Otago Submarine Canyons: Mapping and Macrobenthos

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Abstract

Submarine canyons are steep-sided "V' or "U" shaped valleys that incise continental slopes worldwide. The geophysical and oceanographic features of submarine canyons can produce environmental conditions that cause benthic assemblages to be distinctive and productive compared to those of the adjacent slope; however the assemblages are potentially vulnerable to anthropogenic impacts, including bottom fishing. In order to help inform policy and management, submarine canyons need to be objectively defined topographically and their benthic assemblages characterised. A canyon network occurs off the Otago Peninsula, south-eastern New Zealand, but lack of detailed bathymetric data and adequate benthic sampling has limited study of the canyons. This thesis outlines a method of defining submarine canyon areas and examines epifaunal and infaunal assemblages of the Otago canyons and adjacent slope. Objective definition of the Otago canyon network in the GIS software GRASS along with the steps to use this methodology worldwide are described. Archival count data from 1966-74 on the epifauna are analysed using the PRIMER suite of programs to characterise epifaunal assemblages. Anomurans, polychaetes, asteroids and ascidians make up 70% of the epifaunal canyon assemblage. The epifaunal assemblage is clearly defined by water depth and recognisable from 380 m. Quantitative sampling of infauna in Saunders canyon, Papanui canyon and adjacent slope was carried out to examine infaunal community structure of the canyons and adjacent slope. Infaunal canyon assemblages are dominated by polychaetes, amphipods, ophiuroids, decapods and isopods in canyons, accounting for 75% of collected individuals. Polycheates, malacostraceans, ophiuroids and foraminifera comprise the bulk of collected infauna from the slope environment. A checklist of recorded species found in the Otago canyon network is appended.

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CHAPTER 1 – INTRODUCTION

The Deep-Sea Environment

The deep-sea environment is the most expansive area on earth, covering 324 million km^2 (Bruun 1956) (Figure 1). The deep-sea is usually defined as deeper than 200 m, which contains the bathyal depths (200–2 000 m), the abyssal depths (2 000–6 000 m), and the hadal or ultra-abyssal depths (greater than 6 000 m) (Bruun 1956; Vinogradova 1958; Jones 1969; Gage and Tyler 1991). Before the Challenger expedition in 1872–6, the deep-sea environment was believed to be uninhabitable by Edward Forbes due to the immense pressure, lack of light, and cold temperature that characterise this environment (Gage and Tyler 1991; Anderson and Rice 2006). Forbes proposed his azoic hypothesis based on his work in the Aegean sea, which stated that no animal life could be found at a depth of 300 fathoms (550 m) or greater. The azoic hypothesis was generally accepted even though there was ample evidence to counter it, such as annelid worms and asteroids collected by Captain John Ross and James Clark Ross from depths of 200–800 fathoms (365–1 465 m) (Anderson and Rice 2006). The numerous samples brought up from depths greater than 100 fathoms (183 m) by the Challenger expedition yielded a surprising diversity of life which, along with the already collected evidence against the azoic hypothesis, disproved the prevailing idea that the deep sea was void of life (Murray 1895; Anderson and Rice 2006). This trend of finding higher diversity than expected was consistent among all studied areas of the world's oceans (Bruun 1956; Hessler and Sanders 1966; Jones 1969; Wolff 1970).

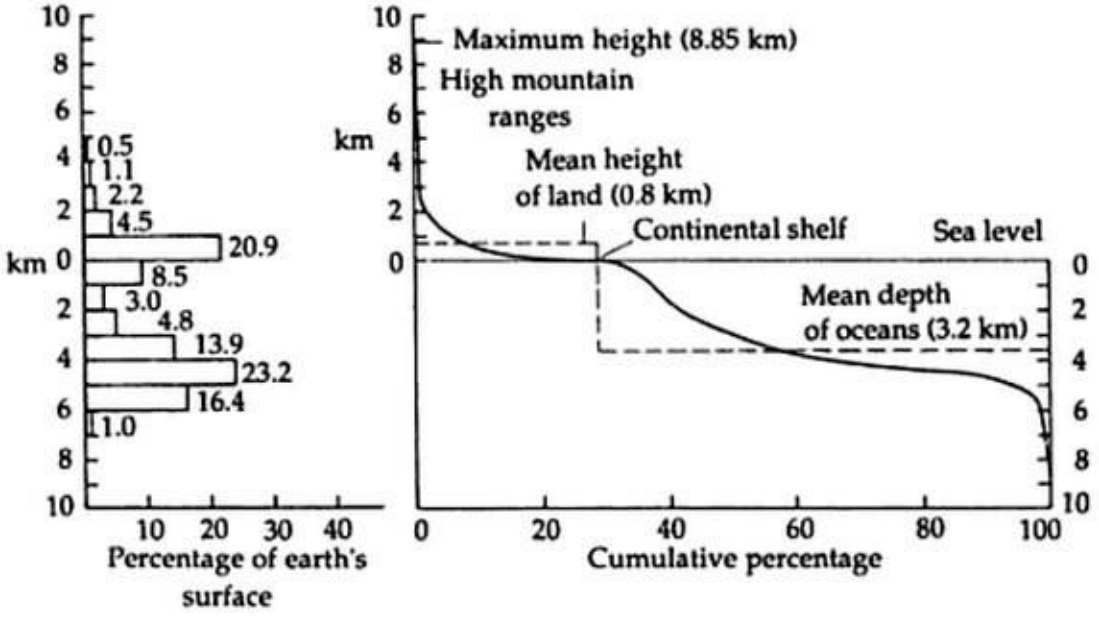


Figure 1: Proportion of earth's surface in relation to elevation. The graph on the left provides specific percentages that different 1 km elevation sections cover on the earth's surface, while the right-hand graph shows the cumulative percentage of cover on the earth's surface by height. The oceans comprise 70.8% of the earth's surface, and most of the ocean's area (> 90%) is categorized as the deep sea. Figure taken from Gage and Tyler 1991.

Deep-sea ecology presents unique challenges for study because the deep sea itself is difficult to access due to physical constraints such as depth, pressure, and lack of light. However, there have been several advances in the field of deep-sea ecology, such as the discovery of chemosynthetic hydrothermal vent environments, whale-fall communities, and underwater brine lakes (Brooks *et al*. 1979; Corliss *et al*. 1979; Bennett *et al*. 1994;). These discoveries highlight the rapidly expanding spread of research in the deep sea, but are mostly in the abyssal depths. Benthic habitats are still being discovered at a fast rate since the late 19th century, about one habitat in every eight years (Ramirez-Llodra *et al*. 2010). The deep sea, while the most extensive area on earth, is among the least known environments. New, but expensive, technology is necessary to study these areas; and since they are in need of systematic study it is difficult to generalise about the deep-sea environment as a whole. Fortunately the shallower parts of the deep sea, such as the continental slope, have been relatively well studied.

The Environment of the Continental Slope

The continental slope is influenced by multiple environmental gradients which help determine the structure of its benthic communities: oxygen levels, food supply (primarily detritus), flow patterns, and both sediment disturbance and grain size (Levin *et al*. 2001). Oxygen minimum zones (OMZ) have been described in midwater regions of 100 to 1 200 m depth (Levin *et al*. 2001). These zones form beneath areas of upwelling where organic matter is degraded. Distribution of the benthos is greatly affected by the presence of an OMZ as molluscs, echinoderms, and crustaceans react poorly to low oxygen levels (Levin *et al*. 2001). The benthic community can be further disrupted through large sediment drifts caused by thermohaline-driven currents or benthic storms (Hollister *et al*. 1984; Lampitt 1985). Due to the lack of primary production aside from chemosynthesis, POM is the primary food source of these habitats; therefore, sediment size can affect benthic community structure (Van Dover *et al*. 2000). POM flux tends to be higher on the slope than in the abyssal depths (Rowe *et al*. 1994). Unsurprisingly, the benthic slope community favours an oxygen-rich environment with a high input of particulate organic matter (POM) and low sediment disruption; therefore, presence/absence of oxygen-rich bottom water, OMZs, and depth affect the structure of the benthic community.

The continental slope areas contain a high diversity of species. Both the megafuana and macrofauna community compositions of the slope environment are correlated with depth (Grassle *et al*. 1975; Smith and Hamilton 1983). Ophiuroids dominate the slope megafauna off the coasts of southern California and the eastern US, the Mediterranean slope is characterised by decapod populations in which the dominant crustacean is determined by seasonal vertical fluxes, and both ophiuroids and bryozoans are among the most conspicuous epifauna of the slope area off of New Zealand's south island (Grassle *et al.* 1975; Probert *et al*. 1979; Smith and Hamilton 1983; Cartes 1998). The slope fauna in the southern ocean tends to have a higher degree of eurybathy than slope fauna worldwide and the collected species can be much larger than other members of the same species elsewhere (Brant *et al*. 2007). Although the slopes of the US, Mediterranean, and Southern ocean have different dominant organisms; polychaetes, amphipods, malacostracans, ophiuroids, bivalves, and gastropods are consistently found throughout the slope

environment worldwide (Hessler and Sanders 1966; Smith and Hamilton 1983; Probert and Grove 1998; Brant *et al*. 2007).

The slope environment has numerous features that can provide hotspots for benthic organisms. Some benthic species use sponges and corals as substrate as depth increases since the sediment becomes finer and more uniform (Buhl-Mortensen *et al*. 2010). Physical features of the slope, such as submarine canyons, can provide areas of high detrital input and act as hotspots of benthic organisms (Vetter 1994; De Leo *et al*. 2010).

Submarine canyons did not receive much attention, and were not even defined, until the 1940s (Sverdrup *et al*. 1942). Study of the geophysical aspect of submarine canyons, especially their origin, was the primary concern after their recognition (Sverdrup *et al*. 1942; Cooper and Vaux 1949). Interest soon moved to the canyon-specific currents generated by their shape, their ecology, and interactions between the geophysical properties of the canyons and their ecology (Cooper and Vaux 1949; Allen *et al*. 2001; De Leo *et al*. 2010).

Geological Aspects of Submarine Canyons

Submarine canyons are deep, long, and narrow "V" or "U" shaped incisions in the continental slope that have an average length of 43 km (Harris and Whiteway 2011). The distance from the head of a typical canyon to the shore varies with faulting and local sedimentary processes, which places the head anywhere from a few hundred metres to over fifty kilometres away from the shore (Sverdrup *et al*. 1942; Lo Iacono *et al.* 2013). The depth ranges of submarine canyons range from 150 m to 6 542 m with a global average of 1 992 m (Allen *et al.* 2001; Harris and Whiteway 2011). The slope of a typical canyon wall varies from 2.9° to 23.7° with a global mean of 5.1° (Harris and Whiteway 2011; Brothers *et al*. 2013). The uppermost segment of the canyons which intersects with the slope tends be the steepest section and has a linear to barely convex profile; the lower segments of the canyons rapidly turn to highly concave profiles (Brothers *et al*. 2013). A total of 5 849 canyons were recorded as of 2011 and are concentrated around the British Isles, Mediterranean Sea, from Vancouver Island to southern California and from Cape Cod to Cape Hatteras (Daly 1936; De Leo *et al*. 2010; Harris and Whiteway 2011). Canyons occur

worldwide along a majority of the world's non-polar coastline and active continental plate margins (Daly 1936) (Figure 2).

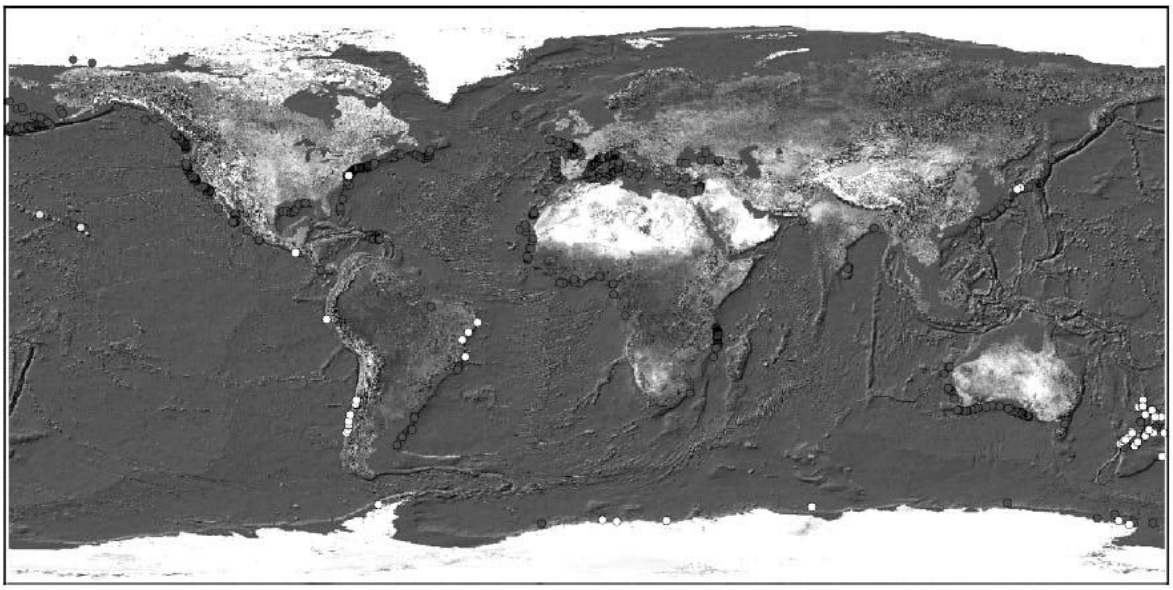


Figure 2: Worldwide distribution of submarine canyons. The dark circles are named canyons, the light circles are recorded but unnamed canyons for all areas except off New Zealand, where the light circles represent canyons counted by De Leo *et al*. from an unpublished source. Figure taken from De Leo *et al*. (2010).

Submarine canyons connect the shelf to the continental slope and allow for the exchange of sediment (mainly down-canyon) and water between shelf and offshore environments. The canyons appear to have been formed by erosion on the shelf caused by a combination of glacial movement, sediment transport, earthquakes, and turbidity currents; these mechanisms are evident in the various sediment deposits in the canyons (Hargrave *et al*. 2004). Muddy dense currents, formed as a result of the eroding sediment, flowed down the continental shelf and slope; which began an erosion process, which still is occurring, similar to that of canyon-forming rivers on land (Daly 1936; Brothers *et al*. 2013). This erosion first started when the continental shelf was left exposed to the tides and wind by the lower sea level that occurred during the Pleistocene period's glacial stages. Daly (1936) estimated that this erosive process occurred for over 200 000 years as the four sets of ice-caps expanded and disappeared over the time since the Ice Age began.

The last period of lowered sea level occurred at the maximum of the Illinoian Glacial Stage over 30 000 years ago; submarine terraces, erosional terraces, and shallow water deposit remains found worldwide correlate with this time period (Donn *et al*. 1962).

The geophysical structure of the slope itself also has an effect on canyon formation and shape. Faulting can be responsible for blocking canyon mouths, vertical displacement, adding knick points to the canyons and extending the length of the canyons (Harris *et al.* 2013). Turbidity currents, which enhance canyon formation, can be created by the head of a canyon if the slope of the head is steeper than four to five degrees by transforming flow along the shelf (Brothers *et al*. 2013). Entrainment of loose sediment widens the path used by the muddy, dense sediment-carrying current created by the canyon head (Daly 1936; Brothers *et al*. 2013). This transport of sediment along the exposed shelf formed, and is still shaping, the submarine canyons found worldwide (Daly 1936).

Sediments in the canyons vary greatly, from fine silt to poorly sorted gravel in the deeper parts of the canyon and from sand to gravel to silt in the upper canyon area (Hargrave *et al*. 2004). Sediment collected from inside and nearby canyon environments has been shown to be a combination of biogenic and terrestrial material (Monaco *et al*. 1999; Oliveira *et al*. 2007). The canyons currently act as sediment conduits and are responsible for transporting terrestrial sediment into the deep sea environment (Daly 1936; Oliveira *et al*. 2007; De Leo *et al*. 2010; Schmidt *et al*. 2013). The amount of transported sediment and its impact vary greatly between canyons due to changes in their longitudinal profile (Covault *et al*. 2011). The Nazaré canyon, off the Iberian peninsula, moves an average of 41 275 g/cm^2/y of sediment, but the Cap-Ferret canyon in the Bay of Biscay transports < 0.015 to > 0.050 g/cm^2/y of sediment (Martín *et al*. 2001; Schmidt *et al.* 2013). During upwelling phases, weakly stratified sediment is resuspended, which causes an increase in total mass flux with depth and a decrease in the variation in chemical composition of the sediment itself (Monaco *et al*. 1999; Oliveira *et al*. 2007). Natural sediment resuspension levels are much lower than those found in canyons that are consistently or periodically dredged by bottom trawls for fishing (Martín *et al*. 2013). Vertical mixing and upwelling events have been found to be localized by the canyons (Cooper and Vaux 1949). These upwelling events generate complex currents inside the canyons which advect most non-migratory zooplankton, displace plankton close to the surface across the canyon, and gather some migratory zooplankton species near the canyon

head (Allen *et al*. 2001). Larger organisms, such as fish, squid, and adult crustaceans, can be concentrated in the canyons as a result of increased POM introduced into the canyon by these currents (Bosley *et al*. 2004).

Oceanographic Aspects of Submarine Canyons

Canyon-specific currents have a substantial impact on distribution of sediment and organisms found inside the canyon environments. Localised upwelling events, which allow deep flow onto the shelf, have been well studied and are a common feature in the canyons (Klinck 1988; Hickey 1997; She and Klinck 2000; Allen *et al*. 2001; Allen and de Madron 2009; (Figure 3). Downwelling along the opposing side of the canyon is paired with these upwelling events, which is a result of Ekman pumping of the upwelled flow (Hickey 1997; Allen 2004). The upwelling and paired downwelling events can also pull detritus into the canyons and focus organic material into the canyons (Schlacher *et al*. 2007). A change in the prevailing wind can lead to a change in pycnocline depth, which allows an up-canyon progressive wave to replace a partly standing wave as the dominant wave inside the canyon walls (Hall *et al*. 2013). In addition to allowing deep water to rise to the shelf, submarine canyons also undergo periodic flushing events caused by a contrast in water density (Canals *et al*. 2006). These events, called dense shelf water cascades, can rapidly affect the benthic environment due to the increased amount of water, sediment, and nutrients they introduce into the canyons in a relatively short amount of time (Canals *et al.* 2006; van Oevelen *et al.* 2011).

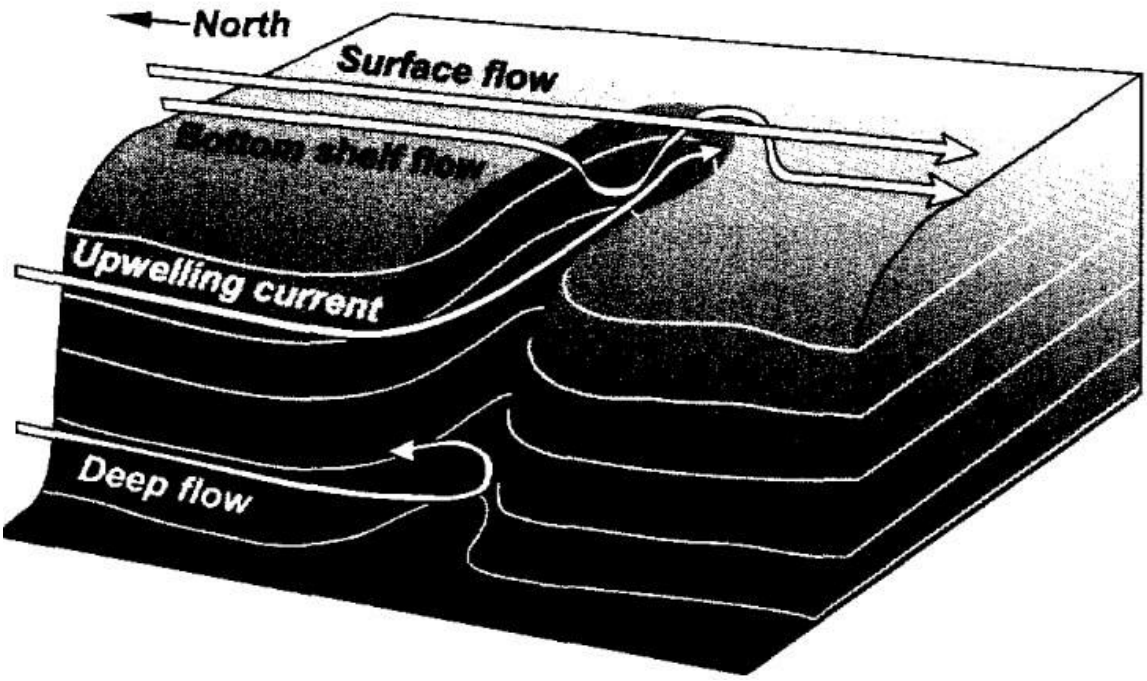


Figure 3: Canyon-specific flow patterns and distortion of flow caused by the canyon presence. Figure taken from Allen *et al*. (2001).

Geophysical factors such as the flushing of the canyons, focused upwelling, and constant flow of sediment greatly affect the local canyon biology and ecology (Soetaert *et al*. 1991; Hickey 1997; Bosley *et al*. 2004; van Oevelen *et al*. 2011). A total of 16–30 % of biodiversity in the canyon environment is accounted for by the slope, transverse profiles and backscatter reflectivity of sediments found in the canyons (De Leo et al. 2013). Canyons with "V-shaped" profiles generally have low biodiversity, as the steep slope encourages a turbulent sediment environment. This turbulent environment makes it difficult for organisms to settle (Garcia *et al.* 2007; De Leo et al. 2013). "U-shaped" profiles tend to be associated with higher diversity as the sedimentary environment is calmer and easier for the benthos to inhabit (De Leo et al. 2013).

Benthos of the Slope vs Canyon Environments

Biomass and benthic abundance in canyon environments tend to be higher than those of adjacent slope areas, suggesting that canyons can be productive environments (Vetter and Dayton 1999; Rex *et al*. 2006; Schlacher *et al*. 2007; De Leo *et al*. 2010).

Vetter (1994) recorded over $3x10^6$ crustaceans per m^2 in La Jolla canyon, which was more than three times higher than the density on the slope areas around the canyon. Rex *et al*. (2006) compiled data from 128 studies to determine an average megafaunal biomass of the deep-sea benthos. The highest biomass concentration they reported was 0.80 g C/ m^2 for depths greater than 500 m. The megafaunal biomass measured in Kaikoura canyon, off eastern New Zealand, was about two orders of magnitude higher (89.0 g C/m^2 compared to 0.80 g C/m^2) than that in the non-canyon areas (De Leo *et al*. 2010) (Figure 4).

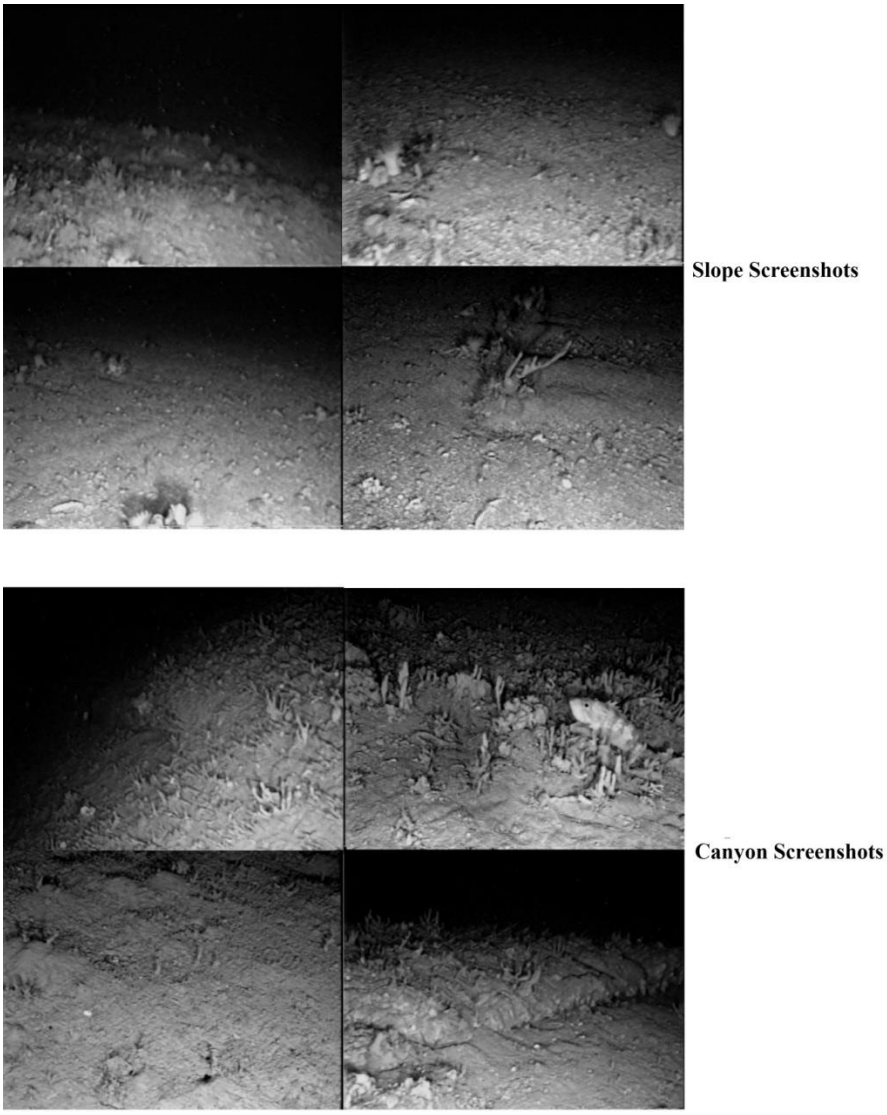


Figure 4: Screenshots taken by Gray (1993) from ROV footage from Karitane canyon which demonstrate the difference in abundance between slope and canyon areas.

Although it is known that upwelling of nutrient-rich water and downwelling pulls detritus into the canyons and that the canyon environment shows a general increase in both the density and biomass of organisms, no studies have empirically linked the upwelling events and productivity (Vetter and Dayton 1999; Garcia *et al*. 2007) (Figure 5). The detritus in the Nazaré canyon environment is fresher, more concentrated, and of higher quality than on the surrounding slope, but the abundance of organisms is higher in the slope environment (Garcia *et al*. 2007). This is thought to be due to a turbulent sediment environment along with low oxic conditions, which impairs the benthic community. A similar observation was made in a canyon network in southern California, where low oxygen conditions have inhibited biodiversity and productivity (Duffy *et al*. 2013). Along with the low oxygen conditions found, the canyons were also "V-shaped." This shape implies that the canyon environment is less habitable when either the oceanographic or sediment conditions change too rapidly (De Leo *et al.* 2013).

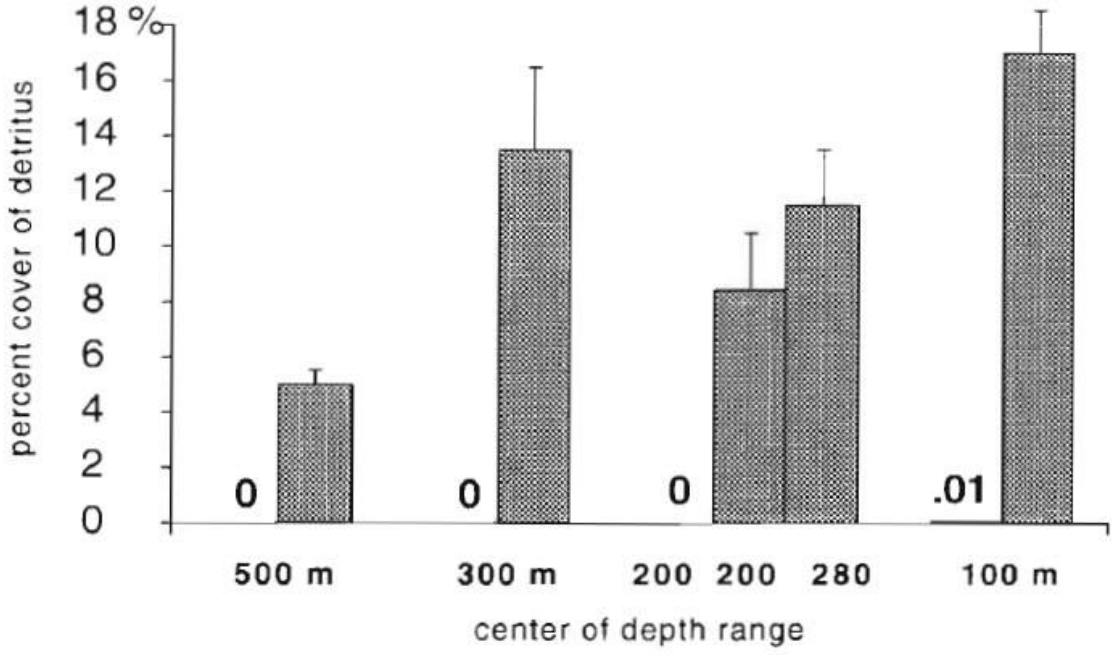


Figure 5: Kelp and surfgrass cover in the La Jolla canyon measured by Vetter and Dayton (1999). Numbers to the left of the columns show percent cover outside of the canyons, columns on the right show percent cover inside the canyons. Figure taken from Vetter and Dayton (1999).

