasmanian-Antarctic region, and thus allowed the ACC to prevail. In addition, the subsidence of this thinned piece of continental crust would help to constrain models that depict passive margin evolution, such as the McKenzie model (McKenzie, 1978), which projects how continental crust stretches, thins, and eventually sinks.
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