The high productivity and intricate currents caused by the shape of the canyons and observed in the canyon environments worldwide are areas of interest in recent studies. Although a number of conclusions can be made about the canyon environments, few canyons have been studied in detail (Probert *et al*. 1979; Vetter 1994; Bosley *et al*. 2004; Garcia *et al*. 2007; Bianchelli *et al*. 2008). One of the most intricate canyon networks, which has not been studied in great detail, lies in the exclusive economic zone (EEZ) of New Zealand. New Zealand's EEZ encompasses a large variety of features, which include: hydrothermal vents, trenches, submarine canyon networks, sea mounts, and the most productive, non-chemosynthetic, deep-sea environment recorded to date, that make the EEZ of New Zealand unique (Batson 2003; Leduc *et al*. 2013).

Submarine Canyons of New Zealand

New Zealand has < 20 submarine canyons located along the east coast of the South Island and a canyon system consisting of eight canyons in the Cook Strait (Houtz *et al*. 1967; Probert *et al*. 1979; Lewis 1994; Lewis and Barnes 1999; Mountjoy *et al.* 2009). The Cook Strait canyon system contains five canyons: Cook Strait canyon, Nicholson canyon, and Wairarapa canyon form the upper part of the network, while Palliser and an unnamed canyon form the lower part of the network. Campbell canyon, Opouawe canyon and Pahaua canyon are also located in the Cook Strait area but are not part of the Cook Strait canyon system. These canyons vary from 14 km (Wairarpa) to 70 km (Cook Strait canyon) in length and have a slope of 3–30° (Mountjoy *et al*. 2009). Kaikoura canyon, located off of the northeastern coast of New Zealand's South Island, has recently become the focus of detailed study due to its unusually high productivity levels (De Leo *et al*. 2010).

New Zealand's canyons typically contain organic debris with gravel in their lower, wider parts and a mixture of gravel, sand, and mud elsewhere (Andrews 1973; Lewis and Barnes 1999). The canyons along the east coast of the South Island can move sediment introduced by the Southern Alps northward (Lewis and Barnes 1999). 40 000 000 tonnes of sediment is introduced into the ocean by the Southern Alps, 1 500 000 of which is carried along the shelf into the Kaikoura canyon and redistributed to deeper parts of the slope (Lewis and Barnes 1999). Kaikoura canyon and Cook Strait canyon are a source of sediment for the Hikurangi Channel, which extends east of New Zealand's North Island, is

1 500 km long, and supplies turbidites to nearby trenches and fan-drifts (Lewis and Barnes 1999). The Hikurangi Channel is an example of many canyon-channel variations such as: fan channels, ocean channels, trench-axis channels and boundary channels that occur worldwide (Lewis 1994; Mountjoy *et al*. 2009).

The typical topography and shape of the canyons is not very well described, beyond most are "V-shaped", as emphasis was placed on general ecology, and detailed bathymetry data are lacking (Andrews 1973). Only the Otago canyon network and the Cook Strait canyon system have been profiled with high resolution data (Mountjoy *et al*. 2009; Rudd 2012). Due to this lack of high quality bathymetry data the exact number of submarine canyons cannot be presently given since there are multiple, small, canyon-like features which may or may not be considered true canyons. The most recent collection of high-quality bathymetry data occurred in August 2012 and revealed the complexities of the Otago canyon network, off of the Otago peninsula, that were previously unknown (Rudd 2012). Off of the Otago Peninsula on the South Island of New Zealand are a number of submarine canyons that form a web-like canyon network that come within 10–15 km of the shore (Batson 2003; Rudd 2012). All but one of the canyons intersect the continental shelf at about 120 m depth; the northern-most canyon, Karitane Canyon, starts around 72 m depth (Andrews 1973).

Benthos of the Otago Canyon Network

The ecology of the canyon network off of the Otago Peninsula has not been well studied previously, but some data on which organisms can be found in the canyons and in what relative abundance they occur have been gathered; however, quantitative data are lacking (Probert *et al.* 1979; De Leo *et al*. 2010). Polychaetes, molluscs, crustaceans, bryozoans, and echinoderms make up the bulk of the canyon epifauna (Probert *et al*. 1979). The benthic community within canyon areas was found to differentiate at a depth of about 450 m, which is where the fauna changed from that resembling fauna in gravelly shelf areas to a canyon specific fauna (Probert *et al.* 1979). The reason for the separation of fauna around 450 m depth is not known, but it is suspected that changes in community structure may be driven by changes in sediment type (Probert *et al*. 1979).

The epibenthic community in the upper canyon areas off the Otago region is dominated by bryozoans, ascidians and asteroids as well as an abundance of anomurans, ophiuroids, and bivalves (Probert *et al*. 1979). Sponges, corals, crabs, gastropods, and polychaetes can also be found in the upper canyon areas. The fauna transitions from upper canyon fauna to the deeper canyon fauna smoothly over a few hundred metres. The community in the deep canyon is primarily composed of gastropods, sponges, anomorans, and bryozoans with few crabs, bivalves, ascidians, asteroids, ophiuroids, and corals (Probert *et al*. 1979). Organisms gathered in canyon samples by Probert *et al*. (1979) were not always counted, but when actual numbers were not recorded, the relative abundance of collected organisms was. It is imperative to obtain quantitative data from the canyon environments in order to expand ecological studies and inform policies dealing with anthropogenic impacts, such as deep-sea fisheries, of the canyon environment. Deep-sea fisheries rely on these assessments, which cannot be done without quantitative data.

Deep-sea fisheries became increasingly important after the Second World War, and since 1964 have globally contributed 800 000–3 600 000 tonnes of fish per year (Koslow *et al*. 2000; FAO 2011). New Zealand has the largest catch rate for its local area, area 81, peaking at 650 000 tonnes in 1998 and 420 000 tonnes in 2009 (FAO 2011). Local fisheries expanded in the 1980s into the deeper environments which caused interest in studies of edible fish location, spawn size and spawn stock. The largest of these fisheries targets *Macruronus novaezealandiae*, the hoki, which spawns in the canyon areas off the west coast of South Island and in the Cook Strait during the winter (Coombs and Cordue 1995). 200 000–250 000 tonnes of hoki were caught per year until 2000 when the catch rate was reduced; 90 000 tonnes of hoki were collected in 2008 and 2009 (FAO 2011). The other species found in the deep-sea fishery sites tend to be poor candidates for fishing as they have late maturity ages, slow growths and cannot reproduce quickly; these deep-water species also are part of a fragile ecosystem with a limited distribution (Koslow *et al*. 2000).

Some submarine canyons have also been found to contain cold-water corals, which are classified as a vulnerable marine ecosystem (Mortensen and Buhl-Mortensen 2005). The appearance of these vulnerable ecosystems and potential interest in fisheries increased attention to canyon areas, and emphasized the need to produce an objective definition of canyon areas (Harris and Whiteway 2011). An objective definition would clarify which areas should be classified as submarine canyons and inform environmental policy making.

Along with this objective definition, it is crucial to gather quantitative data on the submarine canyon ecology, primarily for both a better understanding of the community structure of the canyons and to provide a foundation for further ecological studies but also for any potential importance for deep-water fisheries.

Purpose and Intent of Thesis

In order to better understand the ecology of submarine canyons and assess potential anthropogenic impacts, quantitative data are essential. In order to inform policy making involving Marine Protected Areas and Vulnerable Marine Ecosystems, an objective definition of submarine canyon areas is also essential. This thesis aims to provide and compare assemblages of the submarine canyon areas and the adjacent slope areas off of the Otago Peninsula along with an objective methodology of identifying submarine canyons areas from raw bathymetry data. Due to time constraints of the nature of the MSc degree and vessel time, it was necessary that the ecological sampling and processing took place in the beginning of the year. The bathymetry data used for the re-analysis was supplied by NIWA and Shell Oil and took time to process, sort, and send; finally arriving in the last four months of the degree programme. Ideally the GIS analysis should have been done first along with the analysis of archival data, but due to these restrictions and delays, the infaunal analysis of the canyons was performed first, the archival analysis second and the GIS methodology in the final months.

A methodology to objectively define submarine canyon areas using the GIS software GRASS is shown and explained in Chapter 2. The definition of submarine canyon areas has been mostly arbitrary up to this point, and is still not fully complete (Harris and Whiteway 2011). The canyons themselves stand out on bathymetric maps, but it was only very recently, in August 2012, that good bathymetry data were collected off the south-eastern coast of New Zealand's South Island. These recent data provide far better information on the configuration and topography of the canyons. An objective method of definition using the GRASS programme has been made, which uses predicted flow patterns and changes in slope to identify submarine canyon areas from raw bathymetry data. This removes any human error in drawing arbitrary lines on a map and informs policy making.

The first detailed study of the benthos of the deep-sea environments off the Otago Peninsula was conducted by Elizabeth Batham from 1966–74. Her work included collecting presence/absence and count data on the epifauna of the Otago shelf, slope, and four submarine canyons in the Otago canyon network. The aim of her study was to determine which species were living offshore, and their distribution and relative abundance, as there were very few to no data on the subject at the time. Epifauna were collected using a variety of different sampling methods: a four-foot Agassiz trawl, two-foot Agassiz trawl, otter trawl, circular dredge, and beam trawl. The type of data also varied depending on if the purpose of collection was gathering count data on all species in an area, only one particular species in an area, or gathering presence/absence data. Due to this variation of collection and recording methods only some stations have reliable count data, other stations give only a rough idea of the number and have no count data associated with them. Although the data are not ideal, the useful stations cover a wide swath of the shelf, slope, and canyon areas off of the south-eastern coast of New Zealand's South Island; which make reanalysing the data useful for characterising the submarine benthos of the Otago canyon network and determining the influence of environmental drivers. The statistical models and computer programmes in use today are much more advanced than when an earlier analysis was carried out, allowing for more detailed and quicker computations. The results of the statistical models are compared with the previous results of Probert *et al.* (1979).

A quantitative, ecological study was done in Saunders and Papanui canyons in order to compare the infaunal community structure of the canyons with that of the adjacent slope and to compare the canyons with each other. The lack of quantitative data necessitated this study in order to provide a foundation for future ecological studies, provide accurate infauna abundance numbers, and categorize the infauna found in Saunders and Papanui canyons. The canyons should show higher biodiversity and abundance than the surrounding slope, as the canyon environment in New Zealand tends to be very productive (De Leo *et al*. 2010). These data and the archival data from 1966–76 provide a description of both the epifaunal and infaunal communities in the submarine canyons of the Otago canyon network.

A catalogue of all macrobenthos recorded in the New Zealand canyons was also compiled and is presented alongside the abundance and quantitative analysis (Appendix 1).

This thesis provides a much needed quantitative analysis and compilation of canyon ecology along with an objective way of defining submarine canyon areas.

CHAPTER 2 –DEFINING SUBMARINE CANYONS IN GIS SOFTWARE

Introduction

Submarine canyons are a feature of the continental slope found worldwide that have been shown to play key roles in benthic ecology, such as providing hotspots of nutrients by allowing deep, nutrient-rich water to ascend up to the shallower slope and focusing detritus into the canyon areas (Vetter 1994; Hickey 1997; Vetter and Dayton 1999; She and Klinck 2000; De Leo *et al*. 2010). Although some canyons have been studied in detail and over 5 800 have been recorded, a strict definition of a submarine canyon has yet to be determined (Harris and Whiteway 2011). Guidelines for what defines a submarine canyon can inform policy making for classifying areas of vulnerable marine ecosystems (VME), such as cold-water corals, that appear in the canyon environments (Mortensen and Buhl-Mortensen 2005). Objectively defining canyon areas facilitates the process of identifying where different benthic habitats exist. This definition is useful for ecosystem identifications and deciding if a canyon, or a subarea of a canyon, should be classified as a VME, since this definition more objectively clarifies a canyon's location and extent.

The characteristics that submarine canyons share are a change in slope belonging to the canyon walls, sediment flow and canyon-specific currents. A canyon must have a steeper slope than that of the continental slope in order to stand out and form the physical canyon structure in the first place. Canyons also act as sediment conduits, guiding offshore sediment from the shelf to the deep sea (Daly 1936; Oliveira *et al*. 2007; Schmidt *et al*. 2013). Locallised upwelling and downwelling along with a spiralling, deeper flow are the most described and commonly found canyon-specific currents (Klinck 1988; Hickey 1997; She and Klinck 2000; Allen *et al*. 2001). Although canyons can display marked differences in benthic assemblages, not all canyons show this. "V-shaped" canyons in particular tend to have a similar or slightly lower biodiversity than the surrounding slope due to increased sediment flow; because of this, using changes in communties is not a reliable way to identify submarine canyon areas (De Leo *et al*. 2013; Duffy *et al*. 2013). Water depth is also an unreliable factor in determining if an area belongs to a submarine canyon, as the depth at the head of a canyon can differ greatly, ranging from 150 m to greater than 4 000

m (Allen *et al.* 2001; Harris and Whiteway 2011). Change in slope and sediment conduit activity are measurable attributes and observed in each of the grooves that are indisputably submarine canyons. The simplest way to model and combine these factors from raw data is using Geographic Information Systems (GIS) software.

GIS software has a variety of uses, such as: mapping biomass and carbon pools of fir tree forests, mapping erosion over time, estimating sedimentation rates, and assessing how suitable land is for agriculture (Mendas and Delali 2012; Misir *et al*. 2012; Taheri *et al*. 2013). Delong and Brusven (1991) identified, mapped, and assessed the pollution level of riparian habitats using both shore and riparian slope along with vegetation type, height, and width as categorical factors in GIS software. GIS also has strong hydrography elements and has been used to map watershed delineations, define both drainage areas and stream networks, and predict sedimentation flow and rates (Middelkoop and Van Der Perk 1998; Maidment 2002). The maps and estimates produced by GIS software is generally done by first using digital elevation models to construct the desired maps and area definitions. The ability to map streams, deal with flow patterns, and overall high variety of utility make GIS a useful tool for mapping submarine canyons.

The difficulties in defining submarine canyons in GIS software arise from the need to set specific parameters for each of the main factors used for canyon identification and lack of high-resolution bathymetry data. The amount of variance between the background slope and the slope of the canyon walls varies greatly with location (Covault *et al*. 2011; Harris and Whiteway 2011). The threshold slope used for the cut-off between canyon and non-canyon areas varies with location, and canyon definition would be best suited if an objective slope was defined for each area instead of a set standard. Canyon axes are easily modelled by using the same stream and river models for terrestrial canyons. These stream and river models follow the path carved out by sediment flows, therefore they highlight areas of high or low sediment flow appropriately. Changes in elevation allow for both the stream models to be formed and for terrain analysis to be run to identify channels. The same analysis that displays channels and similar “V” shapes also shows submarine canyons when used.

This chapter describes a method of objectively defining submarine canyon areas based on slope, elevation, and both patterns and accumulation of flow from stream models. This methodology is intended to be used for any dataset worldwide, therefore objective

definition of threshold values with no arbitrary value input were used whenever possible. The software used for this methodology was GRASS (Geographic Resources Analysis Support System) version 6.4.3 (GRASS Development Team 2012). GRASS is a freeware GIS program that is ANSI C, C++, and Python based with the capacity to run on MS-Windows, Mac OSX, and Linux (Neteler *et al.* 2012). The combinations of its cross-platform use and the free to download and update made it the ideal candidate for testing and forming the methodology. Since this method should be applicable worldwide, the freeware nature of GRASS allows anyone to download and use it regardless of system or location constrictions. The methodology presented is a continuation of previous work done by Peter Batson and Léo Chaumillon (Batson 2004, Chaumillion 2013).

Batson's (2004) method used the GRASS software to generate a map of both changes in slope and flow accumulation in the Otago canyon network. The raster data of the stream (flow) map were converted into vector data in order to place a buffer around canyon areas and removed the buffered areas from the elevation map. This buffer allowed GRASS to identify and isolate the canyon areas, so when the buffers were removed the canyon areas were effectively erased from the slope. The slope map was then interpolated to fill in the removed areas, which generates a slope with no canyons, or a prediction of an uneroded continental slope. The uneroded slope was subtracted from the original elevation map and positive and weakly negative residuals were removed. The remaining values highlighted what were identified as the canyon areas.

Chaumillon (2013) modelled the Kaikoura canyon in detail using the ArcHydro extension of ArcGIS and has useful steps that can be used for general identification on canyon areas worldwide using watershed analysis. Topographic holes on the elevation map were filled to avoid any erroneous canyon identification. Flow direction and accumulation models were run along with stream definition and segmentation models. The generated flow and stream models were coupled with drainage line processing to draw the hydrographic network of the canyon and adjacent area. Each stream is aligned with an axis of a canyon and flow modelling identified major and minor canyon axes. Each pixel of the drawn network was assigned a value and the output pixel was defined using catchment grid and batch point delineation; which generates a different watershed basin for each individual canyon. The structure of the drawn stream network and basin layout define both the axis and inner canyon areas.

The methodology outlined in this chapter is an expansion and combination of Chaumillion's (2013) method of using stream and flow maps for identifying canyon axes along with Batson's (2004) method of buffering flow and using slope as a factor of identification. Changes in slope equal to or greater than the global average for submarine canyon walls, identified channels, buffered steams and stream basin maps that yield the canyon axes, inner canyon areas, and outer canyon areas are generated. The combination of these four map types led to a final result of highlighted submarine canyon areas.

Methods and Results

Generating Elevation, Slope, and Features Maps

Raw raster data encompassing a large area (~29 598 km^2) of the shelf and slope off of the Otago Peninsula and surrounding southeast coast of New Zealand's South Island were provided by NIWA and Shell Oil (Figure 1). A Mercator Projection was used to properly read and set up the received data for modelling in GRASS software. GRASS has a majority of the commands used in this methodology already present when it is installed; the other necessary commands (r.threshold, r.stream.order, and r.stream.basins) can be added on to GRASS through the g.extension command. The r.mapcalc command is a useful tool that removes or combines values of one or several maps and is used throughout this methodology. Table 1 displays the specific equations that were used throughout the process of identifying the Otago submarine canyons. The full script to run this methodology in GRASS 6.4.3 is shown in Table 2.

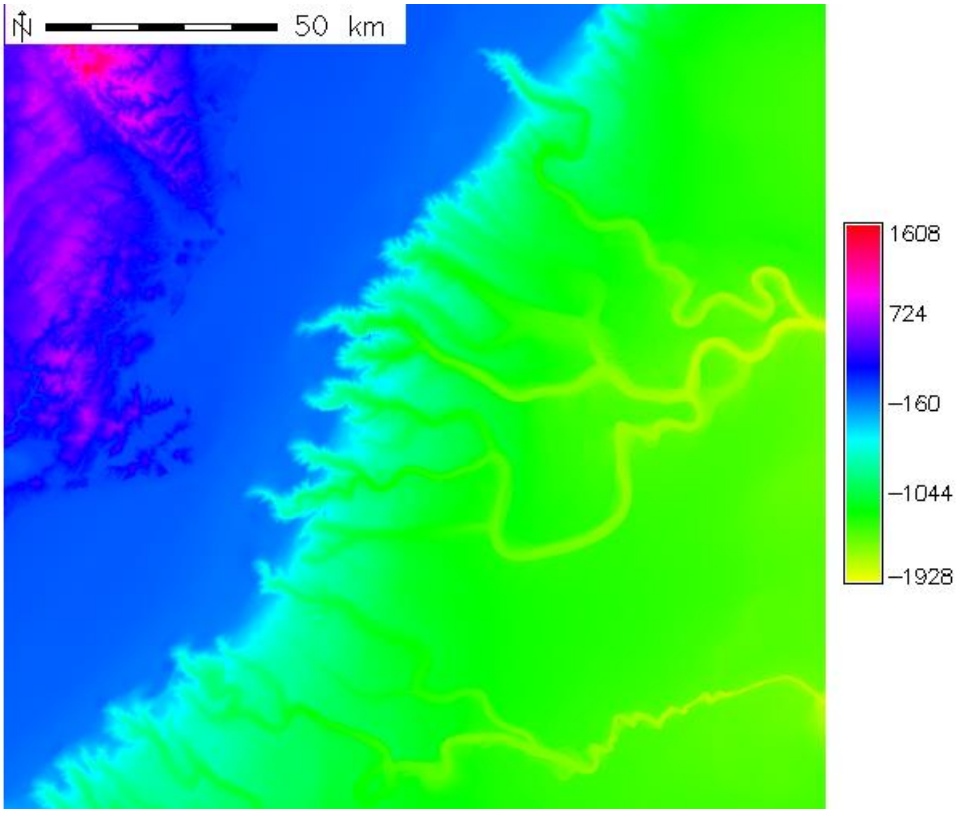


Figure 1: The displayed raw raster elevation data of the Otago area slope, shelf and canyon networks. Elevation is in metres, negative values are below sea level.

The raw elevation data were mapped by telling GRASS to add the raw raster data as a layer. This can be done with the d.rast command and selecting the name of the raw raster data in whichever location the user had saved it. In order to speed up processing and clean up the map display, an elevation map was generated by setting all positive (terrestrial) values to zero using the r.mapcalc command (Figure 2; Table 1).

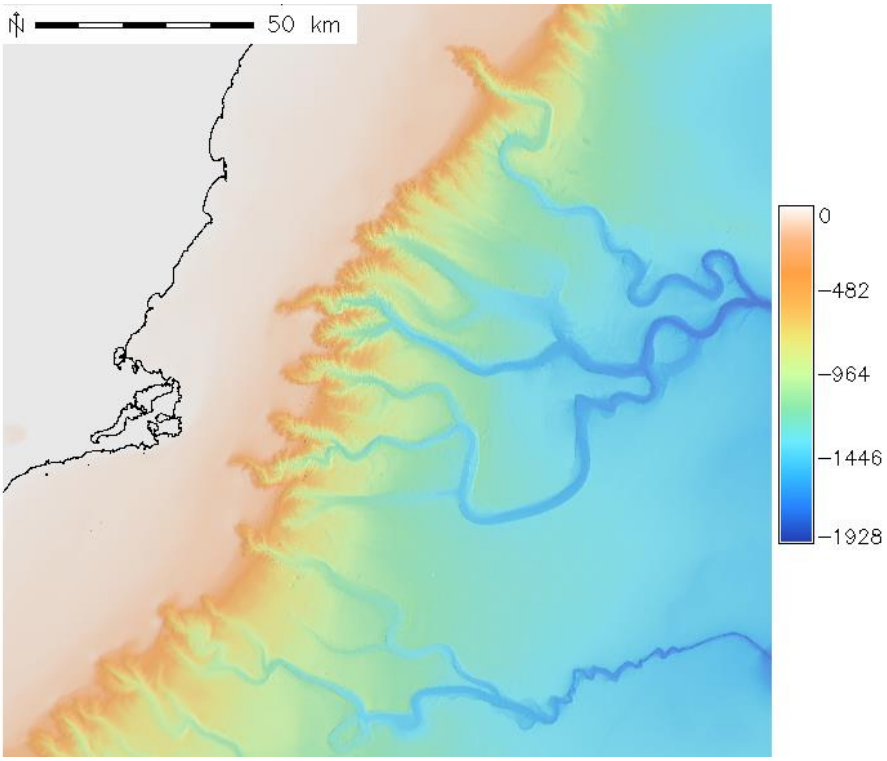


Figure 2: Elevation (in m) of the slope, shelf and canyon networks off of the Otago Peninsula and adjacent coastline.

Changes in slope were mapped using the r.slope.aspect command (Figure 3). This command can generate several outputs of different slopes, curvatures, aspects, and partial derivatives of changes in slope (GRASS Development Team 2012). The generated elevation map without terrestrial values and used for the input and the desired output choice is the slope raster map. The r.mapcalc command was used to remove any values smaller than a 5.1° change and display all terrestrial values as 0 (Figure 4; Table 1). This can also be done by right-clicking on the map layer, selecting properties and under the selection tab specifying values over 5.1; however, this does not change the raster map and is less useful for future application of the r.mapcalc command. The value of 5.1° was chosen from Harris and Whiteway (2011) since it was the global average of submarine canyons. This should isolate and display the canyon areas. The global average slope was selected to allow this method to be applicable for any mapped area of the worldwide slope.

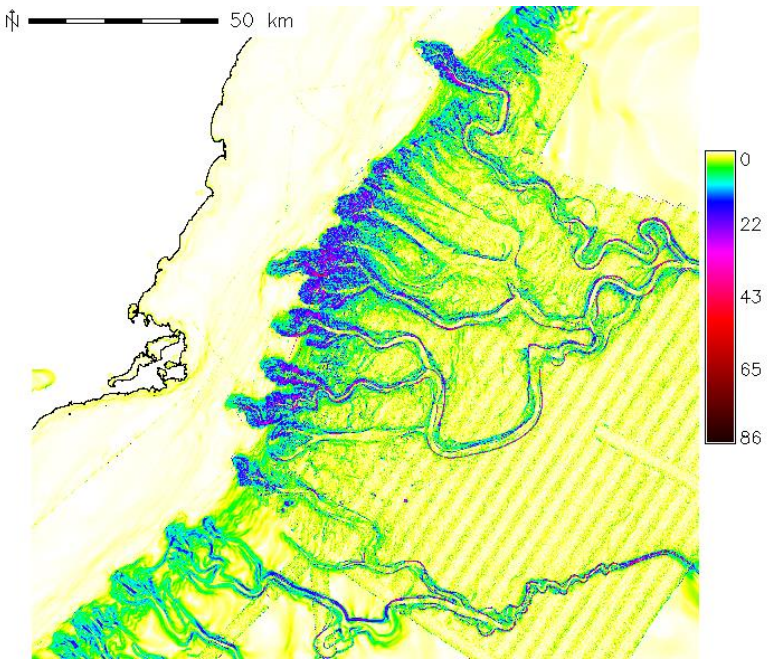


Figure 3: The changes in slope (in degrees) of the Otago submarine canyons and the adjacent continental slope and shelf.

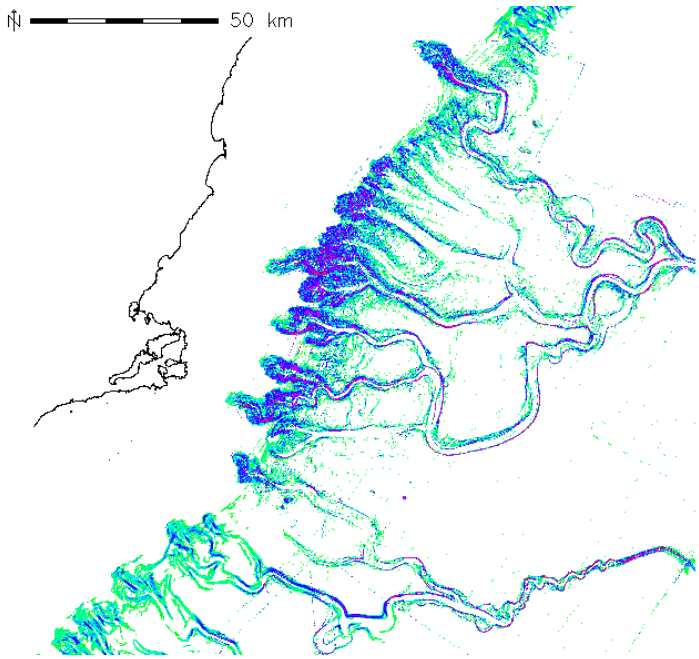


Figure 4: The slope changes greater than the assigned threshold for submarine canyon values set at 5.1°.

The slope maps alone can pick up errors in data collection or large changes in the background slope, which introduces errors when these maps are combined with the stream, basin and feature maps to highlight canyon areas. The r.param.slope command can be used to identify multiple different terrain features, but the most useful option that this command generates is the channels. Selecting “Features” under the “Selection” tab will identify ridges, channels, flat areas and other various terrain features. R.mapcalc can be used to isolate the channel values. The default channel value is 3, but using the display legend tool on the display window will generate a list of features and their assigned colour. The histogram tool found on the display window will show which colour correlates to each value. The elevation map with all zero terrain values was used as an input for the r.param.slope command, and the r.mapcalc command was used to remove all features aside from channels (Figure 5).

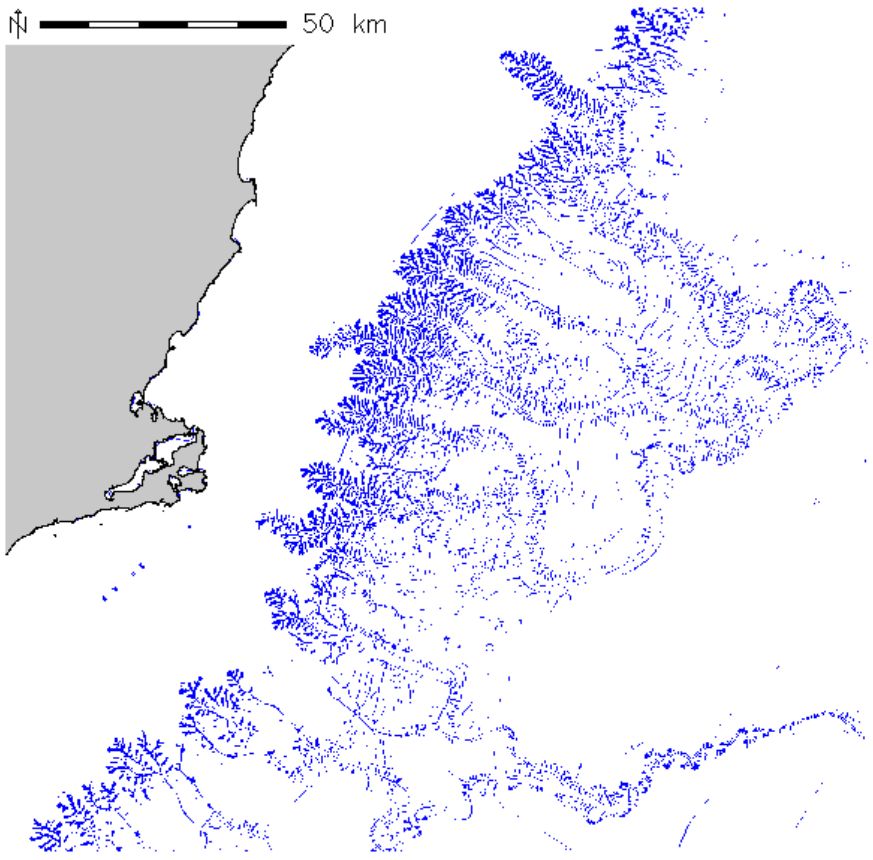


Figure 5: Identified channels from the r.param.slope command.

Generating Streams, Basins, and Buffered Maps

Water movement and accumulation can be modelled using the r.watershed command (GRASS Development Team 2012). This command uses the elevation raster map to display areas of stream formation, direction of flow and drainage, and where flow would accumulate. The streams and flow directions modelled show the axis of each canyon and emphasize the direction that sediment flows down the main parts of the canyon. R.watershed was designed for terrestrial canyons, but the similar structure of terrestrial and submarine canyons along with the similar flow behaviour of river/stream flow on land and sediment flow in submarine canyons allow the r.watershed to be an appropriate modelling tool. The filtered elevation map was used for the input, and maps of the stream network, flow accumulation, and flow direction were generated along with drainage and accumulation maps.

R.watershed needs a threshold value for determining the size of basins, where streams should be generated, and whether streams should be considered either different or one stream with multiple branches. The r.threshold command is built to specify a threshold unique for the dataset in use by measuring changes in slope along with sediment patterns and flow directions (GRASS Development Team 2012). The input for r.threshold uses the accumulation map generated from the r.watershed command, which appears to create an issue if the desired use of the determined threshold value is for the r.watershed command in the first place. Fortunately, any integer can be used in the r.watershed command at first in order to build an accumulation map, and a value of 3 000 proved sufficient for the Otago offshore area. The first generated accumulation map can then be used in r.threshold to generate a recommended value. The calculated value for the Otago canyon network stream threshold was 52 016. The r.watershed command can be run again with this threshold factor to refine the stream, flow direction, and accumulation definition. Re-running r.threshold for different r.watershed maps generated by different threshold values, including the 52 016 value given by r.threshold, did not vary the value produced by r.threshold. The refined stream map highlights the location of the canyon axes (Figure 6). Converting the stream map into a vector map with the use of the r.to.vect command allows the streams to be clearly displayed, but does not yield anything useful in the methodology overall (Figure 7).

The generated stream map should be ordered into categories using r.stream.order. Using categories instead of the streams themselves means that the longer streams, which flow down the axis of the canyons, are given the same value. The best ordering system is the Strahler ordering system, which defines a stream with no branches as 1. When two streams intersect their value is compared and the rest of the downstream flow is redefined. If one of the incoming streams has a higher assigned value than the other stream, the higher value is used downstream. If both incoming streams are of the same value, the downstream becomes one value higher than its two nodes. This means all streams that are minor, not present in canyon areas, or caused by errors in data can easily be discarded by filtering out low values.

A buffer layer was added to the stream map in order to expand the stream width to cover the area of the inner canyons. A length of 1 km was selected as the buffer zone. The r.buffer command expands the streams 1 km on either side, which covers the inner area of the canyons (Figure 8). Adding the buffers by converting the data to vector data and using the v.buffer command achieves the same result but takes much longer to process (between 43–87 minutes on average as opposed to 2–7 minutes).

R.stream.basins can take input from either r.watershed or r.stream.order. Since r.stream.order can greatly reduce the categories (from over 2 500 to 6) and allows for the removal of non-canyon streams, the input for r.stream.basins was the Strahler stream order map produced by r.stream.order. The first two basins were removed from the Strahler ordered basin map with the use of the r.mapcalc function. This produced basins that aligned nicely with the canyon areas (Figure 9). R.stream.basins has an interesting effect when the “last” option is selected. This option only creates basins based on the last output of streams, and when selected produced fewer basins and seemed to match with the canyon networks instead of individual canyons (Figure 10). While not useful for identifying the individual canyons, this may have potential use in defining canyon networks.

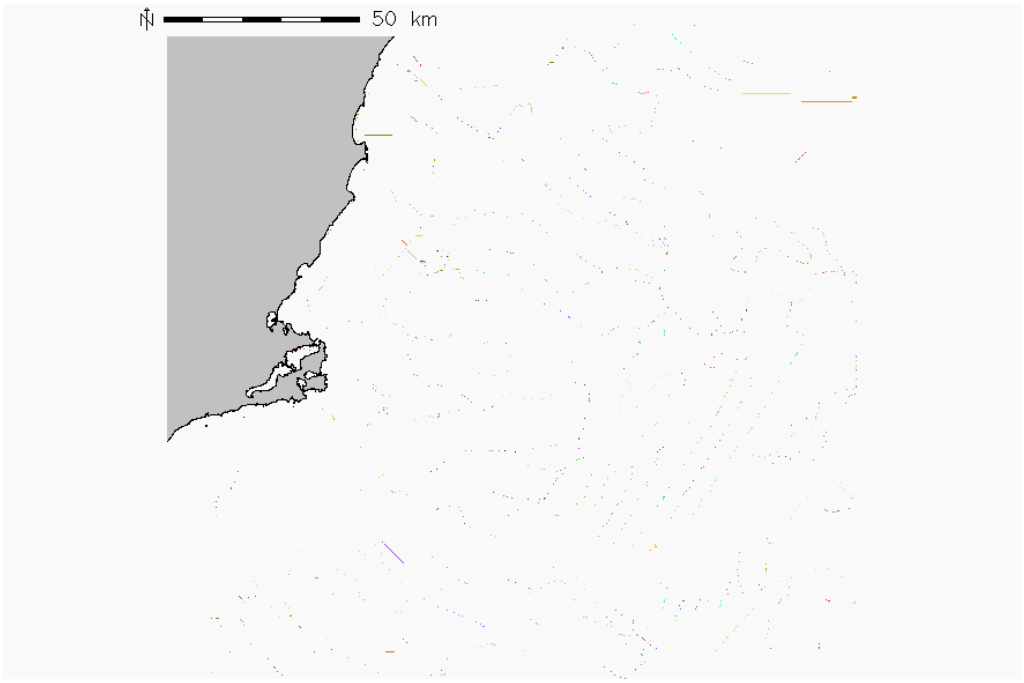


Figure 6: The stream network map produced from the r.watershed command. The streams themselves are difficult to see due to the vast amount of data and limited resolution.

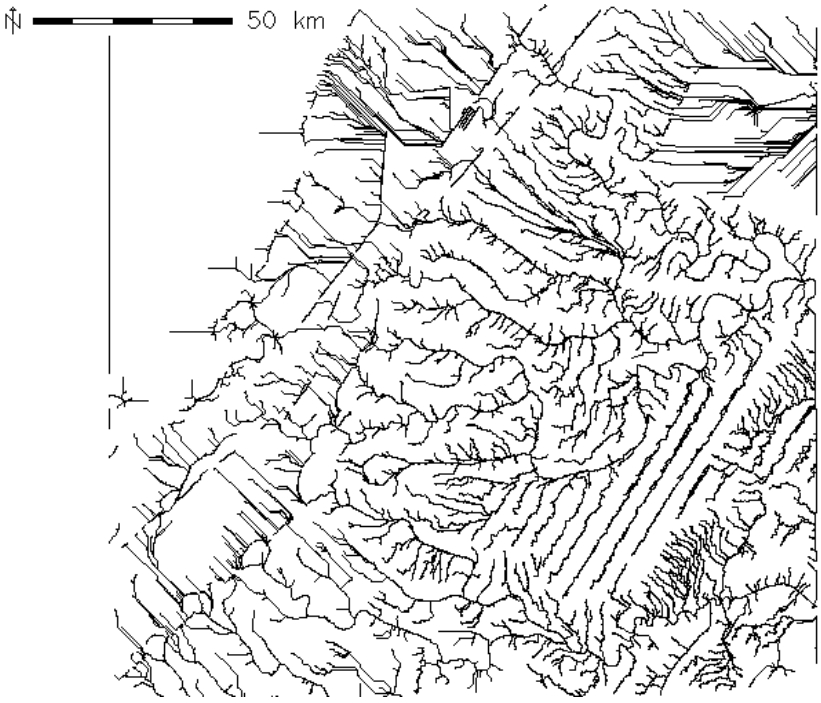


Figure 7: The vector map of the generated streams. Converting the raster stream map into vector data or buffering the streams allows them to become more pronounced.

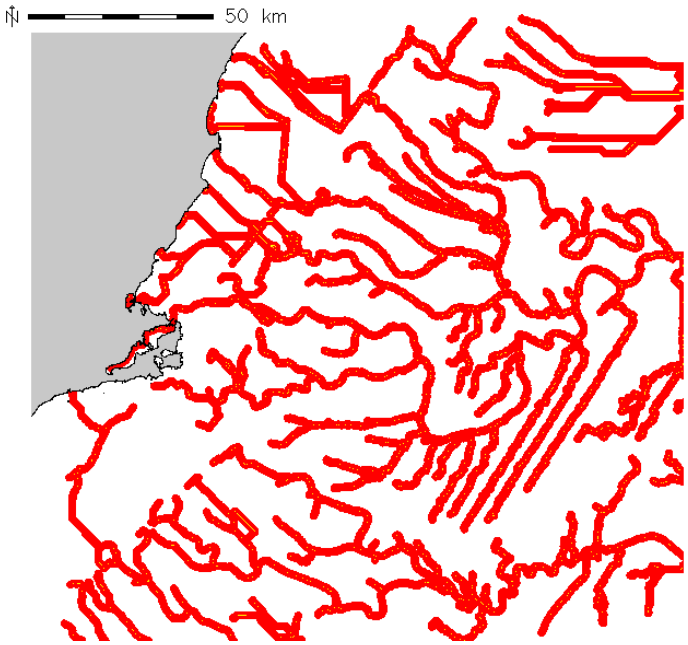


Figure 8: The buffered vector stream map. The added buffers give each stream a length of 21.5 km, which should cover the width of the submarine canyons.

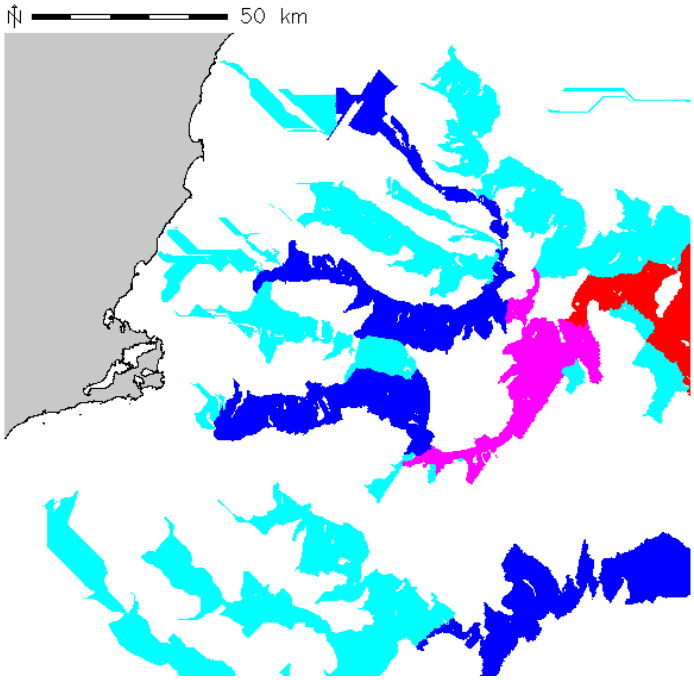


Figure 9: Stream basins ordered with the same categories as the Strahler order stream map. Different colours represent different basins generated by GRASS and do not represent anything specific.

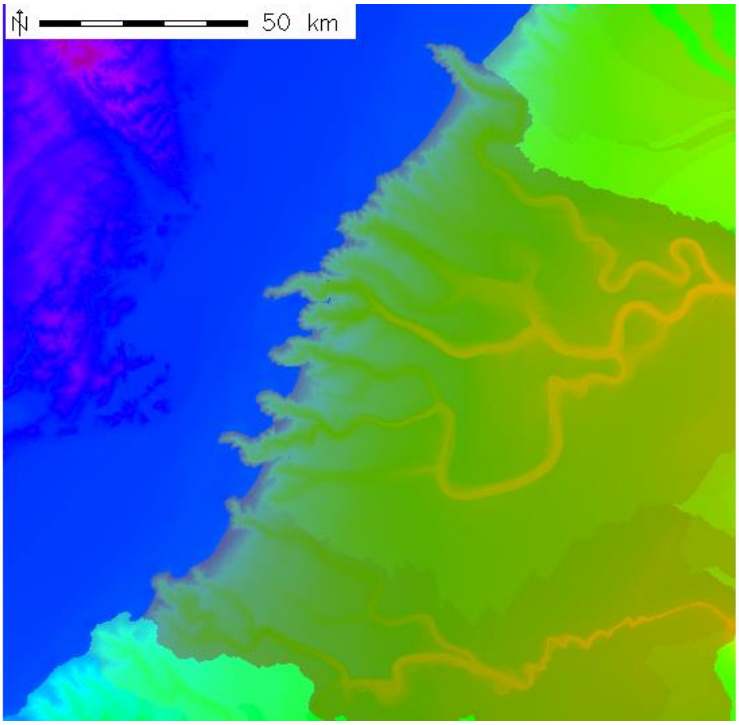


Figure 10: Result of the "last" function of r.stream.basins that causes basins to match the location of the submarine canyon networks instead of individual canyons.

Combining Slope, Features, and Buffered Stream Outputs

The r.mapcalc command was used to combine the generated slope map and the identified channels from the feature map into the outer canyon areas (Figure 11). This was done by selecting the points from the slope map that were greater than or equal to the selected 5.1° change and the values associated with the channel category from the feature map. The buffered stream map and the stream basin map were combined to form the inner canyon areas (Figure 12). The purpose of using the buffered streams with the basin map was to eliminate any areas that were errors of over expansion on the basin map. The r.mapcalc function can used to define boundaries by setting all values not defined by outer canyon areas as null, effectively using the outer canyon as a defining barrier. Unfortunately this also sets all values inside the canyons as null, so directly combining outer and inner canyon maps does not work. The easiest way to combine the maps without including non-canyon areas from either the stream or basin maps is to apply a buffer to the inner canyon

map using the r.buffer command; the buffer should be wide enough to cover the width of the area inside the borders of the outer canyon area map (Figure 13). The buffered inner canyon area map can be added to the inner canyon area map with the r.mapcalc command so that any value unique to either the inner canyon or buffered inner canyon maps is removed. This removes most of the noise and errors produced by the overestimates of basin and stream maps (Figure 14).

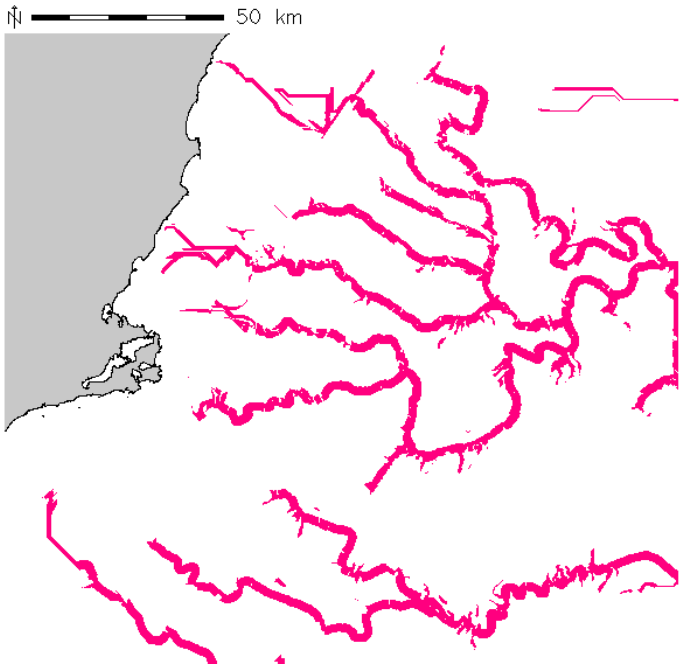


Figure 11: Inner canyon areas as determined by stream basin and buffered stream areas.

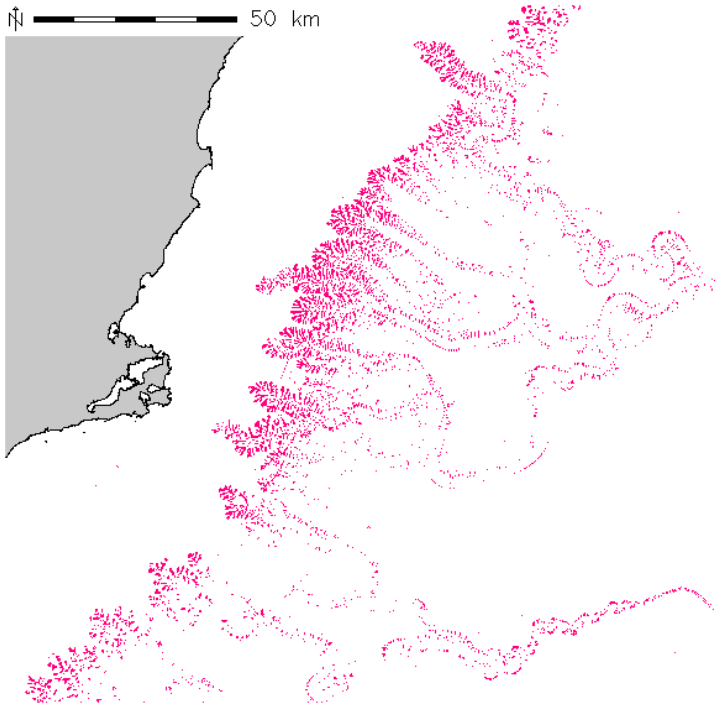


Figure 12: Outer canyon areas as determined by changes in slope greater than 5.1° and identified channels.

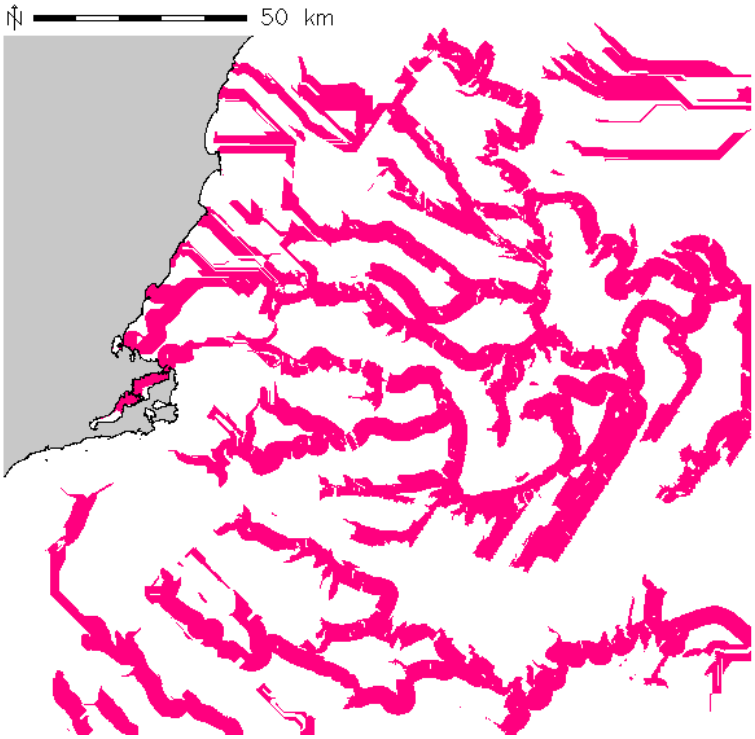


Figure 13: Inner canyon areas with a 1.5 km buffer applied.

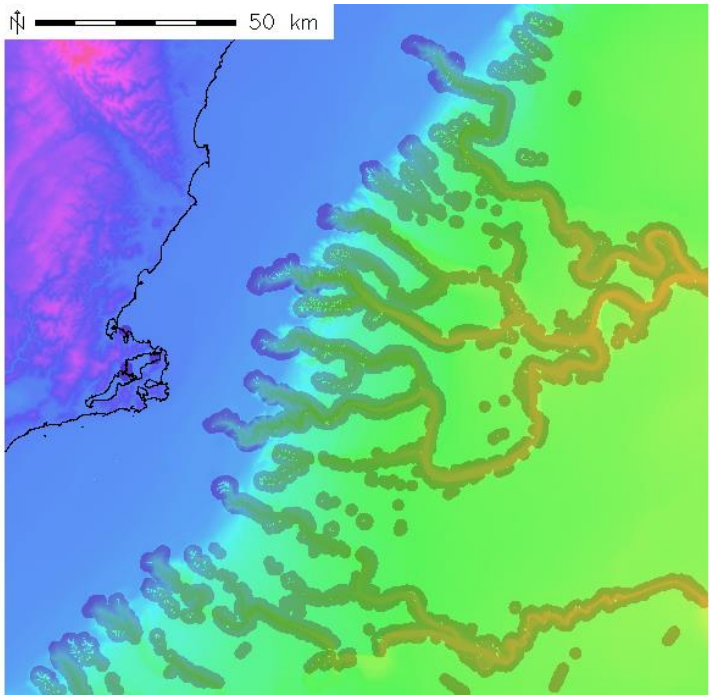


Figure 14: Identified submarine canyon areas overlayed on the raw elevation map (see Figure 1).

Table 1: Specific inputs of the r.mapcalc function that allow generation of specific maps.

Desired Effect	r.mapcalc equation
Remove Terrestrial elevation values	if(Inital raster map name>0,0,Initial raster map name)
Remove Slope values smaller than 5.1°	if(Slope map name>=5.1,1,null())
Remove low order basins	if(Basin map name<=2,null(),Basin map name)
Generate Outer canyon areas	if(Filtered Slope Map Name==1&&Canyon Feature Map ==3,1,null())
Generate Inner canyon areas	if(Buffered Stream Map name>=1&&Strahler Basin Map Name>=3,1,null())
Combine Inner and Outer canyon areas	if((isnull(Buffered Inner Canyon Map Name),0,Buffered Inner Canyon Map name)+if((isnull(Outer Canyon Map Name),0,Outer Canyon Map name)
Displays the Identified canyon areas	if(Canyon Area Map Name<=1,null(),Canyon Area Map Name)

Table 2: All commands used in this methodology with specific r.mapcalc commands and notes.

Command	Effect	Notes
d.rast	Displays raw elevation data	
r.mapcalc	Remove Terrestrial elevation values	if(Inital raster map name>0,0,Initial raster map name)
r.slope.aspect	Generates slope map	5.1° is global canyon average
r.mapcalc	Filters out non-canyon slopes	if(Slope map name>=5.1,1,null())
r.param.slope	Identifies Channels	Channel areas are typically category 3
r.watershed	Generates stream network map	need to set arbitrary value in order to get r.threshold running, 3000 worked for the Otago area
r.threshold	Calculates area-specific threshold value	Calculated value for the Otago region was 52 016
r.stream.order	orders streams according to number of inputs	The Strahler order option provides the best results for this analysis
r.buffer	adds buffer to raster map	A 1km buffer was found to be sufficient for the Stream map. The original or the Strahler order map can be used.
r.stream.basins	Generates basins based on stream maps	Use the Strahler stream map for input
r.mapcalc	Remove low order basins	if(Basin map name<=2,null(),Basin map name)
r.mapcalc	Generate Outer canyon areas	if(Filtered Slope Map Name==1&&Canyon Feature Map ==3,1,null())
r.mapcalc	Generate Inner canyon areas	if(Buffered Stream Map name>=1&&Strahler Basin Map Name>=3,1,null())
r.buffer	adds buffer to raster map	A 1.5 km buffer was found to be sufficient for the Inner Canyon Area Map

r.mapcalc	Combine Inner and Outer canyon areas	if((isnull(Buffered Inner Canyon Map Name),0,Buffered Inner Canyon Map name)+if((isnull(Outer Canyon Map Name),0,Outer Canyon Map name)
r.mapcalc	Displays the Identified canyon areas	if(Canyon Area Map Name<=1,null(),Canyon Area Map Name)

Discussion

Known Deficiencies

The script as described does not perfectly identify the submarine canyon areas. There are still circular areas that are highlighted that should not be present and small areas inside the canyons that should have been highlighted. This is most likely due to a combination of sampling error, as some of these errors are perpendicular to the shore and align with the transects used for bathymetry soundings, and the change in background slope of the continental slope being above the specified slope change of 5.1°. Including a buffer so that the canyons can be correctly displayed also extends the diameter of the erroneous circles, which is not ideal but gives a clearer picture overall of the extent of the canyons. The changes in slope were not high enough in some areas to pick up parts of the submarine canyon walls, which meant that those canyon areas disappeared when the stream and basin maps were combined with the slope and channel maps. Decreasing the specified slope value included most of these areas but provided too much noise along the continental shelf, making it difficult to tell which parts of the shelf were the canyon heads.

The only way to find the ideal slope for differentiating canyon areas was through trial and error; it would be best if the ideal slope could be calculated instead. The current state of this script uses the global average slope (5.1°) for determining canyon areas. It would be best if this could be calculated in a similar fashion to how r.threshold calculates the threshold value for ideal stream maps. R.threshold may be tweaked to work on slope maps, but its current form uses only accumulation data. In order to correctly map the inner canyons and avoid losing areas that should be included in the canyons it was necessary to use a buffer. This buffer, while useful, introduces arbitrary length which may be too wide/not wide enough for other areas. It would be best to either find a way to remove

buffers but not lose any accuracy of mapped areas or to allow the software to calculate an appropriate buffer distance.

The r.threshold command can have some technical issues after downloading as it is the only command used in this method that runs with Python. Python may not work if multiple versions are installed on the computer, as it wants the version that a specific program is using to match the installed default version. This can be solved by either removing a version of Python, which may cause other Python-based programs to malfunction or by updating the default version of Python to match the version used by GRASS and r.threshold. There may also be a bug in the r.threshold.py file, which can be solved by opening the file up in Notepad (or any text program) and editing the "gisprompt" line to read "gisprompt: old,cell,raster". Editing the r.threshold.py file and removing an extra Python version was necessary to allow r.threshold to run without any problems; but this may not be an issue for other users.

Areas of Further Expansion

This script is only the first step in a process which can be expanded to save policy makers time, effort and funds. Backscatter data have been shown to reflect the sediment type an environment is characterised by, which is a proxy for faunal functional groups (Kloser *et al*. 2010). Chaumillion (2013) looked at how backscatter data could be used alongside elevation data to identify different benthic habitats. The elevation data provided a way to isolate different areas based on physical parameters, similar to the method shown in this chapter, and the backscatter data were used to estimate the productivity of the isolated areas. Using both elevation and backscatter data can allow for maps that show the location and type of benthic habitats. The inclusion of backscatter data with the method outlined in this chapter can not only automatically define the canyon areas, but also point out which areas inside the canyon themselves are most likely to be vulnerable marine environments (Rowden *et al*. 2005; Kloser *et al*. 2010).

Further expansion can lead to a script that not only identifies submarine canyons, but other deep-sea habitats and areas of high productivity. This means that after running the script, policy makers can have an objective definition of the various deep-sea environments along with which specific areas are most likely in need of protection.

Research vessel time can then be used more efficiently, by saving fuel costs, cruise time, and skipping unnecessary stops which prevents any unnecessary sampling across the entire EEZ. Quantitative study of the script-identified environments is still necessary in order to characterise the biodiversity and gauge how a habitat would respond to various anthropogenic impacts.

A process to include canyon-specific current identification can also be accomplished by further expansion of the outlined script. Due to the physical structure of the "V" or "U" shape profile of the canyons, localized upwelling and downwelling occur (Klinck 1988; Hickey 1997; Allen and de Madron 2009). These variations in current flow and the gradient between deep-water bodies they cause can be measured with CTD sampling and identified on a computer. GIS software can then be used to map out where these changes are prominent and where these currents occur. The generated current map can be overlaid with that of the identified canyon areas of the provided methodology for further refinement of canyon area definition.

CHAPTER 3 – EPIFAUNAL ASSEMBLAGES OF THE OTAGO CANYONS AND ADJACENT SLOPE

Introduction

Importance of Benthic Biodiversity

Deep-sea habitat covers about 64 % of the earth's surface, yet only a minimal amount has been investigated; for example, the observed area of the hadal depths only covers a few square kilometres out of the total 5.1 million km^2 (Gage and Tyler 1991; Ramirez-Llodra *et al*. 2010). The Exclusive Economic Zone (EEZ) of New Zealand covers 4.2 million km^2 and extends over 30° of latitude but remains largely unexplored (Gordon *et al*. 2010). Some deep-sea habitats, especially hydrothermal vents and submarine canyons, contain unusually high abundances and population densities of benthic fauna (Wolff 1970; Brant *et al*. 2007; Levin and Dayton 2009; Van Dover *et al*. 2000; De Leo *et al*. 2010). Due to the areal extent of deep-sea habitats and their often high biodiversity, it is imperative to use the technology available today to continue to systematically explore and categorise these areas; especially since anthropogenic impacts, such as deep-sea fishing and climate change, have already affected many marine areas (Koslow *et al*. 2000; Levin and Dayton 2009). Effects of such impacts on these little-studied habitats are poorly known.

Continental margins comprise nearly 15 % of the ocean floor, act as a carbon sink for anthropogenic CO_2, are important for fisheries, and can consist of several habitats including: deep-water coral reefs, methane seeps, cold-seeps, and submarine canyons (Koslow *et al*. 2000; Allen *et al*. 2001; Buhl-Mortensen and Mortensen 2004; Sarmiento and Gruber 2006; Levin and Dayton 2009). These habitats, especially deep-water corals and submarine canyons, provide important refugia and food sources to the deep-sea benthos (Bosley *et al*. 2004; Schlacher *et al*. 2007; Buhl-Mortensen *et al*. 2010). Sessile species can serve as biogenic habitat and food in deep-water coral reefs, creating hotspots for benthic organisms on the slope (Buhl-Mortensen *et al*. 2010). Benthic hotspots can also be formed by submarine canyons, since they concentrate detritus through both localised downwelling processes and sediment transfer (Vetter 1994; Hickey 1997; De Leo *et al*.

2010). Trawling or mining can damage or completely remove these organisms; which means that habitats such as methane seep assemblages and biogenic reefs can be damaged before they are even discovered (Levin and Dayton 2009). This makes the systematic study of continental margin habitats, especially areas such as submarine canyons, important in order to determine potential anthropogenic effects but also in order to characterise their faunas.

Major Continental Margin Habitats of New Zealand

New Zealand's EEZ is unusual in the range of benthic habitats it includes and is one of the largest in the world, covering over 15 times the terrestrial area of New Zealand (Batson 2003; Gordon *et al*. 2010). The diversity in the EEZ, which includes 17 135 living species known to date, is nearly equal to that covered in the European Register of Marine Species (ERMS), which spans an area 5.5 times larger than New Zealand's EEZ (Gordon *et al*. 2010). Leathwick *et al*. (2012) describe 15 different divisions, 7 of which are bathyal, of New Zealand's EEZ based on several chemical and physical environmental factors along with distributions of asteroids, bryozoans, fish, foraminiferans, octocorals, polychaetes, scleractinain corals, and sponges. The 15 groups can be further divided into four main groups by depth and environment type: inshore and shelf, continental slope, mid-depth water, and deep water. The shelf area has a depth range of 26–105 m and accounts for 156 955 km^2 of New Zealand's EEZ. The slope area has a depth range of 136–231 m and covers a total area of 244 490 km^2. The mid-depth area ranges 531–1 108 m depth and expands over an area of 797 277 km^2 of New Zealand's EEZ. The deep waters have a depth range of 1 399–2 344 m and cover the largest range of the four depth groups – 1 428 349 km^2 (Leathwick *et al*. 2012). Figure 1 displays the area that these four depth and environment type groups cover. These ranges are useful in an overall view of New Zealand's EEZ, but they lack finer definition of the specific benthic habitats found in the area, such as the seamounts, hydrothermal vents and submarine canyon networks. One of the most defining oceanographic features of New Zealand's EEZ is the Subtropical Front (STF), a zone of convergence between surface subantarctic water to the south and surface subtropical water to the north. The STF therefore represents a strong thermohaline gradient and runs along the south and east coast of the South Island until it encounters the Chatham

Rise, a 1 400 km long ridge that extends off the east coast of South Island, where it turns and continues to flow east (Sutton 2001).

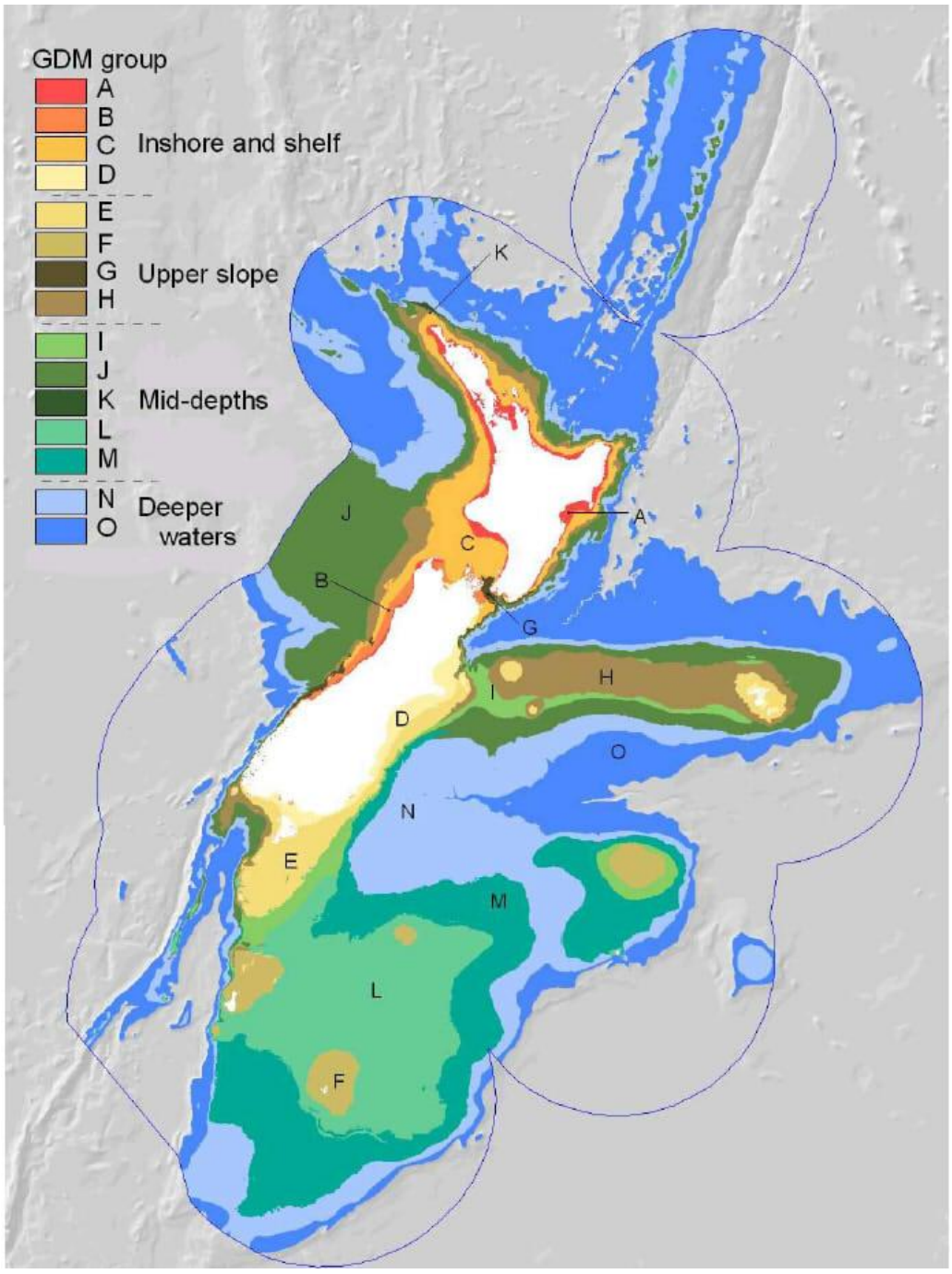


Figure 1: Map of the 15 benthic environment groups adapted from Leathwick *et al*. 2012. The distribution and definition of the four main subgroups of the shelf, slope, mid and deep waters belonging to New Zealand's EEZ are shown.

The Chatham Rise was the focus for a majority of biological studies located in New Zealand's EEZ due to its importance for fisheries and the discovery of minable phosphate (Mackay *et al*. 1984; Francis 1992; Probert *et al*. 1996; Key 2002; Nodder *et al*. 2003; Nodder *et al*. 2007). The abundance and distribution of the Chatham Rise benthos has been shown to be affected by both the STF and strong zonation caused by separation of flow (Chiswell 1994; McKnight and Probert 1997; Nodder *et al.* 2003). Unfortunately, the ecology of other areas of New Zealand's EEZ, such as the submarine canyon networks that are off of the Cook Strait and Otago Peninsula, are not as well-categorised as quantitative data are lacking (Probert *et al*. 1979; Mountjoy *et al*. 2009; De Leo *et al*. 2010; Ramirez-Llodra *et al*. 2010).

The process of studying the Cook Strait canyon system is still young; the studies to date have been focused on the geological components and sediment distribution patterns of the canyon with no mention of any faunal assemblages (Mountjoy *et al*. 2009, 2013). Epifaunal assemblages in the Otago canyon network have been described by Probert *et al*. (1979) revealing that polychaetes, sponges, gastropods, anomurans, and bryozoans are commonly found major taxa throughout the canyon areas. The lower canyon areas are characterised by bivalves and asteroids (Probert *et al*. 1979). Only relative abundances could be given as the count data were estimated on a semi-logarithmic scale of 5, 10, 20, 50, 100, 200, 500, 1 000, 2 000; which only provides a general overview of the benthic community structure. The biomass and productivity of Kaikoura canyon has been studied in some detail (De Leo *et al.* 2010). Samples collected by De Leo *et al*. (2010) averaged 516 individuals m^{-2} and were dominated by: *Molpadia musculus*, a holothuroid, *Alomasoma nordpacificum*, an echiuran and *Maldane theodori*, a polychaete. Average megabenthic biomass in Kaikoura canyon was reported to be more than 100 times higher than that reported for environments deeper than 500 m (Rex *et al*. 2006; De Leo *et al*. 2010).

Purpose of Analysing Archival Data

Due to the biodiversity of the canyon environments and the increasing need to use them for deep-sea fishing it is imperative to characterise and quantify the canyon benthos. It has been shown that benthic environments are directly affected by many physical and

chemical drivers, such as sediment size, oxygen levels, current speed and presence, therefore systematically determining their influence must also be a priority to fully understand and characterise submarine canyon environments (Levin *et al*. 2001). In order to systematically study canyons and their ecology, an important step is to characterise the benthos and to start to tease apart environmental factors influencing their distribution. This characterisation can be supplemented with the archival data collected by Elizabeth Batham from the slope and canyon areas off the Otago Peninsula. Epifaunal samples of the Otago submarine canyon network off the eastern coast of the South Island were collected by Elizabeth Batham over the period 1966–74. The intent behind her studies was to determine what epibenthic species characterise the shelf and submarine canyons off the Otago Peninsula, as little to no data on the benthos existed at the time. Her collection was the first detailed record of offshore species found in the Otago canyon areas. Median and mean grain size analysis of the collected sediments for most samples from 1966-69 were performed for both the entire sample and detritus only portion (Andrews 1973).

These archival data are useful for better understanding the composition of the benthic community of the Otago slope and canyon network. The data were initially used for only a preliminary study and at the time only limited statistics were used due to the lack of efficient methodology (Andrews 1973; Probert *et al*. 1979). The stronger and faster computers and statistics programs today allow for a wider range of and more in-depth analysis of benthic communities identifiable from these archival data. The area covered by the archival data covers a wide swath of the shelf, slope and canyon areas off the Otago Peninsula (Figure 2). Most of the data covers the shelf and slope environment; the stations used for this study are highlighted and primarily in the canyons.

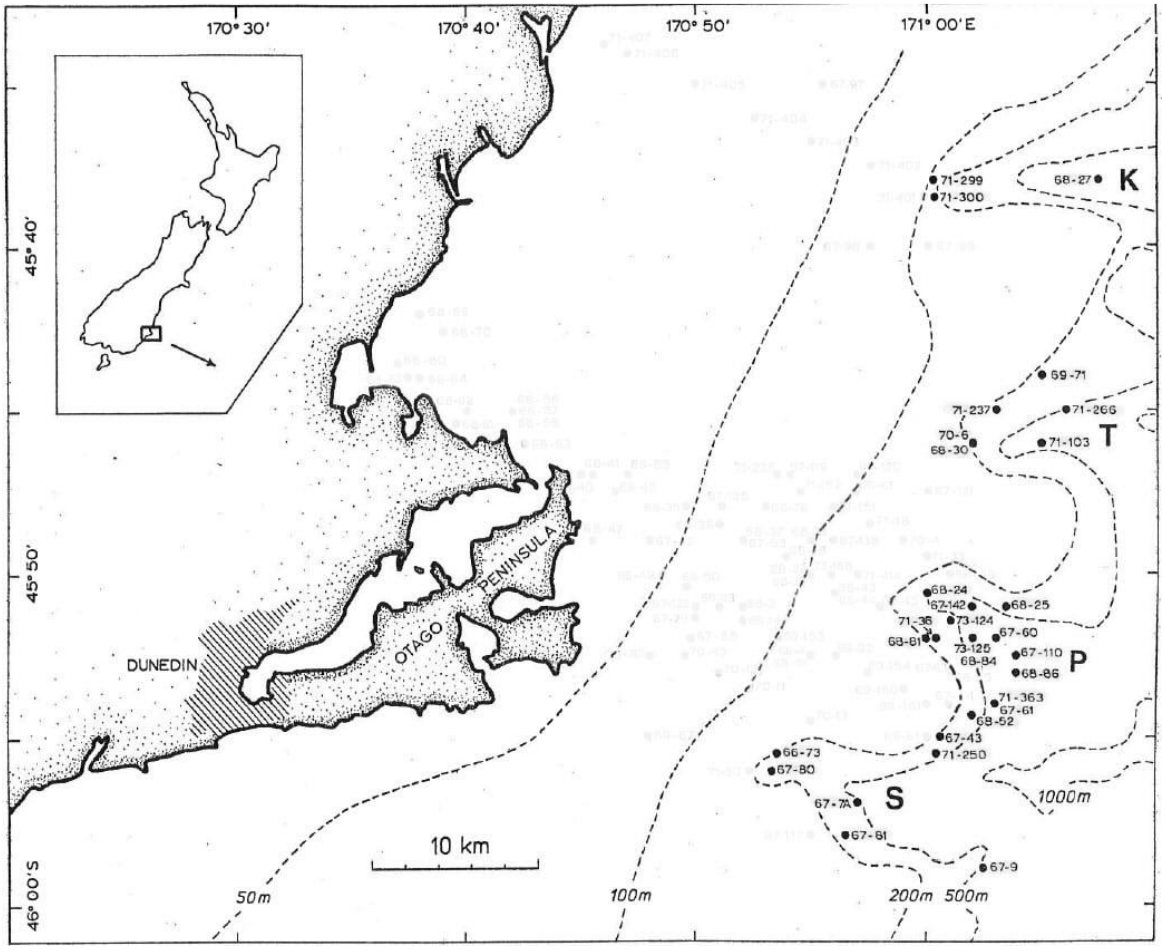


Figure 2: Study area showing the epibenthic stations sampled from 1966–76 that produced the archival data. Shown stations are the ones that fit the criteria for this analysis.

Methods

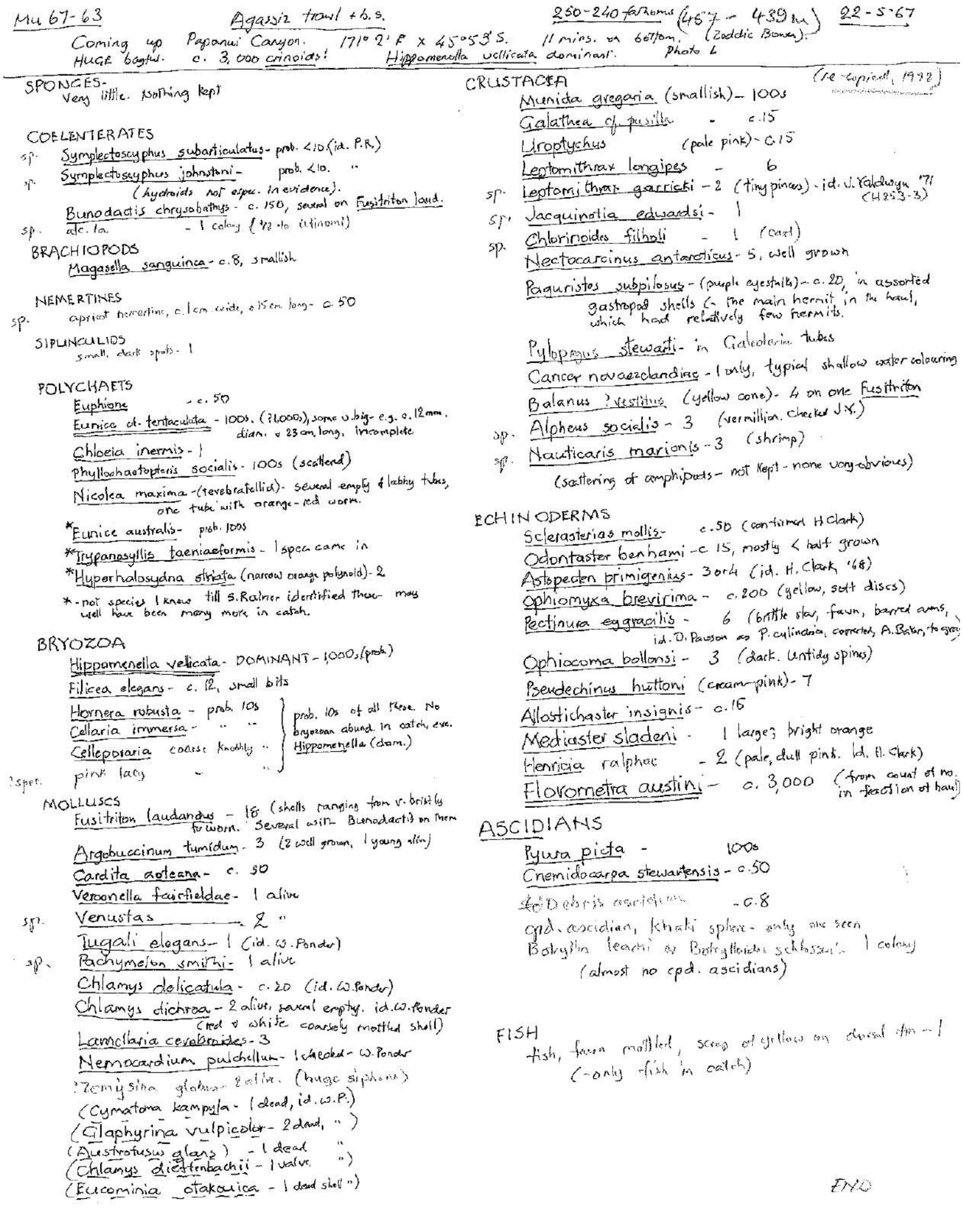
Filtering of Archival Data

The archival data were collected from 426 stations. Sampling methods and collection times varied with each cruise and included the use of various trawls and dredges. 128 stations did not have a sampling method recorded and were removed. Of the remaining 298 stations a majority (72%) of stations were sampled with an Agassiz trawl. Two sizes of Agassiz trawl were used: a four-foot trawl was used for the first three years of the study, after which a two-foot trawl was used for part of 1968–9 and consistently for the following years. Since the Agassiz trawl samples included the most reliable data on epifauna found in

submarine canyon areas and collected a mojrity of the data, only samples collected by Agassiz trawls were used in this analysis. Tow time for Agassiz trawls was variable and ranged from five to twenty minutes. At some stations only targeted species were recorded, where these were the primary focus, and all other organisms were left uncounted and discarded. Due to this variation of collection and recording methods some stations have apparently reliable count data, others have "dominant", "✓" or "numerous" which only gives an approximate estimate of the number, which were of limited use for this analysis.

The wide range of sampling methods and data recorded necessitated filtering the data for those useful to this thesis. Each station has a minimum and maximum depth that the fauna were collected from; therefore, in order to set a specific depth range to run statistical tests, the maximum depth was used for the depth parameter. All samples collected with an Agassiz trawl with a maximum depth of 200 m or greater were examined, as 200 m is commonly taken as the upper boundary for the deep-sea environment. This exclusion left 45 of the original 298 stations. The stations of interest for this analysis were mostly collected from either Saunders, Papanui, Taiaroa, or Karitane canyon. There was only one station, 68-52, that was within the selected depth range that was located outside of the canyon areas. The fauna of the selected stations was totalled and any station with either one or no organisms collected was removed. This excluded 14 of the 45 selected stations. Samples with minimum depths greater than 200 m were labelled "Deep Sea" since the entire sample was collected from depths greater than 200 m.

Any datum entry that was not a number, such as "abundant", "numerous", "Dominant", "✓", etc. was left as blank for the analysis as a zero would imply that there were no organisms collected (Figure 3). Running a separate analysis that is based on presence/absence may exacerbate already existing issues with ecological data and distance-based statistics (Warton *et al.* 2012). Reducing the dominant species, or species recorded without a number, down to one so they are weighted the same as a species only found once would make it difficult to tell whether a particular species actually accounts for a certain amount of variation between samples. The suggested assemblages and effects of variables such as trawl size and station location would be unclear. Species nomenclature follows the New Zealand Inventory of Biodiversity (Gordon 2009; Gordon 2010).


Mu 67-63 Agassiz trawl + b.s. 250-240 fathoms (457 - 439 m) 22-5-67
Coming up Papanui Canyon. 171° 2' E x 45°53' S. 11 mins. on bottom. (Zoddie Bones). HUGE bagful. c. 3,000 crinoids! Hippomenella vellicata dominant. Photo L

SPONGES- Very little. Nothing kept

COELENTERATES
sp. Symplectoscyphus subarticulatus - prob. <10. (id. P.R.)
sp. Symplectoscyphus johnstoni - prob. <10. "
(hydroids not espec. in evidence).
Bunodactis chrysobathys - c. 150, several on Fusitriton laud.
sp. alc. la - 1 colony (?? to crinoid)

BRACHIOPODS
Magasella sanguinea - c.8, smallish

NEMERTINES
sp. apricot nemertine, c. 1 cm wide, c. 15 cm long - c. 50

SIPUNCULIDS
small, dark spots - 1

POLYCHAETS
Euphione - c. 50
Eunice cf. tentaculata - 100s. (?1,000s), some v. big - e.g. c. 12 mm. diam. c 23 cm. long, incomplete
Chloeia inermis - 1
Phyllochaetopteris socialis - 100s (scattered)
Nicolea maxima - (terebratellid) - several empty & flabby tubes, one tube with orange-red worm.
*Eunice australis - prob. 100s
*Trypanosyllis taeniaeformis - 1 spec. came in
*Hyperhalosydna striata (narrow orange polynoid) - 2
* - not species I knew till S. Rainer identified these - may well have been many more in catch.

BRYOZOA
Hippomenella vellicata - DOMINANT - 1,000s (prob.)
Filicea elegans - c. 12, small bits
Hornera robusta - prob. 10s
Cellaria immersa - " "
Celleporaria coarse knobbly "
?spec. pink lacy - "
} prob. 10s of all these. No bryozoan abund. in catch, exc. Hippomenella (dom.)

MOLLUSCS
Fusitriton laudandus - 18 (shells ranging from v. bristly to worn. Several with Bunodactis on them
Argobuccinum tumidum - 3 (2 well grown, 1 young alive)
Cardita aoteana - c. 50
Verconella fairfieldae - 1 alive
sp. Venustas - 2 "
Tugali elegans - 1 (id. W. Ponder)
sp. Pachymelon smithi - 1 alive
Chlamys delicatula - c. 20 (id. W. Ponder)
Chlamys dichroa - 2 alive, several empty. id. W. Ponder (red & white coarsely mottled shell)
Lamellaria cerebroides - 3
Nemocardium pulchellum - 1 checked - W. Ponder
?Zemysina globus 2 alive. (huge siphons)
(Cymatona kampyla - 1 dead, id. W.P.)
(Glaphyrina vulpicolor - 2 dead, ")
(Austrofusus glans) - 1 dead "
(Chlamys dieffenbachii - 1 valve ")
(Eucominia otakauica - 1 dead shell ")

CRUSTACEA (re-copied, 1992)
Munida gregaria (smallish) - 100s
Galathea cf. pusilla - c. 15
Uroptychus (pale pink) - c. 15
Leptomithrax longipes - 6
sp. Leptomithrax garricki - 2 (tiny pincers) - id. J. Yaldwyn '71 (H253-3)
sp. Jacquinotia edwardsi - 1
Chlorinoides filholi - 1 (card)
sp. Nectocarcinus antarcticus - 5, well grown
Paguristes subpilosus - (purple eyestalks) - c. 20, in assorted gastropod shells (- the main hermit in the haul, which had relatively few hermits.
Pylopagurus stewarti - in Galeolaria tubes
Cancer novaezelandiae - 1 only, typical shallow water colouring
Balanus ?vestitus (yellow cone) - 4 on one Fusitriton
sp. Alpheus socialis - 3 (vermillion. checked J.Y.)
sp. Nauticaris marionis - 3 (shrimp)
(scattering of amphipods - not kept - none very obvious)

ECHINODERMS
Sclerasterias mollis - c. 50 (confirmed H Clark)
Odontaster benhami - c 15, mostly < half grown
Astropecten primigenius - 3 or 4 (id. H. Clark, '68)
Ophiomyxa brevirima - c. 200 (yellow, soft discs)
Pectinura eg gracilis - 6 (brittle star, fawn, barred arms, id. D. Pawson as P. cylindrica, corrected, A. Baker, to gra)
Ophiocoma bollonsi - 3 (dark. Untidy spines)
Pseudechinus huttoni (cream-pink) - 7
Allostichaster insignis - c. 15
Mediaster sladeni - 1 large; bright orange
Henricia ralphae - 2 (pale, dull pink. Id. H. Clark)
Florometra austini - c. 3,000 (from count of no. in fraction of haul)

ASCIDIANS
Pyura picta - 100s
Cnemidocarpa stewartensis - c. 50
Debris ascidians - c. 8
cpd. ascidian, khaki sphere - only one seen
Botrylloides leachi or Botrylloides schlosseri 1 colony
(almost no cpd. ascidians)

FISH
fish, fawn mottled, scrap of yellow on dorsal fin - 1
(- only fish in catch)

END

Figure 3: A sample archival data sheet. This is the count data for station Mu 67-73, data was collected from Papanui canyon by an Agassiz trawl.

The data were input into a spreadsheet in Microsoft Excel and set up for analysis in PRIMER (Anderson 2001). The PRIMER suite of programs allows for several statistical tests to be run in order to assess how different parameters of sample collection relate to the species collected and their abundance. The tests selected for this analysis were canonical correlation (CAP), multidimensional scaling (MDS and PCO), CLUSTER, SIMPER and PERMANOVA.

Multivariate Analysis in PRIMER

Even though CAP, MDS and PCO tests are similar, all three were used in order to examine the influence that each variable may have on benthic assemblages. CAP tests are simply designed to examine the relationship between two or more factors. The output on a CAP test can be weighted for a specific variable, therefore an explanation of similarities caused by a specific variable, and how much variation that variable accounts for in total, can be given (Hill and Lewicki 2007). This variable-specific variation was used in order to identify how changing collection parameters, such as depth, length of tow time, and size of the Agassiz trawl, changed which organisms were found in a sample or if any change occurred. This allows for the effects of a specific factor to be drawn out and displayed. The different fauna were used as variables and the differences in depth, length of tow and trawl size were used as factors. The CAP test displays how the samples are clustered in accordance to each factor.

MDS and PCO tests use distance matrices in order to explain similarities, or differences, between samples. The distances used in these tests, like the CAP test, have arbitrary units and cannot be quantified. Since the analysis focuses on creating a distance matrix and then looking at how similar the samples are it is impossible to define an axis on the final MDS/PCO output as a result of a particular variable because the axes themselves are arbitrarily defined (Anderson 2003). The variation between the samples is taken as a distance and these distances are plotted along an axis for each variable (Hill and Lewicki 2007). In two dimensions the distance between each station to each other station is proportional to how different the stations are; this distance has arbitrary units and as such the variation among the samples cannot be quantified. If each variable is selected the MDS/PCO test still works in theory, but the results are hard to display and visualise once

more than three dimensions are used for testing (Hill and Lewicki 2007). While more dimensions increase the accuracy of the test, the result becomes less meaningful, so two or three dimensions were used to calculate the different influences of each factor.

The CLUSTER test produces a dendrogram of the samples in relation to one another (Hill and Lewicki 2007). Sample variance is used to calculate a distance, which is used to define the different levels and size of the clusters themselves. The dendrogram shows the clustering of each station determined by all of their variables in a much more organised fashion than the CAP, MDS or PCO tests. While the other tests are useful for teasing out the effects of one variable at a time, the CLUSTER analysis shows how the samples relate to each other as a whole and suggests the structure of the benthic community on a larger scale, such as canyons and slope assemblages instead of assemblages for a specific canyon or depth.

The SIMPER test picks out which species are the cause for the largest amount of similarity/dissimilarity between the different samples (Warton *et al.* 2012). SIMPER determines the distance between two groups and calculates the percent contribution each species has to that distance. The result is a list of species which account for most of the variation among sample sites. This was used heavily in the analysis because the variables, as far as PRIMER was concerned, were each of the different recorded species. This meant that the species responsible for making each station similar or different from each other station, or group of stations, could be easily picked out and examined while changing the different parameters of each group. This provided multiple assemblages and allowed for those assemblages to be compared with each other and the previously calculated assemblages of 1979.

The PERMANOVA test calculates the p-value through permutations given by distance matrices, similar to the CAP, MDS and PCO tests, rather than the normal ANOVA (analysis of variance) method of using a table. This allows for the test to be run more efficiently when using a multivariate analysis (Anderson 2005). A normal MANOVA, multivariate analysis of variance test, uses the assumption that the data are in a normal distribution, which is unlikely for real data. The PERMANOVA test can use any measured distance run by an ANOVA test to describe variation in samples, which alleviates the poor assumption from the MANOVA test and still allows a robust statistical design to be used (Anderson 2001).

CAP, MDS, PCO, CLUSTER, and PERMANOVA tests were run on the count data collected in order to define the influence of Agassiz trawl size, depth, length of tow time and which canyon the sample was collected from on the sample abundance and collected fauna. The data underwent a square-root transformation and the tests were run using the Bray-Curtis similarity. Median grain size and mean grain size of both the whole sample and detritus only portion of the sample were taken for most samples from 1966-9 (Andrews 1973). While the sediment data can be a very useful factor to help characterise the distribution of local fauna, only 8 of the 31 stations had grain sizes for the whole sample associated with them. Thirteen stations had the detrital fraction analysed, but with only eight of the stations fully analysed and thirteen analysed for only one fraction, any conclusion that could be drawn from that would not be an accurate representation of any of the sampled canyons or slope. The sediment data were left out for this reason.

Several depth parameters were set up to characterise the canyon benthos and find the depth where the canyon benthic assemblages began. Initial depth ranges for testing were chosen as a result of a CLUSTER analysis run on the data. Minimum depths were chosen to ensure that no fauna from outside the selected depth ranges were included.

Data

Appendix 2, located on the attached CD ROM, lists the physical details and collected organisms at the stations of interest.

Results

There were three main groups shown in the CLUSTER analysis – those belonging to a shallow depth (< 300 m) range, those belonging to the deeper (> 500 m) range, and those in depth range of 300 – 500 m. Similarity levels of 70% were used to make this cut off. The shallow depth ranges showed a different assemblage than the deeper range (Figure 4). The intermediate depths had elements of both the assemblages found in the shallow and deeper depths; in order to determine the depth that this change in fauna occurred at, the minimum depths of each sample in the transitionary range (320, 380, and 420 m) were used as a depth cut off for PRIMER to analyse the assemblages at these depths and greater.

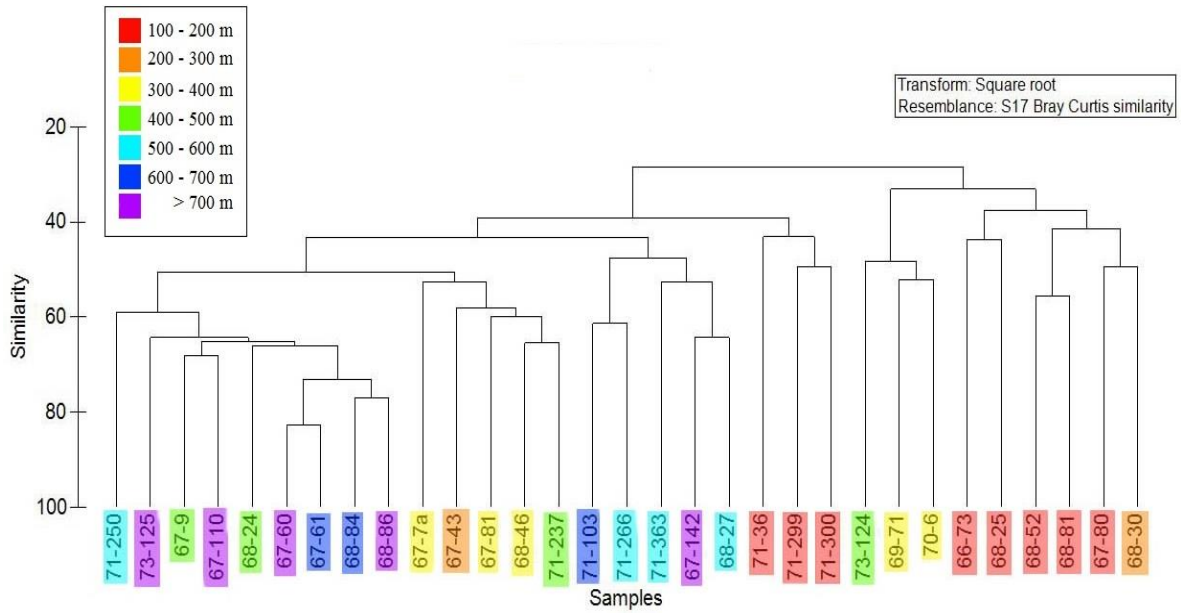


Figure 4: CLUSTER analysis results with depth ranges highlighted. Yellow (depth range 300 – 400 m) and green (depth range 400 – 500 m) are interspersed with the shallower (100 – 300) and deeper (>500 m) clusters. Minimum depths were used to determine the depth brackets.

There was a significant difference between samples depending on both sampling method and depth changes, as shown by the p-values of the PERMANOVA test results; changes in either the tow time of the sample collection or the canyon from which the sample was taken does not make a significant difference between the average assemblages found (Table 1). The two-foot Agassiz trawl yielded significantly different results than the four-foot Agassiz trawl (Figure 5). Since tow time did not affect species richness and the four-foot Agassiz trawl, unsurprisingly, has a more diverse average assemblage than the two-foot Agassiz trawl the statistical tests imply that the two-foot and four-foot Agassiz trawls behave differently. The CAP results showed that samples collected with the two-foot Agassiz trawl had clear differences between the canyons areas and the four-foot Agassiz trawl had clear differences with depth. The two-foot Agassiz trawl seems to yield higher similarities between assemblages separated by depth than the four-foot Agassiz trawl and the four-foot Agassiz trawl seems to yield better results for canyon assemblages with higher similarities than the two-foot Agassiz trawl (Figure 6).

Differing lengths of tow time had no statistically significant impact alone; although the CAP results do show clustering based on different tow times (Figure 7). This clustering is most likely due to influences on the average assemblages from other factors, such as depth range and trawl size. The differences in the collected organisms between each of the four canyons sampled display some clustering and had slightly varying assemblages, although not enough to claim a statistically significant change (Figure 8). Community structure changed significantly with depth, with different assemblages between the three different depth criteria (< 200 m, < 320 m, and < 380 m) (Figure 9). The shallower community was primarily composed of actiniarians, ascidians, asteroids, bryozoans and polychaetes, while decapods, demosponges and isopods were only found in the deeper community. Anomurans and ophiuroids were commonly found throughout both assemblages (Table 2).

The SIMPER results from the different canyons and depth categories suggest that the ophiuroid *Ophiacantha otagoensis* was the most significant cause of similarity between each canyon sample, which suggests it is a characteristic organism in the canyon areas. Bryozoans, anomurans, serpulids and other polychaetes also contributed significantly to the similarity between canyon stations (Table 3). The SIMPER results indicate that *Ophiacantha abyssicola otagoensis*, bryozoans, anomurans and serpulids and other polychaetes are the major characteristic epifauna of the Otago canyon network in general. The shallow slope environment, defined as stations with a minimum depth < 200 m, consisted of mainly bryozoans and polychaetes (20% and 13% of recorded organisms respectively) while asteroids, ophiuriods and anomurans accounted for about 10% of collected individuals each. The remaining representative fauna were actiniarians, serpulids and a few species of molluscs and crustaceans (Table 4). Similar species were found in both the canyon and slope assemblages, but the change in abundance and appearance of canyon-specific species at depths greater than 380 m were enough to make the difference in the two communities statistically significant.

Table 1 – PERMANOVA test results. A p-value of 0.05 or less is regarded as statistically significant. P-values for changes in depth and Agassiz trawl size are significant. P-vales for tow time and changes between canyons are not.

Factor	Levels	df	Pseudo-F	P-value
Depth	3	2	2.585	0.034
Trawl Size	2	1	2.236	0.047
Tow Time	7	6	0.943	0.591
Canyon	5	4	1.107	0.439

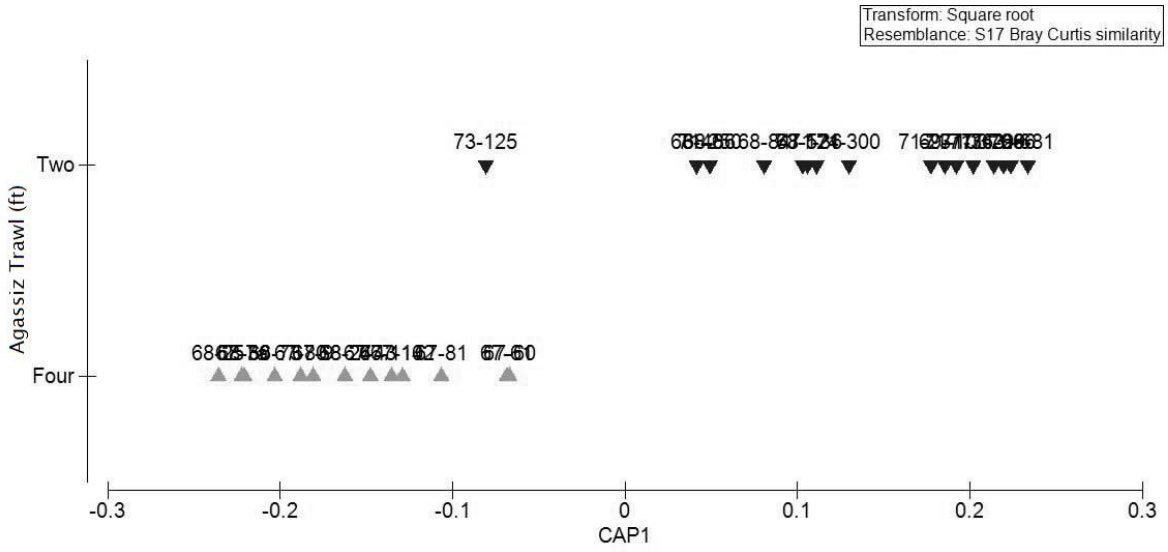


Figure 5 – CAP test results for the influence of Agassiz trawl size on collected samples.

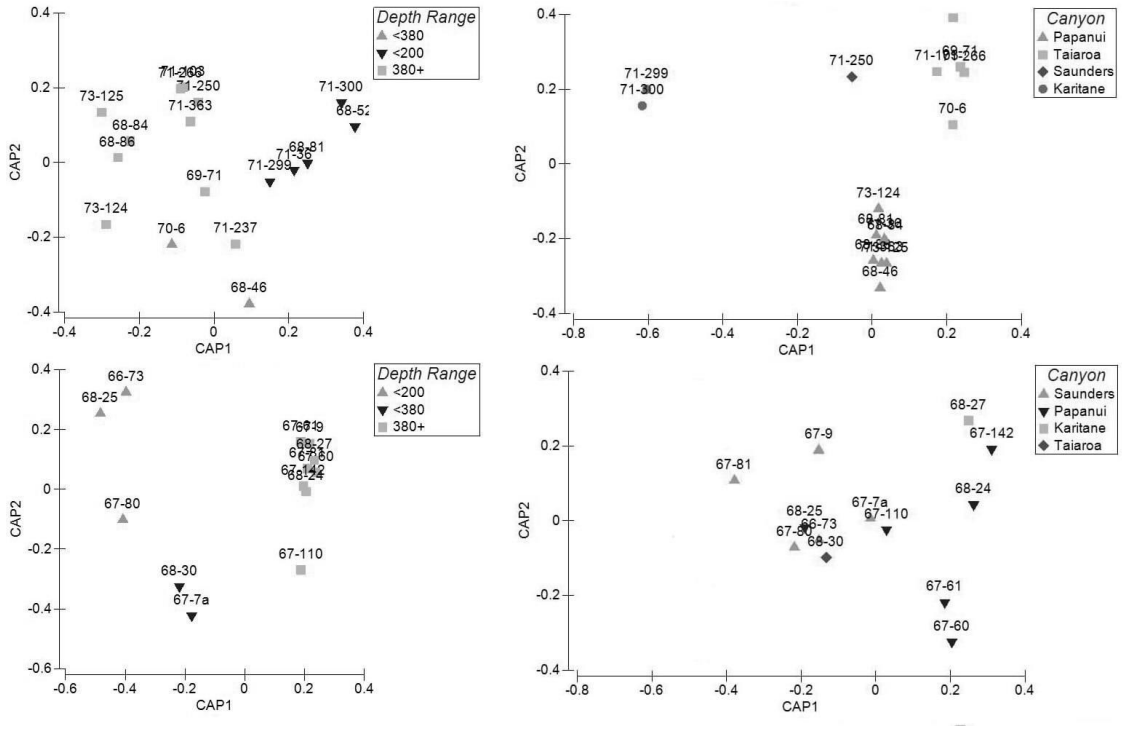


Figure 6 – CAP test results for the influence of Agassiz trawl size on depth and location. The top graphs are the two-foot Agassiz trawl samples, the bottom graphs are the four-foot Agassiz trawl samples.

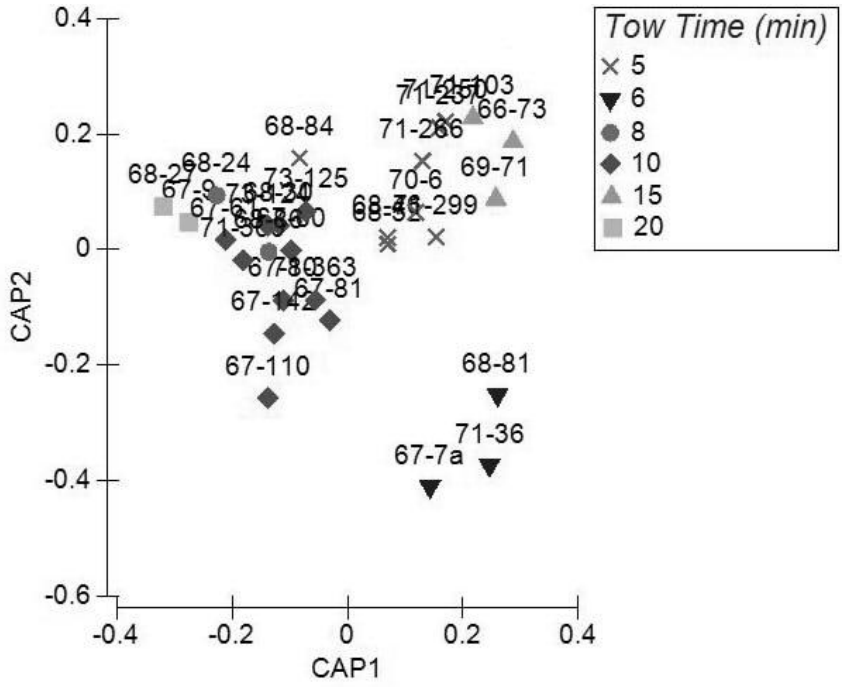


Figure 7 – CAP test results for the effect of changing the tow time on collected samples.

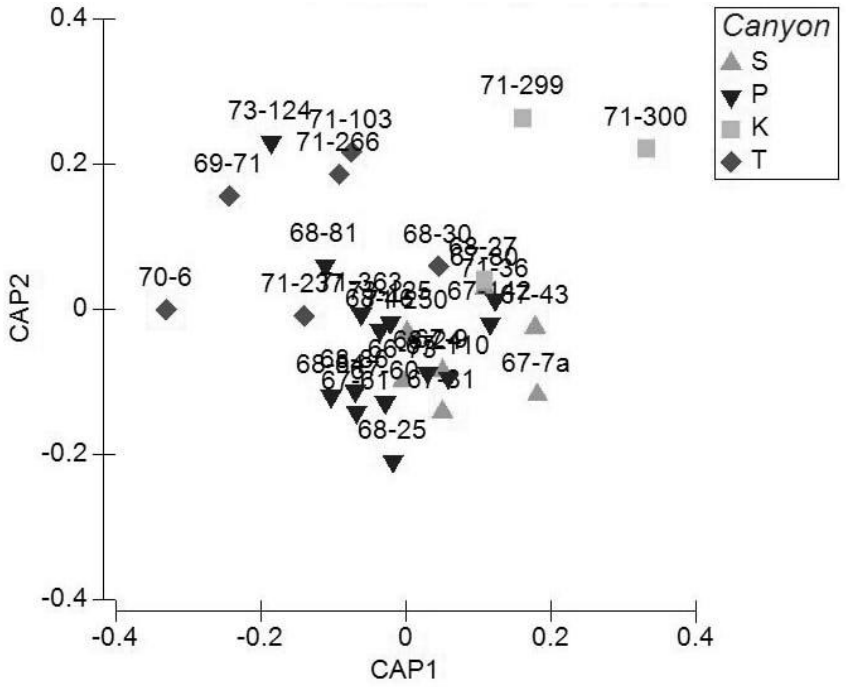


Figure 8 – CAP test results of changes between samples found in the four canyons and on the slope. “S” stations are found in Saunders canyon, “P” in Papanui, “T” in Taiaroa, ‘K” in Karitane.

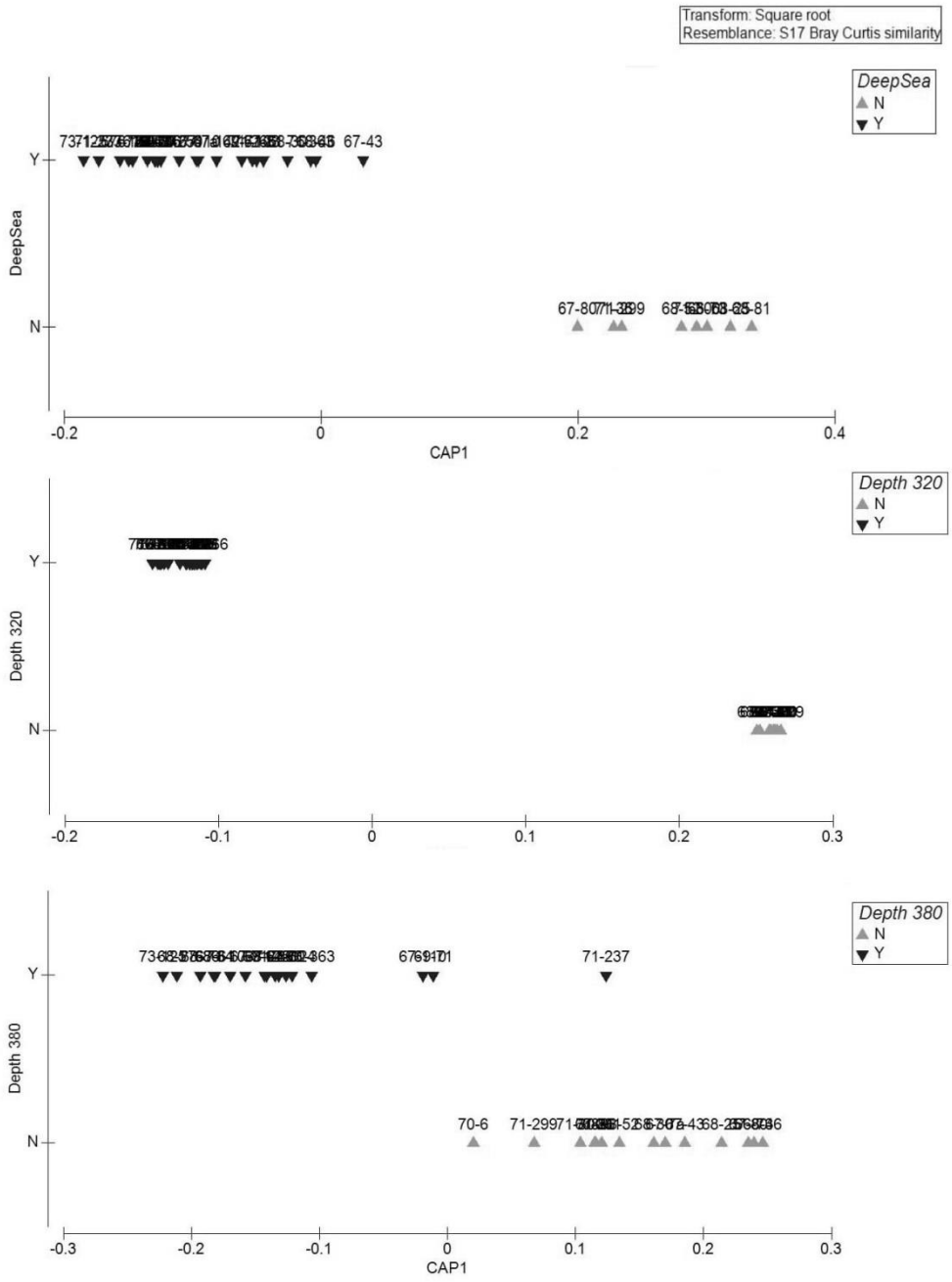


Figure 9 – CAP results for the influence of depth. If the station's minimum depth was greater than or equal to the depth specified on the graph, then the station was sorted under "Y". "N" stations do not meet the minimum depth criteria. The top graph looks at the deep-sea environment (depth cut-off of 200 m).

Table 2: List of species and the average number of individuals collected per sample in each of the benthic communities found at the three major depth ranges identified. The shading of the different species shows which depth ranges that particular species first appears in.

Major taxa	Species	Average Number of Individuals per sample		
		< 200 m depth	200-380 m depth	> 380 m depth
Porifera	Sponge calcareous pyriform	-	-	0.82
Demospogiae	*Stylocordyla borealis*	-	-	4.48
Demospogiae	*Tetilla australe*	-	-	1.03
Zoantharia	*Bunodactis chrysobathys*	3.84	2.54	
Zoantharia	*Hormathia* sp	0.48	-	-
Zoantharia	*Paracalliactis rosea*	-	0.69	1.4
Nemertinea	Nemertinea unIDed	0.47	-	-
Polychaetea	*Oligobrachia kernohanae*	-	-	1.28
Polychaetea	*Eunice tentaculata*	1.19	-	-
Polychaetea	*Phyllochaetopterus socialis*	4.61	2.6	-
Polychaetea	*Spirobranchus latiscapus*	2.68	5.16	-
Gastropoda	*Comitas onokeana vivens*	-	-	0.5
Gastropoda	*Sassia kampyla*	-	-	0.87
Gastropoda	*Fusitriton magellanicus laudandus*	1.5	0.63	-
Bivalvia	*Zygochlamys delicatula*	2.35	-	-
Bivalvia	*Parvamussium maorium*	-	-	1.06
Pycnogonida	Pycnogonida unIDed	0.58	-	1.71
Malacostraca	*Campylonotus rathbunae*	-	-	0.94
Malacostraca	*Chirostylus*	-	-	0.84
Malacostraca	*Cymonomus bathamae*	-	-	0.94
Malacostraca	Isopoda	-	-	0.46
Malacostraca	*Leptomithrax longipes*	1	-	-
Malacostraca	*Trizocheles spinosus*	0.38	-	-
Malacostraca	*Munida gregaria*	2.18	8.97	-
Malacostraca	Paguridae sp.	-	-	1.76
Malacostraca	*Nectocarciuus antarcticus*	-	0.81	-
Malacostraca	*Paguristes subpilosus*	1.48	-	-
Malacostraca	*Sympagurus dimorphus*	-	-	2.35
Malacostraca	*Lophopagurus lacertosus*	-	-	1.19
Malacostraca	*Lophopagurus stewarti*	3.35	0.93	-
Malacostraca	*Brucerolis ?hurleyi*	-	-	0.74
Crinoidea	*Florometra austini*	3.39	-	0.73
Stenolaemata	*Cinctipora elegans*	3.78	1.98	2
Stenolaemata	*Hippellozoon novaezelandiae*	0.79	-	-
Gymnolaemata	*Celleporaria* ' coarse knobbly'	4.29	-	-

Gymnolaemata	*Celleporaria* 'grey disc'	1.55	1.56	3.04
Gymnolaemata	*Euthyroides episcopalis*	-	-	1.99
Gymnolaemata	*Hippomenella vellicata*	7.65	-	-
Gymnolaemata	*Melicerita angustiloba*	-	-	2.93
Asteroid	*Astropecten primigenius*	0.87	-	-
Asteroid	*Heuricia ralphae*	0.92	-	-
Asteroid	*Odontaster beuhami*	2.35	1.4	-
Asteroid	*Pteraster bathamae*	-	0.57	-
Asteroid	*Sclerasterias mollis*	2.52	0.79	-
Ophiuroid	*Ophiacantha otagoensis*	1.66	1.47	4.24
Ophiuroid	*Ophiactis hirta*	0.83	-	0.67
Ophiuroid	*Ophiozonella stellamaris*	-	-	1.17
Ophiuroid	*Ophiomyxa brevirima*	1.93	-	-
Ophiuroid	*Ophiura irrorata*	-	-	0.9
Echinoidea	*Goniocidaris parasol*	0.88	-	2.98
Holothuroidea	*Bathyplotes nataus*	-	-	0.65
Ascidiacea	Ascidian unIDed	-	-	0.96
Ascidiacea	*Cnemidocarpa stewarteusis*	1.48	-	-
Ascidiacea	Debris ascidian	0.92	-	-
Ascidiacea	*Didemnum morteuseui*	-	3.2	-
Ascidiacea	*Pyura picta*	1.51	-	-
Actinopterygii	*Hermerocoetes*	-	0.6	-
Actinopterygii	Macrourid	-	-	0.57
Maxillopoda	Scalpellid	-	-	0.47

Table 3: List of major taxa and species that categorise each of the canyons

Major Taxa	Species	Average Number of Individuals per Sample			
		Saunders	Papanui	Taiaroa	Karitane
Porifera	Sponge calcareous pyriform	-	0.83	-	-
Demospogiae	*Stylocordyla borealis*	1.36	4.05	-	3.8
Demospogiae	*Suberites* sp	-	0.4	-	-
Hydroida	*Symplectoscyphus johnstoni*	0.88	-	-	-
Anthozoa	Alcyonaria 4	0.65	-	-	-
Zoantharia	*Bunodactis chrysobathys*	1.41	-	2.65	-
Zoantharia	*Hormathia* sp	0.52	-	-	-
Zoantharia	*Paracalliactis rosea*	0.49	1.51	0.67	-
Polychaetea	*Oligobrachia kernohanae*		1.45		
Polychaetea	*Galeolaria hystrix*	1.46	-	-	-

Polychaetea	*Phyllochaetopterus socialis*	2.44	–	6.41	0.91
Polychaetea	*Serpulid Spirobranchus latiscapus*	–	1.56	6.3	1.63
Gastropoda	*Comitas onokeana vivens*	–	–	0.81	–
Gastropoda	*Sassia kampyla*	–	0.95	–	1.05
Gastropoda	*Fusitriton magellanicus laudandus*	–	0.91	0.9	–
Bivalvia	*Chamys delicatula*	0.53	–	–	–
Bivalvia	*Parvamussium maorium*	–	0.57	–	–
Pycnogonida	Pycnogonida unIDed	0.86	0.82	1.92	–
Malacostraca	*Campylonotus reathbunae*	–	0.84	–	–
Malacostraca	*Chirostylus*	0.64	–	–	–
Malacostraca	*Cymonomus bathamae*	–	–	1.27	–
Malacostraca	Isopoda	0.34	–	–	–
Malacostraca	*Trizocheles spinosus*	–	0.43	–	–
Malacostraca	*Munida gregaria*	–	–	10.65	–
Malacostraca	Paguridae sp.	–	1.72	0.69	–
Malacostraca	*Paguristes subpilosus*	–	–	0.95	–
Malacostraca	*Sympagurus dimorphus*	0.55	2.17	0.87	2.49
Malacostraca	*Lophopagurus lacertosus*	–	0.8	0.98	–
Malacostraca	*Lophopagurus stewarti*	–	–	3.08	–
Malacostraca	*Uroptychis*	–	–	0.74	–
Crinoidea	*Florometra austini*	1.65	2.18	–	–
Stenolaemata	*Cinctipora elegans*	1.41	2.94	3.65	–
Gymnolaemata	*Cellaria tenuirostris*	–	–	5	–
Gymnolaemata	*Celleporaria* ‘ coarse knobbly’	1.46	1.04	–	–
Gymnolaemata	*Celleporaria* ‘grey disc’	–	1.69	7.43	1.79
Gymnolaemata	*Euthyroides episcopalis*	–	2.18	–	–
Gymnolaemata	*Hippomenella vellicata*	3.83	–	0.86	–
Gymnolaemata	*Hornera robusta*	1.71	–	–	–
Gymnolaemata	*Melicerita angustiloba*	–	3.08	1.03	0.94
Asteroidea	*Asteropecten primigenius*	–	0.37	–	–
Asteroidea	*Henricia ralphae*	0.61	–	–	–
Asteroidea	*Odontaster beuhami*	0.9	0.94	1.79	–
Asteroidea	*Peribolaster lictor*	0.72	–	–	–
Asteroidea	*Pteraster bathamae*	–	–	0.71	–
Asteroidea	*Sclerasterias mollis*	1.58	–	1.16	–
Ophiuroidea	*Ophiacantha otagoensis*	1.09	2.44	7.47	3.46
Ophiuroidea	*Ophiactis hirta*	–	0.65	1.16	–
Ophiuroidea	*Ophiomyxa brevirima*	0.77	0.62	–	–
Ophiuroidea	*Ophiozonella stellamaris*	–	0.34	1.84	–
Ophiuroidea	*Ophiura irrorata*	–	0.65	–	–
Echinoidea	*Goniocidaris parasol*	0.79	1.45	4.54	2.36
Holothurioidea	*Bathyplotes nataus*	0.4	0.35	–	–

Ascidiacea	Ascidian unIDed	0.53	-	-	-
Ascidiacea	cpd ascidian green	-	-	1.62	-
Ascidiacea	Debris ascidian	-	-	-	0.67
Asciciacea	*Didemnum morteuseui*	-	-	1.1	-
Ascidiacea	*Pyura picta*	0.7	-	-	-
Actinopterygii	Macrourid	-	0.35	-	-
Maxillopoda	Scalpellid	0.55	-	-	-

Table 4: List of major taxa and species that categorise the shallow slope (stations depth minimum of < 200 m).

Major Taxa	Species	Average Individuals per Sample
Zoantharia	*Bunodactis chrysobathys*	3.84
Nemertinea	Nemertinea unIDed	0.47
Polychaetea	*Phyllochaetopterus socialis*	4.61
Polychaetea	*Spirobranchus latiscapus*	2.68
Gastropoda	*Fusitriton magellanicus laudandus*	1.5
Bivalvia	*Zygochlamys delicatula*	1.5
Bivalvia	*Chamys* spp.	1.35
Bivalvia	*Paguristes subpilosus*	1.48
Pycnogonida	Pycnogonida unIDed	0.58
Malacostraca	*Trizocheles spinosus*	0.38
Malacostraca	*Munida gregaria*	2.18
Malacostraca	*Lophopagurus stewarti*	3.35
Crinoidea	*Florometra austini*	3.39
Stenolaemata	*Cinctipora elegans*	3.78
Stenolaemata	*Hippellozoon novaezelandiae*	0.79
Gymnolaemata	*Celleporaria* 'grey disc'	1.55
Gymnolaemata	*Celleporaria* spp.	2.53
Gymnolaemata	*Celleporaria* 'coarse knobbly'	1.76
Gymnolaemata	*Hippomenella vellicata*	7.65
Gymnolaemata	*Hormathia* sp	0.48
Gymnolaemata	*Leptomithrax longipes*	1
Asteroidea	*Odontaster benhami*	2.35
Asteroidea	*Sclerasterias mollis*	2.52
Asteroidea	*Astropecten primigenius*	0.87
Asteroidea	*Henricia ralphae*	0.92
Ophiuroidea	*Ophiomyxa brevirima*	1.93

Ophiuroidea	*Ophiacantha otagoensis*	1.66
Ophiuroidea	*Ophiactis hirta*	0.83
Echinoidea	*Goniocidaris parasol*	0.88
Ascidiacea	*Pyura picta*	1.51
Ascidiacea	Debris ascidian	0.92
Ascidiacea	*Cnemidocarpa stewartensis*	1.48

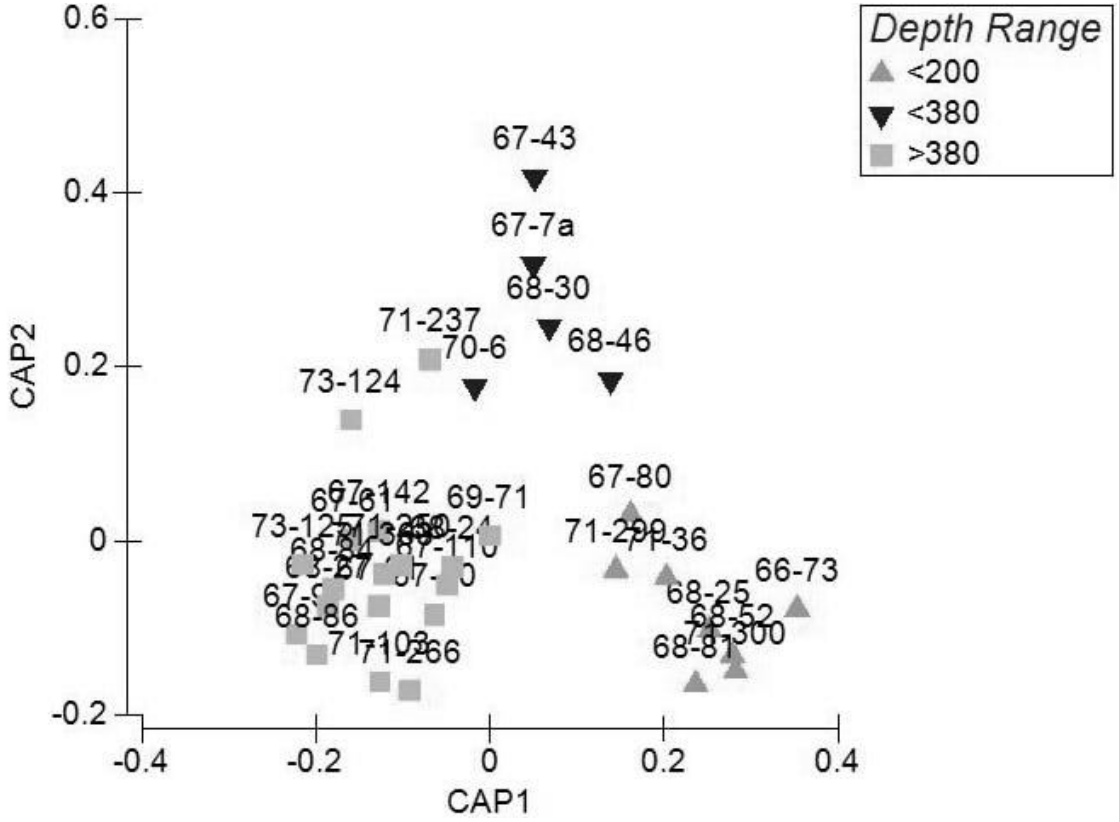


Figure 10: CAP test results of the three different depth ranges as indicated by the CLUSTER and SIMPER analysis.

Discussion

The CAP results for both the length of tow time and the differences between the individual canyon assemblages show clustering, which implies these two factors have some effect on the species collected and their abundance. The PERMANOVA tests, however, show that neither of these factors has a significant impact. The clustering of the tow time factor, although present, does not present any sort of pattern. Five- and fifteen-minute tows are most similar to each other, while six-minute tows are less similar to any other time. The clustering is a result of the low sample size for six-, eight-, nine- and

twenty-minute tows and the change in the assemblages are more dependent on other factors, such as depth and size of the Agassiz trawl.

The type and size of trawl used to collect samples have been shown to account for a significant portion (up to 47%) of species variability in a sample (Fock *et al*. 2002; Greenwood 2008). Although Fock *et al.* (2002) and Greenwood (2008) compared different sampling devices, instead of comparing two different sized Agassiz trawls, their results agree with the results produced by the CAP and SIMPER tests in this study. Agassiz trawl size appears to account for a statistically significant portion of sample variation, but not enough to affect the assemblages presented in the CLUSTER analysis (Figure 4). All depth ranges had multiple stations sampled by both the four-foot and two-foot dredge. Previous work done on zooplankton collection suggests that longer tows and larger nets reduces sampling error, but does not change the collected assemblages (Wiebe 1972). This also agrees with the observed results in this study, as changing the length of the tow time had no significant effect on the collected assemblages.

The SIMPER analyses of benthic community changes with depth suggest that a characteristic canyon faunal community occurs from around 380 m and deeper (Figure 10). Benthic assemblages at 320 m depth begin to resemble that of the deeper canyon areas as *Paracalliactis rosea*, *Didemnum mortenseni*, and *Pteraster bathamae* become more commonplace. At 380 m the average assemblage greatly resembles that of the deep canyon areas. Anomurans (*Chirostylus* sp., Paguridae sp., *Sympagurus dimorphus* and *Lophopagurus lacertosus*), bryozoans (*Euthyroides episcopalis* and *Melicerta angustiloba*), molluscs (*Parvamussium maorium* and *Comitas onokeana vivens)*, crustaceans (*Cymonomus bathamae* and *Campylonotus rathbunae*) and sponges (*Stylocordyla borealis* and Sponge calcareous pyriform) are commonly found and compose the bulk of the community. This suggests that the canyon fauna starts to appear at 320 m and transition over the next 60 m to the same distribution of that found in the canyons. The CAP results agree with the SIMPER analysis. The 320 m depth CAP analysis clearly shows difference in the assemblages with depth. The overlap of samples in the 380 m depth CAP analysis is due to the inclusion of some stations with a transitionary assemblage at depths of 320–380 m in the shallower category (Figure 9).

A previous analysis by Probert *et al*. (1979) concluded that the canyon benthos started to appear around 450 m depth. Their analysis included 111 stations covering the

shelf and slope, including the canyons. They identified eight benthic assemblages separated by depth, over half of which had species that occurred in canyon samples. All species suggested to occur in the canyon environment by this earlier analysis are listed in Table 5. Groups 4 – 5 of Probert *et al.*'s (1979) analysis are characteristic of both the slope and canyon environment. Groups 6 – 8 include species mainly found in the canyon environment. Both groups also include species that did not show up in the analysis of the continental slope or any of the four canyon groups described in this chapter. The shallower groups of the earlier analysis also produced more bryozoans (*Cellaria immersa*, *Gigantopora* sp.), and one more ophiuroid, asteroid, sponge and bivalve (*Clarkcoma bollonsi*, *Sclerasterias mollis*, *Cliona celata*, and *Cardita aoteana*) than the recent analysis showed. The deeper group assemblages showed increased octocoral, polychaete and bryozoan presence than the canyon groups of this analysis. The inclusion of more species in the original analysis is likely due to two factors. First, the SIMPER test showed that 90% of the variation among canyon samples was explained without the presence of the species that appear in the original, but not the recent, analysis; so these organisms are likely not a cause for variation in these environments. Second, the original analysis formed groups solely by depth while the analysis done in this chapter looked at the canyon areas specifically. The additional polychaetes and bryozoans found in the original analysis appear in the SIMPER test for a depth cut-off of 380 m, but not in the canyon assemblages. The lack of these organisms in the canyons suggests that they are present in these depths but are not prevalent enough to characterise the canyon environments.

Table 5: A list of the species found in canyon areas in Groups 4 – 8 of Probert *et al*. (1979). The species highlighted in grey did not appear in the canyon or slope assemblages of the recent analysis.

Major Taxa	Species
"Group 4 - 5" (Probert *et al.* 1979)	
Demospongiae	*Cliona celata*
Zoanthia	*Bunodactis chrysobathys*
Polychaetea	*Phyllochaetopterus socialis*
Gastropoda	*Fusitriton magellanicus laudandus*
Bivalvia	*Cardita aoteana*
Bivalvia	*Zygochlamys delicatula*
Bivalvia	*Paguristes subpilosus*

Malacostraca	*Leptomithrax longipes*
Malacostraca	*Lophopagurus stewarti*
Stenolaemata	*Cinctipora elegans*
Stenolaemata	*Hippellozoon novaezelandiae*
Gymnolaemata	*Cellaria immersa*
Gymnolaemata	*Cellaria tenuirostris*
Gymnolaemata	Celleporaria 'course knobbly'
Gymnolaemata	Gigantopora Sp.
Gymnolaemata	*Hippomenella vellicata*
Asteroidea	*Astropecten primigenius*
Asteroidea	*Odonaster benhami*
Asteroidea	*Sclerasterias mollis*
Ophiuroidea	*Ophiomyxa brevirima*
Ophiuroidea	*Clarkcoma bollonsi*
Ascidiacea	*Cnemidocarpa stewartensis*
Ascidiacea	*Didemnum mortenseni*
Ascidiacea	Debris ascidian'
"Group 6 - 8" (Probert *et al.* 1979)	
Demospongiae	*Coelosphaera globose*
Demospongiae	*Stylocordyla borealis*
Demospongiae	*Suberites australiensis*
Demospongiae	*Suberites microstomus*
Demospongiae	*Tetilla australe*
Anthozoa	Octocoral 1
Anthozoa	Octocoral 4
Zoanthia	Hormathia sp.
Polychaeta	*Chloeia inermis*
Polychaeta	*Hyalinoecia tubicola*
Polychaeta	*Oligobranchia kernohanae*
Gastropoda	*Comitas onokeana vivens*
Gastropoda	*Sassia kampyla*
Gastropoda	*Aeneator recens*
Gastropoda	*Falsilunatia powelli*
Gastropoda	*Malluvium calcareus*
Gastropoda	*Penion fairfieldae*
Bivalvia	*Parvamussium maorium*
Malacostraca	*Campylonotus rathbunae*
Malacostraca	*Cymonomus bathamae*
Malacostraca	*Trizocheles spinosus*
Malacostraca	Pagurid 'smooth, apricot'
Malacostraca	*Parapagurus dimoprhus*
Malacostraca	*Pontophilus acutirostratus*
Malacostraca	*Lophopagurus lacertosus*

Crinoidea	*Florometra austini*
Stenolaemata	Fasciculipora cf. fruticosa
Gymnolaemata	Celleporaria 'grey disc'
Gymnolaemata	*Euthyroides episcopalis*
Gymnolaemata	*Melicerita angustiloba*
Gymnolaemata	*Odontionella cyclops*
Asteroidea	*Peribolaster lictor*
Asteroidea	*Pteraster bathamae*
Ophiuroidea	*Ophiacantha otagoensis*
Echinoidea	*Goniocidaris parasol*
Holothurioidea	*Bathyplotes natans*

A SIMPER analysis of the data was carried out using a depth cut-off of 450 m, which in the earlier analysis was suggested as the depth at which the canyon fauna appeared. This analysis was mainly done to generate an assemblage of what would have been considered canyon fauna using the depth-cut off defined by Probert *et al*. (1979) in order to compare the suggested assemblage with those generated for the four individual canyons. The generated list of species for the 450 m depth assemblage shares 85% of the organisms within its assemblage with the other four canyon areas generated by the canyon SIMPER analysis (Table 6). There are only five species that the original depth cut-off lists as canyon species that are not found in the suggested assemblages, and they make up less than 4% of the variation among the archival canyon assemblage itself. *Tetilla australe* and *Aeneator recens* are present in the original analysis of the slope environment, implying that these five species may be found in more shallow areas.

Table 6: The assemblage generated by the use of the 450 m depth cut-off defined by the original analysis. Cells with a "-" indicates that the listed species was found in at least one of the analysed canyon assemblages but not in the canyon assemblage produced by Probert *et al*. (1979). Species highlighted in grey are found in the assemblage formed with the 450 m depth cut-off but not in any of the four re-analysed canyon assemblages.

Major Taxa	Species	Archival
Porifera	Sponge calcareous pyriform	0.87
Demospongiae	*Stylocordyla borealis*	4.74
Demospongiae	*Suberites* sp	-
Demospongiae	*Tetilla australe*	1.09
Hydroida	*Symplectoscyphus johnstoni*	-
Anthozoa	Alcyonaria 4	-
Zoanthia	*Bunodactis chrysobathys*	-
Zoanthia	*Hormathia* sp	-
Zoanthia	*Paracalliactis rosea*	0.83
Polychaetea	*Galeolaria hystrix*	-
Polychaetea	*Oligobrachia kernohanae*	1.35
Polychaetea	*Phyllochaetopterus socialis*	-
Polychaetea	*Spirobranchus latiscapus*	-
Gastropoda	Bathytoma parengonius	0.43
Gastropoda	*Comitas onokeana vivens*	0.52
Gastropoda	*Sassia kampyla*	0.86
Gastropoda	*Ellicea receus*	0.44
Gastropoda	*Fusitriton magellanicus laudandus*	-
Bivalvia	*Chamys delicatula*	-
Bivalvia	*Parvamussium maorium*	1.12
Pycnogonida	Pycnogonida unIDed	1.53
Malacostraca	*Campylonotus reathbunae*	0.99
Malacostraca	*Chirostylus*	0.83
Malacostraca	*Cymonomus bathamae*	0.69
Malacostraca	Isopoda	0.48
Malacostraca	*Trizocheles spinosus*	-
Malacostraca	*Munida gregaria*	-
Malacostraca	Paguridae sp.	1.27
Malacostraca	*Paguristes subpilosus*	-
Malacostraca	*Sympagurus dimorphus*	1.56
Malacostraca	*Lophopagurus lacertosus*	1.16
Malacostraca	*Lophopagurus stewarti*	-
Malacostraca	Serolis	0.49
Malacostraca	*Brucerolis ?hurleyi*	0.78

Malacostraca	*Uroptychis*	-
Crinoidea	*Florometra austini*	2.09
Stenolaemata	*Cinctipora elegans*	-
Gymnolaemata	*Cellaria tenuirostris*	-
Gymnolaemata	*Celleporaria* 'coarse knobbly'	-
Gymnolaemata	*Celleporaria* 'grey disc'	1.81
Gymnolaemata	*Euthyroides episcopalis*	1.84
Gymnolaemata	*Hippomenella vellicata*	-
Gymnolaemata	*Hornera robusta*	-
Gymnolaemata	*Melicerita angustiloba*	3.1
Asteroidea	*Asteropecten primigenius*	-
Asteroidea	*Henricia ralphae*	-
Asteroidea	*Odontaster beuhami*	-
Asteroidea	*Peribolaster lictor*	-
Asteroidea	*Pteraster bathamae*	-
Asteroidea	*Sclerasterias mollis*	-
Ophiuroidea	*Ophiacantha otagoensis*	2.63
Ophiuroidea	*Ophiactis hirta*	0.65
Ophiuroidea	*Ophiomyxa brevirima*	-
Ophiuroidea	*Ophiozonella stellamaris*	1.24
Ophiuroidea	*Ophiura irrorata*	0.96
Echinoidea	*Goniocidaris parasol*	2.62
Holothurioidea	*Bathyplotes nataus*	0.69
Asciciacea	*Didemnum morteuseui*	-
Ascidiacea	cpd ascidian green	-
Ascidiacea	Debris ascidian	-
Ascidiacea	*Pyura picta*	-
Ascidiacea	Ascidian unIDed	0.88
Actinopterygii	Macrourid	0.6
Maxillopoda	Scalpellid	0.49

The analysis of the archival data shows that the average canyon assemblage in the Otago canyon network is primarily composed of ophiuroids, bryozoans, anomurans, and polychaetes. The original analysis of the data varies slightly from this analysis (~15% of variance between species) and includes more bryozoans, sponges, and corals than the analysis performed in this chapter. The slope is characterised by mainly: bryozoans, polychaetes, actiniarians, asteroids, and ophiuroids; which agrees with the slope assemblages made in the original analysis (Probert *et al*. 1979).

This slope assemblage is similar to that found worldwide, as both have polychaetes and ophiuroids as dominant taxa, but malacostracans and molluscs tend to occur in higher

numbers globally (Hessler and Sanders 1966; Smith and Hamilton 1983; Brant *et al*. 2007). The assemblage of the Otago canyon network is similar to that of global canyons; both have polychaetes and ophiuroids as dominant organisms but copepods, molluscs and isopods are more common and both bryozoans and anomurans are much rarer globally.

Echinoderms, crustaceans, and molluscs are commonly found on the slope of the Chatham Rise area (McKnight and Probert 1997). Crustaceans and molluscs were found to be common in the Otago canyons as well, but the species found varied significantly, while echinoderms did not characterise the Otago canyons. McKnight and Probert (1997) described three communities from the Chatham Rise, of which community "A" is the most comparable to the slope community described in this chapter since "A" occurs at the shallowest depths (237–602 m) and the only slope samples analysed in this chapter are from <200 m depth. *Serolis bromleyana* and *Spatangus multispinus* dominated the community and *Campylonotus rathbunae, Fusitriton retiolus, Ophiura irrorata, Micantapex paregonius, Cominella alertae, Columbarium mariae, Falsilunatia powelli* and *Nassarius ephamillus* were also commonly found on the Chatham Rise (McKnight and Probert 1997). *Campylonotus rathbunae* and *Ophiura irrorata* were found to characterise the Otago canyons along with a species of *Fusitriton* (*F. magellanicus laudandus)* in the recent analysis and *Serolis bromleyana* was found to characterise canyon assemblages in the previous analysis. *Spatangus multispinus, Cominella alertae, Columbarium mariae, Falsilunatia powelli, Nassarius ephamillus* and *Micantapex parengonius* were not found to characterise the Otago canyons.

Although this analysis broadly defines the epifaunal community in the canyons, the benthic community as a whole still needs to be systematically studied. Collection of infauna in addition to epifauna from the canyons can provide a more detailed assemblage and community structure than analysing archival data.

CHAPTER 4 – INFAUNAL MACROBENTHOS OF SAUNDERS AND PAPANUI CANYONS

Introduction

Previous ecological work in the submarine canyons areas of New Zealand has focused on the infaunal mega and macrobenthos in Kaikoura canyon and the epifaunal macrobenthos of the Otago canyon network (Probert *et al*. 1979; De Leo *et al*. 2010). The megabenthos of Kaikoura canyon are unusually abundant, averaging 516 individuals per m^{-2} and a biomass level of 89 g C per m^{-2} (De Leo *et al*. 2010). This level of abundance is 100 times higher than previously recorded for deep-sea detritus based habitats; the biomass level also exceeds the previous literature by greater than 100 times (Rex *et al*. 2006; De Leo *et al*. 2010). *Molpadia musculus*, *Alomasoma nordpacificum* and *Maldane theodori* (a holothuroid, echiuran and polychaete) accounted for over 75% of macrofaunal biomass collected. This extremely high level of productivity is unusual, especially for a non-chemosynthetic deep-sea habitat. The epifaunal macrobenthos of the Otago canyon network is not as dramatically abundant or productive as the Kaikoura canyon environment.

The Otago canyon areas are characterised by ophiuroids, polychaetes, anomurans, bryozoans and serpulids (Probert *et al*. 1979). This earlier study also suggests sponges and corals are commonplace in these canyon areas, but the analysis in Chapter 3 suggests that these organisms are present but not enough to characterise the environment. Detailed lists of species that characterise each of the canyon environments and the adjacent slope environment can be found in Chapter 3, Tables 3 and 4. The benthic community does not strongly differ between canyons and adjacent slope in the Otago canyon network. Previous work by Probert *et al*. (1979) and a later analysis of archival data (Chapter 3) indicate that the fauna in the canyons and on the adjacent slope overlap considerably (72% of species collected on the slope were also found in the canyons). The benthic community of the canyon areas consists of more than just the epifauna; in order to understand the community structure of the canyons it is necessary to study the infauna as well.

This study was done to gather quantitative data on the infaunal macrobenthos of the Otago canyon network and the adjacent slope environment. Time constraints placed on

vessel availability and the duration of the MSc programme allowed for either a broad swath of samples in the canyon network, or more detailed study of two of the canyons. Since detailed, systematic study is lacking in this canyon network two canyons became the focus of this study: Saunder's canyon and Papanui canyon. These canyons form the southern half of the Otago canyon network (Figure 1a, 1b). Samples were collected from four locations inside each canyon and three on the slope adjacent to each canyon in order to compare the canyon infauna with that of the adjacent slope (Table 1). The collected organisms and sediment provide an insight into the faunal distributions found in these canyons and nearby areas.

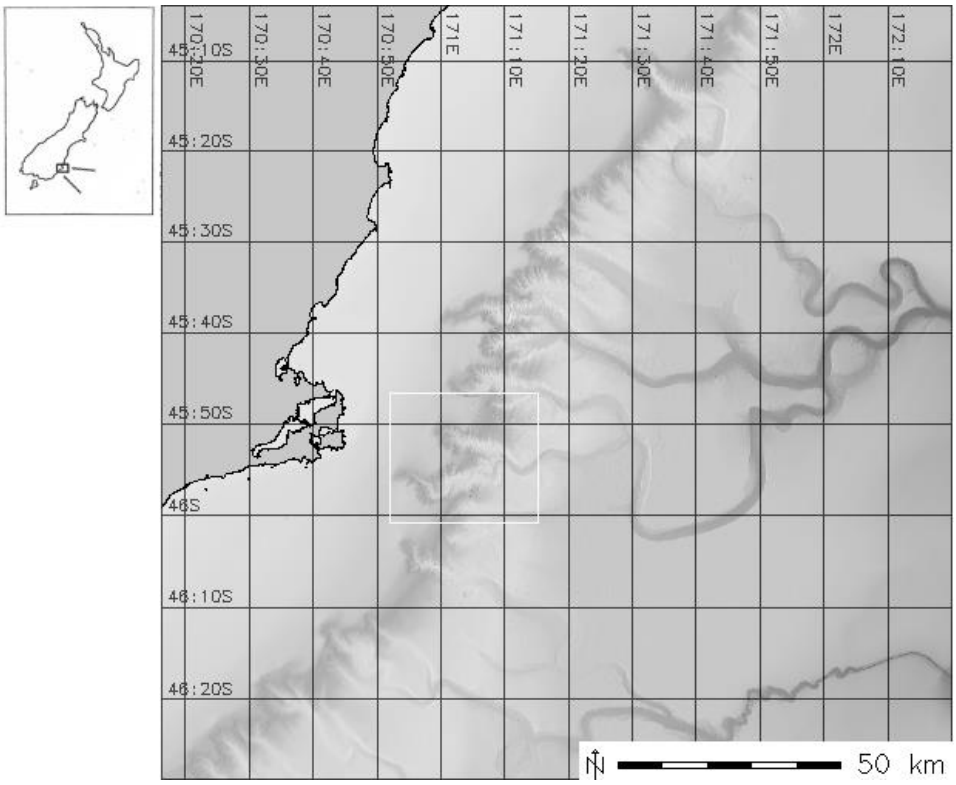


Figure 1a: Location of Study Area off of the Otago Peninsula.

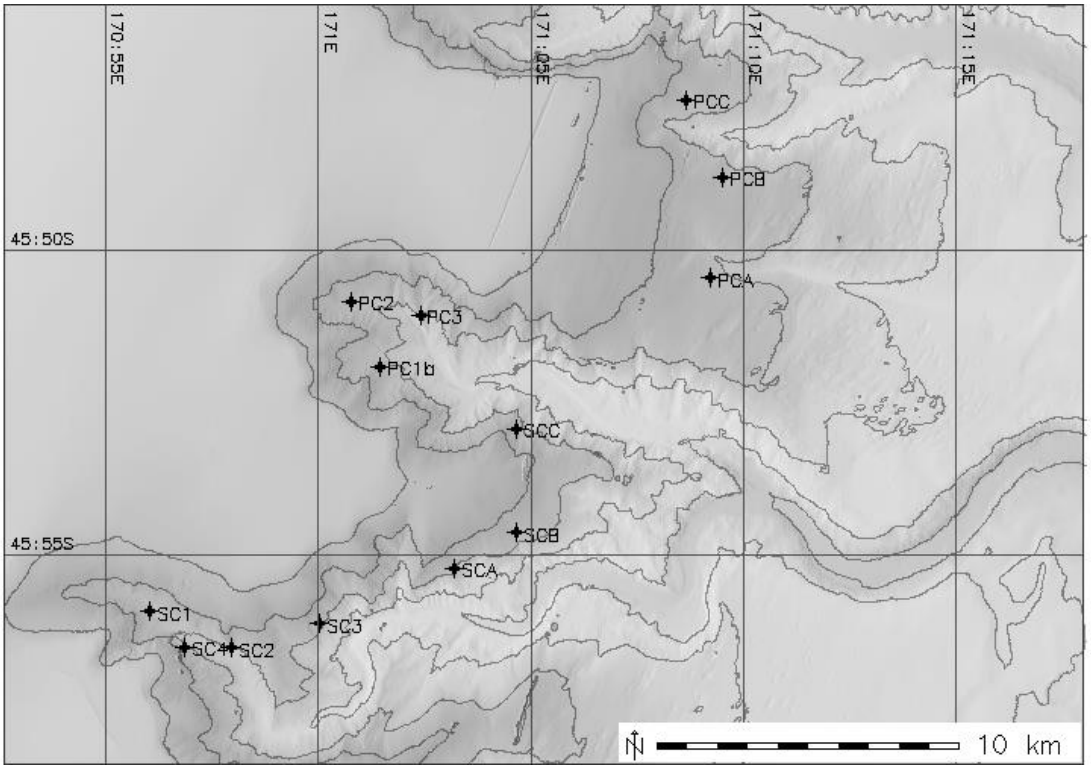


Figure 1b: Map of Study Area with station locations.

Table 1: Sample location, depth, and sediment volume, and area for the infaunal study of Saunders and Papanui Canyon. Samples ending in a number (SC1-4 and PC1a-3) were collected in a canyon, samples ending in a letter (SCA-C and PCA-PCC) were collected on the slope. Samples beginning with SC are from the Saunders canyon area and adjacent slope. Samples beginning with PC are from the Papanui canyon area and adjacent slope.

Sample	Sediment Description	Latitude (S)	Longitude (E)	Depth (m)	Volume (cm3)	Sieved Vol. (cm3)	Sampled Area (m2)
SC1	Fine Clay, Blue/Grey, Some sand	45°55.9263	170°56.0402	540	50400	25200	0.25
SC2	Fine Clay, Blue/Grey, Some sand	45°56.5200	170°57.9714	590	29232	14600	0.15
SC3	Sandy, slightly coarse, Grey/brown	45°56.1284	171°00.0219	540	23184	11600	0.12
SC4	Sandy, Calcarious Material	45°56.5163	170°56.8500	590	14112	7000	0.07
SCA	Fine Clay, Grey/Blue, Some sand	45°55.2137	171°03.2078	530	38304	19000	0.19
SCB	Muddy Sand, Brown	45°54.6375	171°04.6634	530	17136	8600	0.09
SCC	Sandy, Muddy, Brown	45°52.9362	171°04.6503	510	28224	14100	0.14
PC1a	Soft, Fine Silt/Clay, Brown	45°51.9083	171°01.4636	550	too little	N/A	N/A
PC1b	Fine Silt/Mud, Brown	45°51.9083	171°01.4636	550	22176	11100	0.11
PC2	Silt/Mud, Brown	45°50.8467	171°00.7702	540	22176	11100	0.11
PC3	Mud/Silt, Brown	45°51.0602	171°02.3980	520	34272	17100	0.17
PCA	Sand/Mud, Brown	45°50.4574	171°09.2230	560	26208	13100	0.13
PCB	Mud/Sand, Brown	45°48.8026	171°09.4976	505	29232	14600	0.15
PCC1	Sand/Mud, Brown	45°47.5299	171°08.6460	540	too little	N/A	N/A

Methods

Sampling Design Testing

The instrument of collection was originally intended to be a box corer; however, preliminary trials using a Wildco box corer with box size of 150 x 150 x 230 mm proved unsatisfactory and indicated that it would not be able to retrieve suitable samples. No other suitable box corer or grab was available and it was decided to use instead an anchor-box dredge, as this would be robust enough to operate successfully in the canyon environment, yet provide data comparable to that from a box corer (Probert 1984). The original design of the anchor-box dredge is outlined in Carey and Hancock (1965) (Figure 2). For the present study a smaller version was constructed with box dimensions of 180 x 335 x 700 mm, which gives the anchor-box dredge a volume of roughly 42 litres. The anchor-box dredge

has a planing edge on the front which is designed to control the depth that the dredge digs into the sediment; the dredge used in this study was designed to penetrate to a sediment depth of 10 cm.

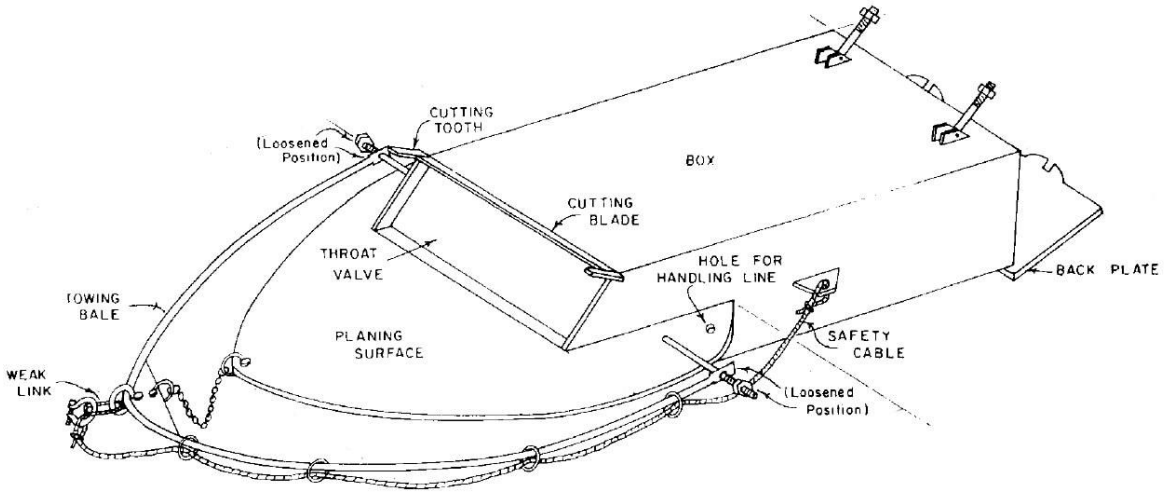


Figure 2: The original design of the anchor-box dredge by Carey and Hancock (1965).

The anchor-box dredge was tested in Otago Harbour on 6 September 2012 before sampling in the canyons in order to ensure that it functioned the way it was designed to. The dredge was towed along the harbour bottom while two divers filmed and monitored the dredging process. A system of two lines was set up between two vessels, the *Polaris II* and the *Beryl Brewin*, in order to control the angle the dredge was towed at and facilitate the diver's filming. The first line was run from the dredge to a mussel buoy then to the winch on the *Polaris II*. The second line was run from the *Beryl Brewin* to the same mussel buoy. This mussel buoy was included so the line angle from the *Polaris II* to the dredge would remain constant, or be adjusted by either tightening or slackening the line. The second line was included to keep the mussel buoy from drifting and to orient the divers while filming.

The dredge was towed a total of five times by using the winch on the *Polaris II* to perform the tow and resetting its position using the winch on the *Beryl Brewin*. The original dredge design did not collect the full depth of sediment it was designed to, only penetrating the top three to five centimetres of sediment (Figure 3). Observations of similar problems were observed by Gage (1975), but resolved themselves when the dredge was

used in finer sediments than the sand found in environments such as the Otago Harbour. Small ‘arms’ were added to the outer edges of the cutting blades to help the dredge penetrate the sediment more efficiently. The arms and the finer sediment found in the canyons appeared to enable the dredge to dig in to the sediment to the full ten centimetres when used for sampling. Once the dredge was modified it was used to collect samples from the canyon and slope environments.

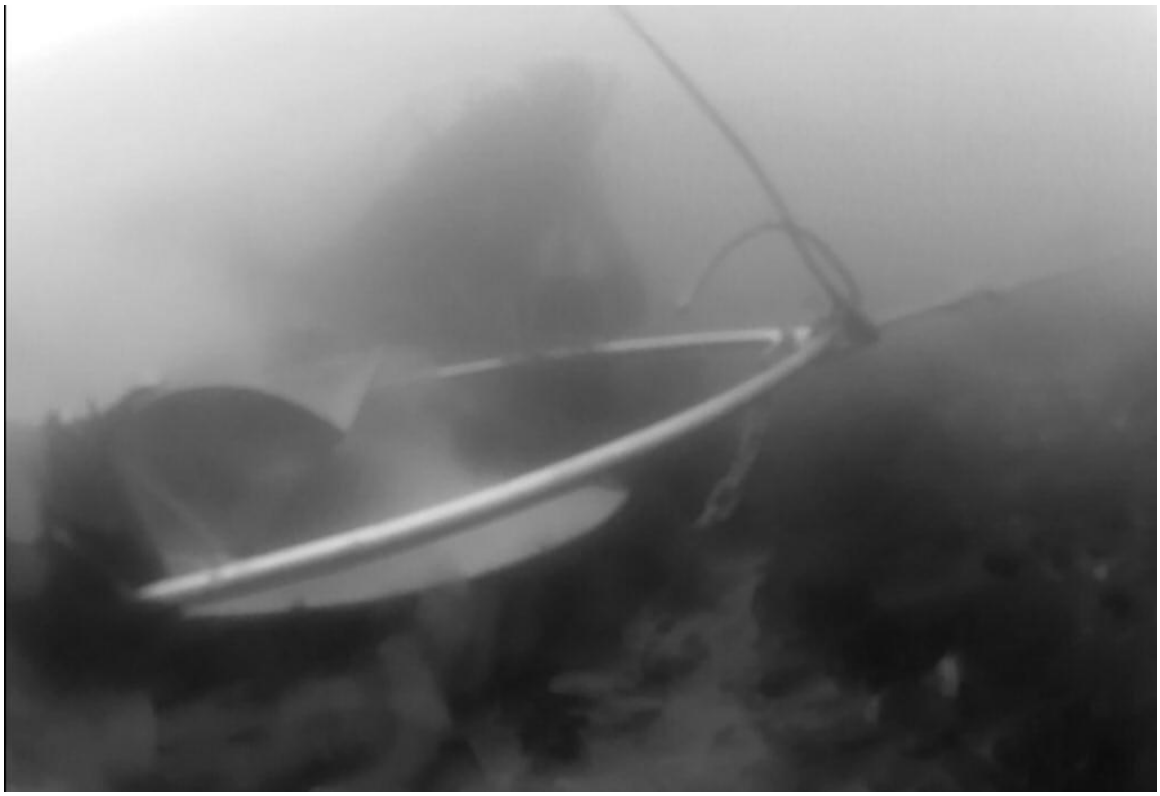


Figure 3: The anchor-box dredge being towed along the bottom of the Otago Harbour. Without the additional arms it penetrated only the top few centimetres of sediment.

Shipboard Processing of Samples

Fourteen samples were collected on January 15th and 16th, 2013 from the *RV Polaris II* using an anchor-box dredge at 500 – 600 m depth from Saunders Canyon, Papanui Canyon, and the adjacent slope environment (Table 1). Four stations were located in each of the canyons (SC1-4 and PC1a-3) and a total of six stations were on the adjacent slope (SCA-C and PCA-C). Station PC1 was sampled twice because some of the material

collected on the initial tow was lost and what remained was too little to work with. The 500 – 600 m depth range was chosen in order to sample the canyon-specific fauna, as a previous study suggested this faunal assemblage should start at 450 m (Probert *et al.* 1979), to attempt to minimise results being confounded by bathymetric zonation of fauna, and because a narrower depth range could not be selected due to the rapid change in canyon slope and low precision of available bathymetric data. Samples had to be collected prior to GIS work (Chapter 2) and analysis of archival data (Chapter 3) due to restrictions on vessel availability, which is why the previous depth value of canyon-specific fauna was used. Fortunately, the further analysis of the archival data suggested this canyon-specific assemblage starts at 380 m depth, so the collected samples are still within the intended sampling depth.

Samples were emptied on the deck of the *Polaris II* into a container with a known area and the depth of the sample was measured to obtain the collected sediment volume (Table 1). Sediment subsamples were taken from each tow and retained for later laboratory analysis. The samples were halved (quartered for station SCA) due to a combination of the large amount of sediment collected, the difficulty of wet sieving the fine mud/clay, and the limited cruise time available. Once halved, the samples were sieved through a 0.5 mm mesh sieve on deck. The sieved material was fixed in buffered formalin for later analysis at the Portobello Marine Laboratory.

Sample Sorting

At the laboratory, samples were sieved into 1 mm and 0.5 mm fractions and preserved in isopropanol for sorting and identification. The 1 mm fractions were sorted and the collected organisms extracted. The 0.5 mm fractions were re-preserved in isopropanol but not processed due to time constraints and large numbers of individuals in 0.5 mm size fractions. Organisms in the 1 mm fractions were identified and counted.

Identifying the organisms to species was not feasible due to the seemingly high diversity of this poorly-known fauna; however, in order to obtain meaningful results from subsequent analysis identification to a consistent taxonomic level was necessary. Special attention was given to the polychaetes as they are usually the most abundant macrofauna in marine sediments and likely to provide an adequate proxy for the infauna as a whole

(Fauchaldi and Jumars 1979; Hutchings 1998). Identification of polychaetes to at least family level was achievable and sufficient for statistical examination of benthic assemblages (Gaston 2000; Olsgard *et al*. 2003).

Grain-size Analysis

Grain-size analysis was run on sediments collected from all stations. The wet sediment samples were split into subsamples weighed in a pre-weighed 100 ml beaker. Initially 25 g subsamples were taken but became difficult to wet sieve, and later subsamples were reduced to either 15 or 10 g depending on how fine the collected sediment was. Since material finer than 63 microns may agglutinate when heated, a total dry weight of the sample was not taken. The coarse and fine fractions were split and then were both wet and dry weighed. The dry weights were totalled and kept track of throughout the process to ensure minimal loss of sediment.

The samples were wet sieved using distilled water through a 63 micron sieve to separate the sample into sand and mud (clay/silt) fractions. The samples were dried in a convection oven at 60° C. The samples were allowed to dry overnight and once dried were weighed. Gross dry sample weight minus the weight of the beaker gave the net dry sample weight. The coarse fraction was dry sieved at one-phi intervals from 2 mm to 0.063 mm on a sediment shaker (Endecotts Minor 230V model) for 10 minutes. Once sieving was completed the sand fractions were checked for aggregates and weighed. The weights were totalled to make note of any lost material.

Gravity filtration was used to determine the mass of the fine fraction. Dried pre-weighed filter paper was placed in a funnel on top of a 1 L cylindrical beaker, and the water and sediment left over from the wet sieving process was slowly poured onto the filter paper. Once filtration was completed the filter paper plus fine fraction was dried in the oven and weighed. This totalled with the weight of the coarse fraction gave the total sediment weight.

Statistical Tests

The suite of PRIMER programs was used for data analysis. CAP, MDS, SIMPER, and PERMANOVA tests were run in order to look at the influence of station location on the infauna (Anderson 2001, 2003, 2005). These tests use calculated distances, based on sample similarity/dissimilarity, to define the effects of each variable. SIMPER tests were run in order to ascertain which taxa had the most effect on sample variation and best characterised the different locations (Warton *et al*. 2012). An explanation of each test can be found in the Methods section of Chapter 3. The two major locations used in the tests were labelled "Area" and "Zone". "Area" samples belonged to either the "Saunders" area or "Papanui" area. Samples taken from Saunders Canyon and the slope adjacent to Saunders Canyon were labelled as belonging to the "Saunders" area (SC1-C). Samples taken from Papanui Canyon and the nearby slope were labelled as the "Papanui" area (PC1a-C). "Zone" was either inside a submarine canyon, labelled "Canyon", or part of the slope, labelled "Slope". Location, depth and faunal assemblage were the main factors used for the CAP and MDS analyses. The CAP tests are able to weight specific variables to highlight similarities caused by the specified variable (Hill and Lewicki 2007). The MDS tests also select a specific variable to show similarity, but generate results based on a distance matrix instead of linear changes in between each sample (Hill and Lewicki 2007). Both tests were used to confirm the results and patterns generated by linear distances and distance matrices. PERMANOVA tests are multivariate ANVOA tests that allow for a better explanation of ecological data since they do not use the assumption, like a normal MANOVA test, that the data are normally distributed (Anderson 2001).

Results

A majority of the collected sediment at all stations were less than 250 μm in diameter (Table 2). The sediment in the canyons tended to be somewhat coarser and more variable than the sediment found on the slope, but differences were slight and still within the "fine sand" category of sediment. Most stations had very little or no material with a

diameter greater and 1 mm and the material greater than that size tended to be bryozoan fragments or bivalve shells.

Table 2 – Grain size distribution for the 14 stations. SC is the Saunders Area, PC is the Papanui Area. Stations ending in a number (SC1-4, PC1a-3) were taken from a canyon, stations ending in a letter (SCA-C, PCA-C) were taken from the slope.

SC1	Distribution (%)		**SCA**	Distribution (%)		**PC1a**	Distribution (%)		**PCA**	Distribution (%)
2mm	0		2mm	0		2mm	0.16		2mm	0.27
1mm	0		1mm	0.64		1mm	0.28		1mm	0.94
500µm	0.41		500µm	0.76		500µm	0.32		500µm	1.68
250µm	0.54		250µm	0.25		250µm	1.78		250µm	5.71
125µm	2.97		125µm	0.89		125µm	30.47		125µm	29.08
63µm	20.41		63µm	9.40		63µm	44.61		63µm	52.72
<63µm	75.68		<63µm	88.06		<63µm	22.39		<63µm	9.60
SC2	Distribution (%)		**SCB**	Distribution (%)		**PC1b**	Distribution (%)		**PCB**	Distribution (%)
2mm	0		2mm	0.07		2mm	0.27		2mm	0.19
1mm	0.29		1mm	0.22		1mm	0.27		1mm	0.26
500µm	0.57		500µm	0.60		500µm	0.27		500µm	0.58
250µm	1.43		250µm	3.27		250µm	4.84		250µm	3.36
125µm	6.16		125µm	36.53		125µm	41.28		125µm	32.00
63µm	20.77		63µm	50.15		63µm	32.93		63µm	52.23
<63µm	70.77		<63µm	9.15		<63µm	20.16		<63µm	11.38
SC3	Distribution (%)		**SCC**	Distribution (%)		**PC2**	Distribution (%)		**PCC**	Distribution (%)
2mm	0.40		2mm	5.80		2mm	2.68		2mm	0.70
1mm	1.26		1mm	4.37		1mm	1.54		1mm	0.56
500µm	4.30		500µm	3.65		500µm	1.94		500µm	0.77
250µm	13.10		250µm	5.15		250µm	7.70		250µm	3.43
125µm	41.16		125µm	29.86		125µm	48.59		125µm	26.38
63µm	31.77		63µm	42.44		63µm	28.45		63µm	49.97
<63µm	8.01		<63µm	8.74		<63µm	9.10		<63µm	18.19
SC4	Distribution (%)					**PC3**	Distribution (%)			
2mm	20.40					2mm	1.59			
1mm	14.74					1mm	2.16			
500µm	10.20					500µm	1.95			
250µm	10.04					250µm	2.96			
125µm	25.99					125µm	25.76			
63µm	12.15					63µm	34.05			
<63µm	6.48					<63µm	31.53			

4 032 individual organisms were collected from the 14 stations, which were dominated by ammodiscid foraminifera, polychaetes, amphipods and ophuiroids (Table 3). 25 families of Polychaeta were identified, the most common of which were Lumbrineridae (19% of collected polychaetes), Hesionidae (17%), Paraonidae (9%), Amphinomidae (8%)

and Onuphidae (6%). Polychaetes were commonly found throughout all stations, composing 17% of all individuals found, but accounted for the majority of individuals in only two stations - PC2 and PC3. Identified polychaete families were assigned to trophic groups according to Fauchald and Jumars (1979) (Table 4). Carnivorous polychaetes, mainly Hesionidae and Lumbrineridae, were most commonly found throughout the study area (50–89% at each station) The stations located inside a canyon had an average of 6–8% fewer carnivorous polychaetes and 8–10% more filter-feeding and deposit-feeding families (Table 4).

Table 3 – Infauna count data from Saunders and Papanui Canyons and the adjacent slope.

	Saunders Canyon				Slope			Papanui Canyon				Slope		
	SC1	SC2	SC3	SC4	SCA	SCB	SCC	PC1a	PC1b	PC2	PC3	PCA	PCB	PCC
Bryozoan														
Ctenostomata	0	0	1	0	0	0	0	0	0	0	13	0	0	0
Cnidaria														
Actiniaria	0	0	0	0	0	0	0	0	0	0	3	0	0	0
Alcyonacea A	0	0	0	0	1	0	0	0	0	0	1	0	0	0
Alcyonacea B	0	0	0	45	0	0	0	0	0	0	32	0	0	0
Crustacea														
Ostracoda	0	1	3	1	1	3	72	0	0	2	0	2	12	0
Amphipoda	83	52	32	71	5	3	65	14	22	26	40	40	48	6
Anomura	1	1	2	2	0	0	0	1	0	0	0	1	0	0
Cumacea	0	0	0	1	0	2	5	0	0	1	0	4	4	1
Decapoda	0	0	1	1	1	0	26	0	2	2	9	6	15	3
unIDed Malacostracea	11	10	11	16	1	2	25	0	7	2	22	10	5	0
Isopoda	2	4	2	1	0	0	2	0	8	1	5	0	4	1
Gnathia	1	0	0	0	1	0	1	0	1	0	1	0	0	0
Pycnogonida	0	1	0	1	0	1	6	0	0	1	0	6	3	2
Echinodermata														
Asteroidea	0	0	0	0	0	0	0	0	0	0	1	0	0	0
Echinoidea	0	0	0	1	0	0	0	0	0	0	0	0	0	0
Ophiuridea	6	6	36	22	1	6	78	18	5	3	32	25	23	9
Foraminifera														
Ammodiscidae	0	5	0	4	43	3	16	472	227	26	54	60	115	735
Cibicidae	0	0	0	0	0	0	0	0	0	1	0	2	0	8
Mollusca														
Polyplacophora	0	0	0	0	0	0	2	0	0	2	0	0	0	0
Bivalvia														

Pectinidae	8	0	2	14	2	0	4	0	0	0	0	2	0	0
Pholadidae	4	2	0	11	0	1	2	0	21	5	6	6	1	0
Cuspidariidae	0	0	0	0	1	0	0	1	1	0	0	0	0	1
Mytilidae	0	0	1	0	0	0	0	0	0	1	0	0	0	0
Gastropoda														
Mesogastropoda	8	1	32	0	1	0	4	1	1	4	0	0	0	1
Neogastropoda	0	0	1	0	1	1	5	0	1	1	0	0	0	0
Hipponicidae	0	0	0	0	0	0	0	0	0	1	2	0	0	0
Marginellidae	0	0	1	0	4	0	0	0	0	0	0	0	0	0
Naticidae	0	1	0	2	2	3	9	2	2	3	1	2	0	2
Polychaetea														
Ampharetidae	3	2	0	1	0	0	0	2	2	0	2	0	0	3
Amphinomidae	3	9	0	4	0	1	6	2	7	1	8	1	4	5
Cirratulidae	0	0	0	0	0	0	0	0	1	2	1	0	0	0
Cossuridae	0	0	0	0	1	0	0	0	2	2	1	1	2	2
Eunicidae	7	2	6	3	0	0	1	1	0	0	5	5	0	1
Flabelligeridae	0	0	2	0	2	0	2	0	0	1	1	2	0	3
Hesionidae	0	0	8	14	0	3	23	7	9	14	18	7	5	7
Lumbrineridae	6	10	0	2	7	0	9	8	32	2	25	3	15	11
Maldanidae	0	0	0	0	0	0	0	0	0	2	0	0	0	0
Nereididae	1	0	0	0	0	0	0	2	0	0	1	2	0	0
Oenonidae	0	0	0	1	0	1	0	0	0	1	4	0	0	2
Onuphidae	4	3	1	3	4	2	5	2	6	3	4	1	4	2
Opheliidae	0	0	0	0	2	0	0	0	0	2	4	1	0	2
Orbiniidae	0	0	2	0	0	0	0	0	0	0	0	0	0	0
Paraonidae	0	0	0	0	0	0	0	7	11	2	24	0	3	14
Phyllodocidae	6	2	0	1	0	3	3	2	2	2	0	1	4	1
Polynoidae	1	0	4	0	0	0	0	0	1	2	1	6	5	0
Sabellariidae	0	0	0	1	0	0	0	0	0	0	0	2	0	1
Sabellidae	2	2	3	3	0	2	3	2	1	0	2	1	0	2
Scalibregmatidae	1	0	0	0	0	0	0	3	6	6	6	1	0	1
Serpulidae	0	0	3	4	0	1	0	0	0	1	0	1	0	0
Spionidae	3	1	4	2	0	0	1	0	1	0	4	0	0	0
Syllidae	2	2	0	4	0	4	0	2	4	2	5	4	2	6
Terebellidae	0	0	0	0	0	0	0	0	2	0	0	1	0	1
Trochochaetidae	0	0	0	0	0	0	0	0	0	0	4	1	0	2
Porifera														
Demospongiae A	0	0	0	0	1	0	1	0	0	0	0	0	0	0
Demospongiae B	0	0	0	0	0	0	0	2	1	0	0	0	0	0
Stylocordyla borealis	0	0	4	0	21	0	0	13	12	0	1	0	0	0
Sipunculid														
Sipunculus nudus	0	0	1	0	0	0	0	0	3	0	0	0	0	0

Phascolion tuberculosum	0	0	0	7	1	0	6	0	9	0	0	17	0	2
Nephasoma diaphanes	0	0	0	0	0	0	0	7	5	1	0	0	0	28

Table 4: Polychaete Families sorted by trophic level with percentages of each feeding-type per station.

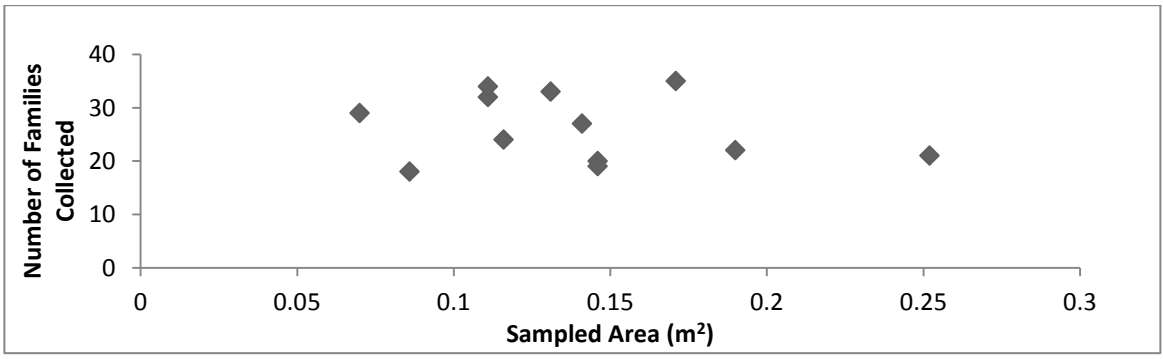
Polycheate Family	SC1	SC2	SC3	SC4	SCA	SCB	SCC	PC1a	PC1b	PC2	PC3	PCA	PCB	PCC
Ampharetidae	3	2	0	1	0	0	0	2	2	0	2	0	0	3
Amphinomidae	3	9	0	4	0	1	6	2	7	1	8	1	4	5
Cirratulidae	0	0	0	0	0	0	0	0	1	2	1	0	0	0
Cossuridae	0	0	0	0	1	0	0	0	2	2	1	1	2	2
Eunicidae	7	2	6	3	0	0	1	1	0	0	5	5	0	1
Flabelligera	0	0	2	0	2	0	2	0	0	1	1	2	0	3
Hesionidae	0	0	8	14	0	3	23	7	9	14	18	7	5	7
Lumbrineridae	6	10	0	2	7	0	9	8	32	2	25	3	15	11
Maladonidae	0	0	0	0	0	0	0	0	0	2	0	0	0	0
Nereididae	1	0	0	0	0	0	0	2	0	0	1	2	0	0
Oenonidae	0	0	0	1	0	1	0	0	0	1	4	0	0	2
Onuphidae	4	3	1	3	4	2	5	2	6	3	4	1	4	2
Opheliidae	0	0	0	0	2	0	0	0	0	2	4	1	0	2
Orbiniidae	0	0	2	0	0	0	0	0	0	0	0	0	0	0
Paraonidae	0	0	0	0	0	0	0	7	11	2	24	0	3	14
Phyllodocidae	6	2	0	1	0	3	3	2	2	2	0	1	4	1
Polynoidae	1	0	4	0	0	0	0	0	1	2	1	6	5	0
Sabelleridea	0	0	0	1	0	0	0	0	0	0	0	2	0	1
Sabellidae	2	2	3	3	0	2	3	2	1	0	2	1	0	2
Scalibregmatidae	1	0	0	0	0	0	0	3	6	6	6	1	0	1
Serpulidae	0	0	3	4	0	1	0	0	0	1	0	1	0	0
Spoinidae	3	1	4	2	0	0	1	0	1	0	4	0	0	0
Syllidae	2	2	0	4	0	4	0	2	4	2	5	4	2	6
Terebellidae	0	0	0	0	0	0	0	0	2	0	0	1	0	1
Trochochaetidae	0	0	0	0	0	0	0	0	0	0	4	1	0	2
Carnivore %	56	79	39	65	69	76	87	58	70	58	51	56	89	48
Omnivore %	21	6	18	7	0	0	2	8	0	0	5	17	0	2
Deposit feeder %	18	9	24	7	25	0	6	30	26	33	35	12	7	36
Suspension feeder %	5	6	18	19	0	18	6	5	1	2	2	10	0	5
OTHER %	0	0	0	2	6	6	0	0	2	7	8	5	5	9

Although foraminifera tests accounted for 44% of total individuals, two stations contained a majority (68%) of the tests, suggesting that foraminifera are not good indicative organisms despite their large abundances. The collected tests could be from foraminifera that were already dead prior to sampling, so using these numbers as a pure abundance is unreliable. Due to their large abundance and time restrictions, it was not feasible to determine if the foraminifera were alive at the time of collection. Ammodiscid foraminifera accounted for the bulk of collected foraminifera tests, numbering 1 760 individuals. However, the tests were much more common in the Papanui area, spiking at stations PC1 and PCC. Cibicid foraminifera were represented by only 11 individuals, and all except one were found on the Papanui slope. 95% of the sipunculan worms, mainly of the species *Phascolion tuberculosum* and *Nephasoma diaphanes*, were in the tests of ammodiscid Foraminifera. Amphipods were commonly found in all samples, accounting for 58% of crustacean individuals and 13% of total individuals. Malacostracans were more common in canyon environments and ophiuroids were commonly taken, accounting for 7% of total individuals.

Average densities were calculated with the ammodiscid counts removed and ranged from 1 170-1 558 individuals m^{-2} (Table 5). Abundances found on the slope environment were about 20% less than those measured in the canyon areas, indicating that the canyon areas support significantly higher population densities than the adjacent slope. The sampled area varied greatly between stations, from 0.07 to 0.252 m^2 (Table 1). Although larger samples would, in theory, contain more individuals and a higher diversity of species, there appeared to be no relationship between sample size and the number of collected taxa or measured diversity regardless of whether the ammodiscid foraminifera were counted (Figure 4). Neither graph indicates any relationship between the variation of sediment volume collected and either number of species or individuals. PERMANOVA results indicated that there was no significant effect of sample volume on multivariate analysis patterns (p-value of 0.262).

Table 5: Abundances for the most common taxa found in Saunders canyon, Papanui canyon and the adjacent slope with the counts of Ammodiscid formainifera removed.

	SC1	SC2	SC3	SC4	SCA	SCB	SCC	PC1b	PC2	PC3	PCA	PCB
Lumbrineridae /m^2	24	68	0	29	73	0	64	288	18	146	23	103
Hesionidae /m^2	0	0	69	200	0	35	163	81	126	105	53	34
Paraonidae /m^2	0	0	0	0	0	0	0	99	18	140	0	21
Amphinomidae /m^2	12	62	0	57	0	12	43	63	9	47	8	27
Onuphidae /m^2	16	21	9	43	42	23	35	54	27	23	8	27
Polychaeatea /m^2	155	226	284	614	167	198	376	784	405	702	313	301
Amphipodea /m^2	329	356	276	1014	52	35	461	198	234	234	305	329
Malacostracea /m^2	44	68	95	229	10	23	177	63	18	129	76	34
Ophiuridea /m^2	24	41	310	314	10	70	553	45	27	187	191	158
Total Indidviduals /m^2	647	767	1405	3414	635	453	2596	1694	919	1690	1252	1089
Average Abundance	1558				1228			1434			1170	



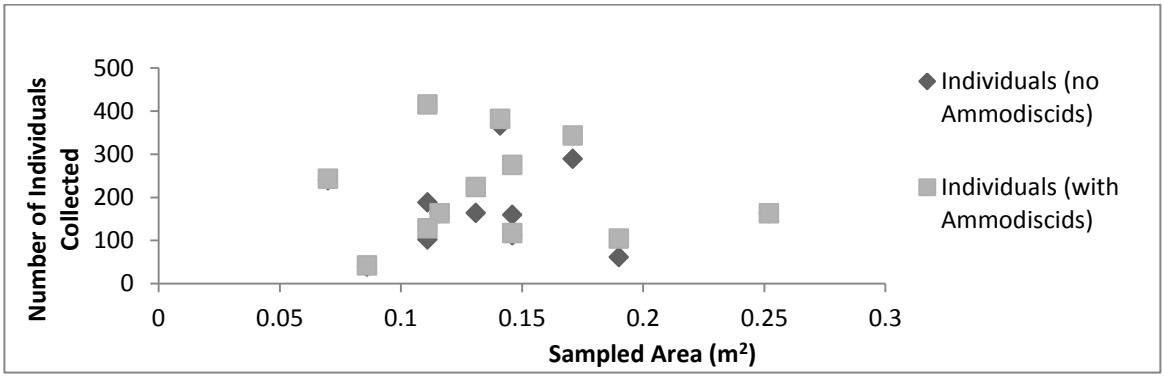


Figure 4: Sampled area plotted against number of Families and number of individuals.

The PERMANOVA test results indicated that the only location factor that has a significant impact on the community structure is if the samples were collected in the Saunders area or the Papanui area (Table 6). A p-value of 0.05 shows that the variation can be explained by the change in location alone. The p-value of 0.003 shown for the "location" factor suggests that the difference between the Saunders and Papanui areas has a significant impact but the p-value of 0.102 for the canyons implies that while there is some impact of canyon areas it is not statistically significant. The effect of the samples being from the canyon environment was present but not significant with a p-value of greater than 0.05. This conclusion is supported by both the CAP and MDS tests (Figures 5 and 6). CAP and MDS tests use distance matrices, therefore the axes are arbitrary and cannot be labelled. The clustering of the Papanui and Saunders areas suggests that they are less similar to each other than the Canyon or Slope groups. The canyon and slope environments are much more intertwined, suggesting less similarity between the two groups, which is reflected in both the CAP and MDS results.

Table 6 – Results from the PERMANOVA test. The P-value shows the significance of the change between the Saunders and Papanui area (Location) or the sample being taken from a canyon or the slope (Zone).

Factor	Levels	df	Pseudo-F	P-value
Zone	2	1	1.577	0.102
Location	2	1	2.826	0.003

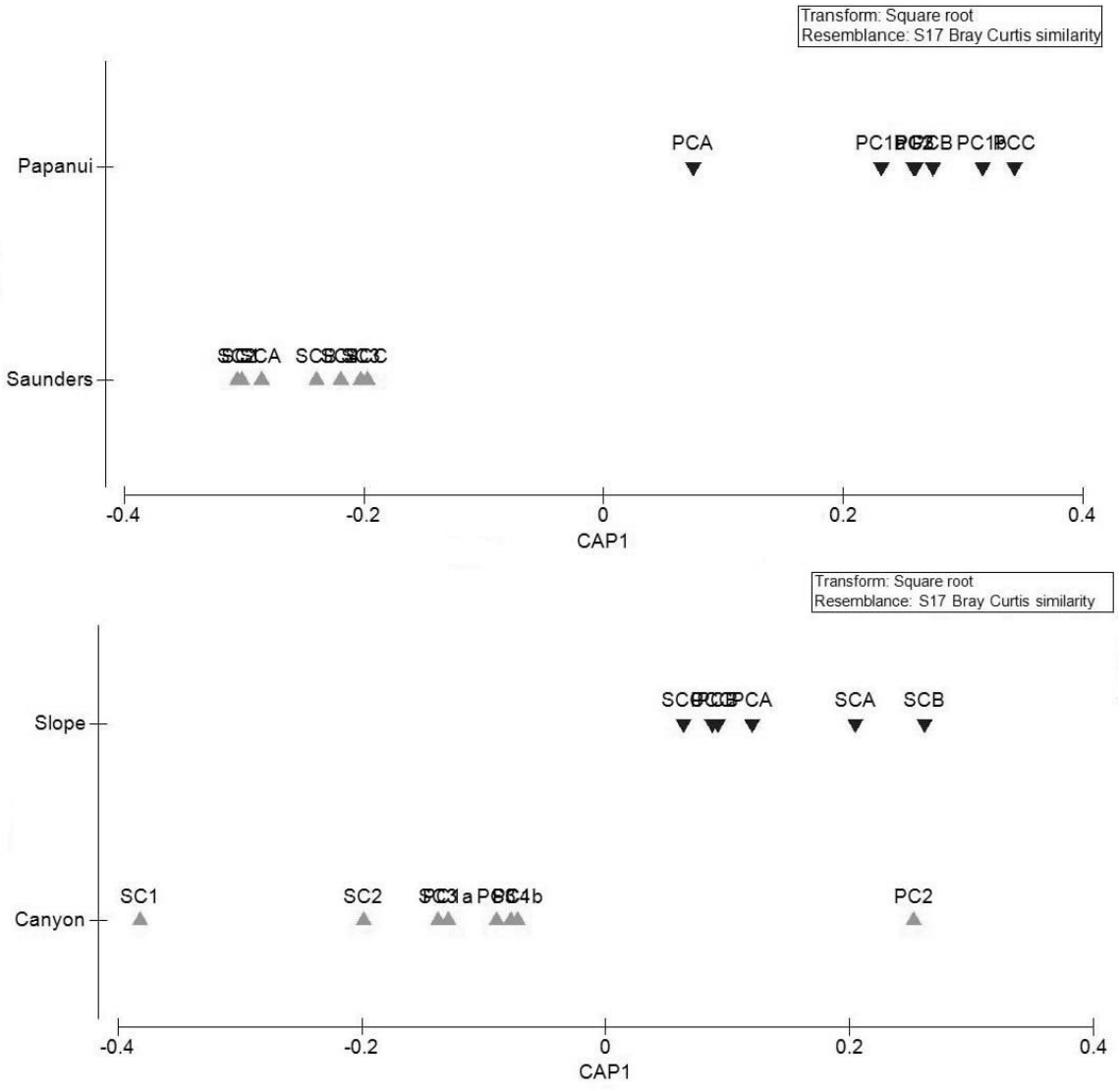


Figure 5 – CAP test results. The top graph shows the differences between samples based on which area (Saunders or Papanui) they were collected in. The bottom graph shows the differences between samples collected on the slope or in a canyon.

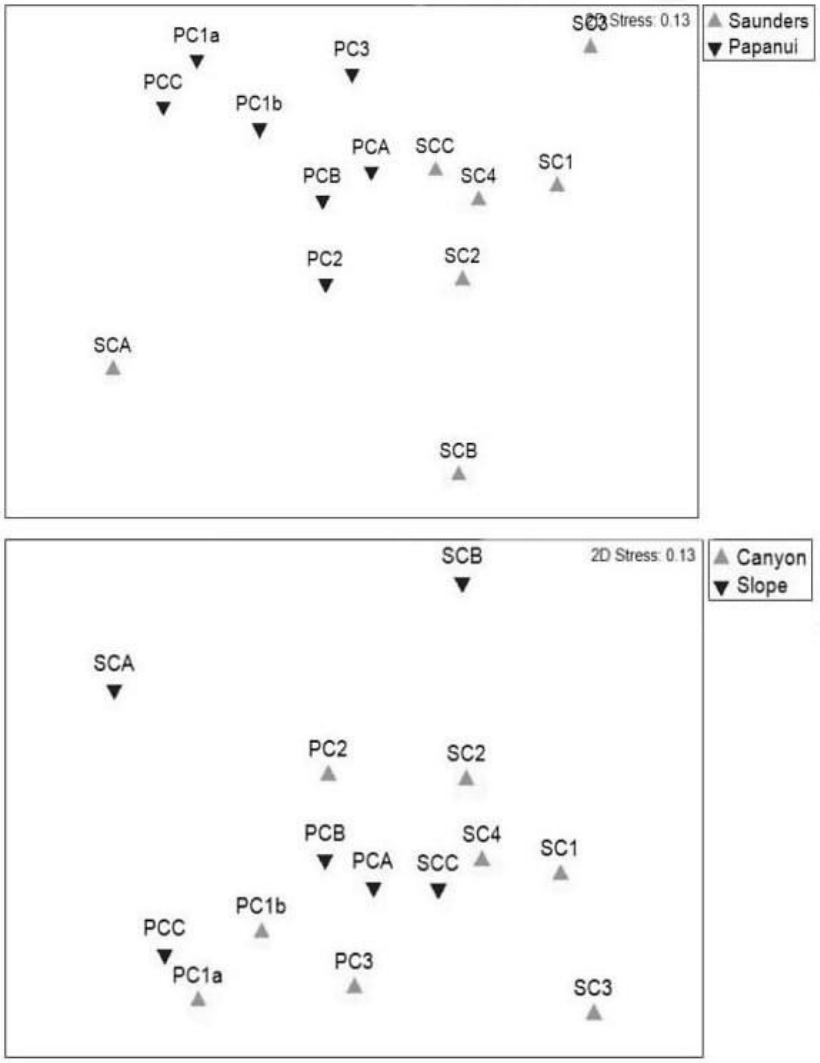


Figure 6 – MDS test results. The upper graph shows the differences between the Saunders and Papanui areas, the bottom graph shows the differences between canyon and slope areas.

The grain size data showed that the most commonly found sediment grains in Saunders and Papanui canyon are between < 63 and 250 µm in diameter while the grains found on the slope tend to be around the 63 – 125 µm diameter bracket. There appears to be a slight correlation between the sediment sizes and abundance, which increases as grain size increases (Figure 7). Polychaetes and malacostraceans also show this trend as a whole, but no trend is apparent when the polychaete families are spilt into feeding types. Amphipods, ophiuroids and ammodiscid foraminifera abundances seem to be higher in

samples with finer sediments. The PRIMER results for this apparent relationship between sediment grain size and organism abundance show there is no statistical correlation.

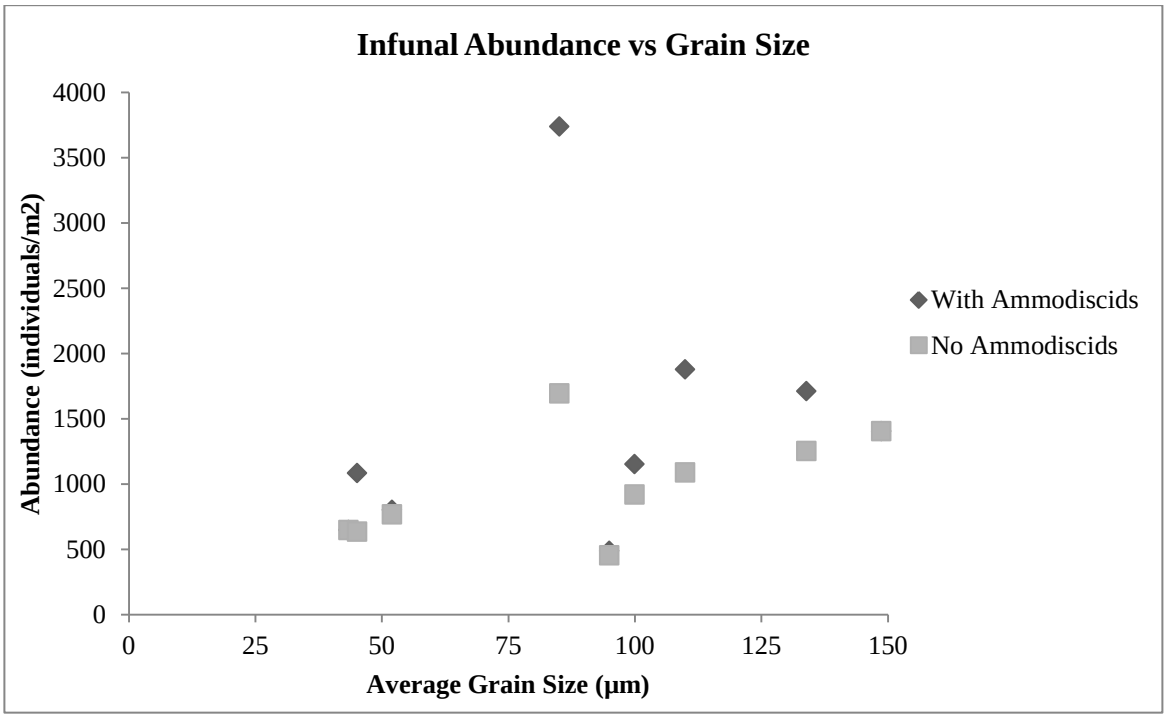


Figure 7: Infaunal abundance both including (diamonds) and excluding (squares) ammodiscid foraminifera plotted against grain size.

Discussion

The SIMPER results showed that amphipods and ammodiscids accounted for 27–29% of the variation between samples found inside the canyons and those on the slope. Ophiuroids, onuphid, hesionid and lumberinerid polychaetes along with the amphipods and ammodiscids contributed to 52% of sample variation on the slope and 48% of canyon sample variation. The variation between Saunders and Papanui area samples were influenced by amphipods and ophiuroids. The Saunders area was further influenced by onuphid, eunicid and sabellid polychaetes, and malacostracans (accounting for a total 54% of variation) while the Papanui area was strongly influenced by ammodiscids, hesionids and lumberinerids (accounting for a total 50% of variation). The lack of foraminifera in the Saunders area is the most likely cause for the increased influence of onuphids, eunicids and

sabellids. Interestingly the more common polychaete families, especially lumberinerids and hesionids, were still commonplace in the Saunders area.

The average dissimilarity of the Saunders and Papanui area samples calculated by the SIMPER test is 54% while the average dissimilarity of the canyon and slope samples is 50%. This implies that while there are some differences between canyon and slope samples, the dissimilarity is stronger overall between the Saunders and Papanui areas, which was the same result the PERMANOVA test indicated. This implies that the difference in assemblage was primarily due to whether or not the sample was in the Saunders or Papanui area rather than in the canyon or adjacent slope areas. The influence and abundance of these amphipods, polychaetes (specifically Hesionidae and Lumbrinderidae) and ophiuroids in the samples and in the PRIMER results suggest that the canyon and slope areas are characterised by these taxa. The numbers and distributions of these organisms change slightly with location but not enough to show that these parts of the canyon and the adjacent slope differ greatly in their ecology.

Polychaetes are characteristic of the Chatham Rise and slope area off the west coast of South Island and serve as an indicator of the local ecology (Hucthings 1998; Probert and Grove 1998; Probert *et al.* 2001; Probert *et al.* 2009). The polychaete distribution found in the Otago slope differs considerably from that described in the Chatham rise area and the slope off South Island's west coast. Members of the Lumbrineridae and Onuphidae families were among the most common for both the Chatham Rise and Otago areas, but the Chatham Rise also had numerous members of the Spionidae, Ampharetidae, and Nephtyidae. Spionids and ampharetids were found primarily in the canyon environments and rarely on the slope. The slope of the west coast of South Island is characterised by primarily spionids. Paraonoid, nephtyid, magelonid, maldanid and capitellid polychaetes, amphipods, bivalves, ophiuroids, and isopods comprise the remaining bulk of the infauna (Probert *et al*. 1996; Probert *et al*. 2001). Paranoidae is the only polychaete family found commonly in both the Otago and South Island west coast slope areas. No members of the Nephtyidae, Magelonidae or Capitellidae were recorded in this study and only two individuals of the Maldanidae were collected in this study.

The Nazaré, Cascais, Setúbal canyons, located off the Iberian Peninsula, Carson canyon, located on the edge of the Grand Banks east of Newfoundland, and La Jolla canyon, located off Southern California, have the most well-studied infaunal assemblages

(Houston and Haedrich 1984; Vetter 1994; Vetter and Dayton 1998; Cúrdia *et al*. 2004; Cunha *et al*. 2011). The bulk of submarine canyon infauna found in these canyons consists of polychaetes, bivalves, and crustaceans (Houston and Haedrich 1984; Vetter and Dayton 1998; Cúrdia *et al*. 2004; Cunha *et al*. 2011).

The polychaete and crustacean assemblages found in Saunders and Papanui canyons resemble those found in other canyons worldwide. Lumbrinerids and onuphids are commonly found in the Nazaré, Cascais, and Setúbal canyons and both Saunders and Papanui canyons (Cunha *et al*. 2011). Amphipods, isopods, and cumaceans are the most commonly found crustaceans in La Jolla canyon and are also commonly found in Saunders and Papanui canyons. The bivalves collected in Saunders and Papanui canyons did not match those found in La Jolla, Nazaré, Cascais or Setúbal canyon. Nuculidae and Veneridae were dominant in the Portuguese canyons, and Nuculanidae, Veneridae, and Lucinidae dominated the La Jolla canyon (Vetter and Dayton 1998; Cunha *et al*. 2011).

Pectinidae and Pholadidae were the most commonly found bivavle families in both Saunders and Papanui canyon, no members of Nuculidae, Nuculanidae, Lucinidae or Veneridae were identified. Houston and Haedrich (1984) did not identify infauna of Carson canyon to family, but the recorded assemblage is similar to that of Saunders and Papanui canyons. Polychaetes, cumaceans, amphipods, sipunculans and isopods comprised the bulk of infauna in Carson canyon (Houston and Haedrich 1984). Polychaetes and amphipods were also common in both Saunders and Papanui canyons; however sipunculans, isopods, and cumaceans were found in but not dominant taxa of either Saunders or Papanui canyons.

Submarine canyon environments have been found to have a more variable sediment type most likely due to their function as a sediment conduit and their shape (Oliveira *et al*. 2007; Mountjoy *et al*. 2013). Coarser, terrestrial sediment from above the sampled depths can be carried through the lower parts of the canyon, accounting for the larger average grain size found in the canyon sediment samples (Andrews 1973). Further study of the current patterns, nutrient levels and sediment disturbance in the Otago canyon network would provide insight on their ecological significance.

CHAPTER 5 – SUMMARY AND CONCLUSIONS

Summary

Quantitative data on the macrobenthic community of the Otago canyon network and adjacent slope have been lacking and high-quality bathymetric data of the upper slope area off the Otago Peninsula were only recently collected. The bathymetric data were used to objectively define the extent of the Otago submarine canyon network; this definition is detailed in Chapter 2. This method is applicable to any canyon system worldwide, and uses only one value (the slope value of canyon areas) that is not calculated from the elevation data of the selected region. Epifaunal assemblages of Saunders, Papanui, Taiaroa, and Karitane canyons and the adjacent slope are described using archival data in Chapter 3 and compared to an earlier analysis. Infaunal assemblages of Saunders and Papanui canyons and the adjacent slope are described in Chapter 4.

Objective Definition of Canyons in GIS software

Flow accumulation and pattern models along with changes in slope and elevation were derived from bathymetry data and used to define submarine canyon areas of the offshore area of the Otago Peninsula. This definition was performed in GRASS, a freeware GIS program, and is applicable to areas of the worldwide slope containing submarine canyons. A detailed description of the method is outlined in Chapter 2. The script uses the global average canyon slope of 5.1° as the only arbitrary value; a slope that is specific to the mapped area can be further refined through trial and error. Inner areas of the canyons are identified by combining buffered stream patterns, which align with the canyon axes, and generated stream basins. The buffer is necessary to cover all areas inside of the canyon; excess areas will be filtered out in the final steps. Outer canyon areas are identified by combining identified channels and changes in slope greater than 5.1°. The outer canyon areas are used to define the outer limit of canyon areas and the inner areas that lay within the confines of the outer canyon areas are added to the outer canyon map. This forms a final map with both the confined inner and outer canyon areas, displaying the full extent of the canyon network.

The slope value of 5.1° was not large enough for an ideal slope cut-off value for the slope off the Otago Peninsula. Some canyon areas were not selected by this value. Decreasing the value to include these canyon areas also included areas of the slope where the background change was also selected or where errors occurred in the bathymetry data. This led to unwanted noise on the slope maps, which made it difficult to identify the location of the canyon heads.

Epifaunal Assemblage of the Otago Canyon Network

The epifaunal assemblage of the Otago canyon network that is outlined in detail in Chapter 3 was derived from archival data collected by Elizabeth Batham. An identifiable epifaunal canyon assemblage starts to appear around 380 m. The epifaunal community of the canyons as a whole is mainly characterised by anomurans, polychaetes, ophiuroids, and bryozoans (64% of collected individuals). The epifauna of the adjacent slope environment primarily consist of bryozoans, actiniarians, polychaetes, asteroids and ascidians (70% of collected individuals).

The recorded slope assemblage contains few species in common with the Chatham Rise area of New Zealand. Crustaceans and molluscs are common on the slope of both the Chatham Rise and off the Otago Peninsula (McKnight and Probert 1997). *Campylonotus rathbunae*, *Ophiura irrorata,* and a *Fusitriton* sp. (*Fusitriton retiolus* on the Chatham Rise and *Fusitriton magellanicus laudandus* on the Otago slope) also characterise both slope environments (McKnight and Probert 1997). Polychaetes and ophiuroids are abundant globally and in the slope off the Otago Peninsula, but malacostracans and molluscs are more abundant globally (Hessler and Sanders 1966; Brant *et al*. 2007).

Polychaetes, ophiuroids, copepods, molluscs, and isopods are commonly found in submarine canyons worldwide. The described epifaunal assemblage of the Otago canyon network is similar to the global canyon assemblage; both have polychaetes and ophiuroids as dominant taxa but anomurans and bryozoans are not commonly found in most submarine canyons (Smith and Hamilton 1983; Garcia *et al*. 2007; De Leo *et al*. 2013). Isopods, and molluscs are more common in the global canyon epifaunal assemblages than in the Otago canyon network (Soetart *et al*. 1991; Garcia *et al*. 2007; De Leo *et al*. 2013).

The epifaunal assemblages of the Cook Strait canyon network and Kaikoura canyon, the other main submarine canyons located in New Zealand's EEZ, remain largely unstudied.

Infaunal Assemblages of Saunders Canyon, Papanui Canyon, and the Adjacent Slope

The infaunal assemblages of both Saunders and Papanui canyons and the adjacent slope are described in detail in Chapter 4. Amphipods, polychaetes, ophiuroids, decapods, and isopods comprised more than 75% of collected individuals in both canyon environments. The remaining 25% was primarily composed of alcyonaceans, foraminifera, mesogastropods, bivalves, bryozoans and the sponge *Stylocordyla borealis*. Saunders canyon had more than twice the abundance of mesogastropods but less than 1% of the foraminiera tests found in Papanui canyon. The infaunal community of the adjacent slope environment was characterised by amphipods, polychaetes, ostracods, decapods, ophiuroids and foraminifera; which comprised 85% of the collected individuals. Sipunculans, gastropods, bivalves and the sponge *Stylocordyla borealis* accounted for the remaining 15%. Both the canyon and slope environments have crustaceans (primarily amphipoda), polychaetes and ophiuroids forming a large majority (75–90%) of collected individuals. The remaining 10–25% consisted of mainly alcyonaceans and mesogastropods in the canyon areas and foraminifera and sipunculans on the slope.

The measured differences in assemblages suggest that for the sampled depths there was only a subtle difference in the infaunal communities of the canyons and the adjacent slope, mostly in the proportion of the commonly found major taxa within the canyons and on the slope. The results from the PERMANOVA test suggest that the differences between the infaunal assemblages were stronger between the Saunders area and Papanui area than between the canyon or slope areas, which complements the observation that there is little difference between the canyon and slope infaunal assemblages. The main difference was in the distribution of foraminifera tests, and along with them the sipunculans *Phascolion tuberculosum* and *Nephasoma diaphanes*, that inhabit ammodiscid tests. These tests and worms were more common in the slope environment, although the tests themselves were also commonly found in Papanui Canyon.

Polychaete families found on the slope off the Otago Peninsula differ from those recorded in the Chatham Rise and the west coast of South Island, New Zealand.

Lumbrineridae, Onuphidae, and Paranoidae families were found on the Otago slope, and Spionidae, Lumbrineridae, Onuphidae and Ampharetidae were found in the Otago canyon areas, which has some overlap with the Chatham Rise area but little overlap with South Island's west coast slope. Polychaetes, isopods, cumaceans, amphipods and bivalves are commonly found infauna of canyons worldwide, which agrees with the observed assemblage of both Saunders and Papanui canyons.

Areas of Further Study

GIS Methodology Expansion

The submarine canyon identification process outlined in Chapter 2 can be applied to any area of New Zealand's EEZ in order to identify all submarine canyon areas of New Zealand; it can also be tested on any submarine canyon worldwide. This would highlight any problems moving from theory to practical use of GIS software and any issues with the program itself. Using this method to define canyon areas can refine borders of submarine canyons and possibly borders of canyon areas that are considered vulnerable marine areas. Canyon-specific currents can be mapped and introduced as vector maps into GRASS, which would allow for further refinement of the script. Changes in temperature and oxygen levels indicative of canyon-localised upwelling or downwelling can be measured with a CTD and located. Combining the areas of localised upwelling with the identified canyon areas shown by the script outlined in Chapter 2 will allow for specification of canyon areas and should reduce noise caused by either sampling error or the background slope changes.

Backscatter data can be added to the factors used in order to determine sediment type. Sediment type is a major determinant of benthic environments, which means not only can canyons be objectively identified, but other benthic habitats as well (Kloser *et al*. 2010; Rowden *et al*. 2005). Changes in elevation can be highlighted, isolated, or categorised based on physical structure which, when combined with backscatter measurements, should be able to identify the location and extent of different habitat types. The ability of backscatter data to identify habitat types would make the modelling process even more useful for policy makers, reducing costs and time spent on sampling an entire area instead of specific sections. Refinement of habitat identification in GIS may allow for

identification of areas that should be classified as vulnerable marine environments, which would further simplify policy making.

Future Ecological Work

The only other canyon located in New Zealand's EEZ studied in biological detail, specifically the infaunal assemblages, is Kaikoura canyon (De Leo *et al*. 2010). Kaikoura canyon is characterised by polychaetes, holothuroids, echinoids, and echiurans; the lack of holothuroids, echinoids, and echiurans and abundance of amphipods, isopods, and ophiuroids suggest that the infauna found in the Otago canyon network greatly differs from that found in Kaikoura canyon. Although both the Otago canyon network and Kaikoura canyon have presently been studied in some biological detail, the process of categorising the canyon benthos of New Zealand's EEZ is still young. The Cook Strait canyon network remains unstudied biologically and only the infaunal mega- and macrofauna were recorded in Kaikoura canyon (De Leo *et al*. 2010). The epifaunal assemblage of both the Cook Strait canyon network and Kaikoura canyon remain unstudied along with the meiofaunal assemblage of the Otago canyon network, Cook Straight canyon network and Kaikoura canyon. Ecological work characterising the meiofauna of New Zealand canyons, the epifauna of Kaikoura canyon, and the benthos of the Cook Strait canyon network should be conducted.

The infaunal communties of Taiaroa and Karitane canyons have yet to be investigated. Future work in the canyons could involve determining the structure of the infaunal communities in these canyons, or examining the effects of different geological or oceanographic factors. The effects that localised upwelling, localised downwelling, or spiral currents in the deeper canyons may have on benthic community structure can be teased out. The effects of increased or decreased sediment flow along the canyon axis on the benthic canyon communities can be determined.

The epifaunal analysis indicates an identifiable community occurring from about 380 to 910 m water depth (the maximum depth of sampling); however, there is a transitionary depth where the canyon and adjacent slope communities are more similar. The infaunal analysis of Saunders and Papanui canyons showed the communities only showed a subtle difference with the slope environment. The similarity between the canyons

and slope may be explained by three things: this study collected organisms from this transitionary stage, the assemblages are not actually that different from one another, or the analysis was not able to resolve a difference since it was not feasible to identify collected organisms to species. It is possible that the infaunal community also shows a transitionary stage with depth, similar to that described in the analysis of the archival data, but deeper than both the previously stated 450 m, calculated 380 m, and the sampled 500–600 m. Sampling along the canyon axis at depths greater than 600 m and comparing collected species to those found in the canyons from 500–600 m depth will determine if the canyon assemblage changes significantly at greater depths; a study along this vein will determine if 500–600 m is a transitionary stage for the benthic assemblages.

Conclusion

The importance of gathering quantitative data on the infaunal community of the canyons and analysis of archival data on the epifaunal community was to better characterise the benthic community of the Otago canyons. Epifaunal and infaunal assemblages were identified through these analyses and a method of identifying submarine canyon areas in GIS software was achieved and outlined. The outlined methodology, epifaunal assemblages, and infaunal assemblages provide a detailed description at the Otago canyon network extent and benthos. The extent and location of the canyons off the Otago Peninsula were identified successfully using GIS software. The epifauna of the Otago canyon network was characterised by polychaetes, ophiuroids, bryozoans, and anomurans. The collected infaunal assemblages of the slope and canyon areas did not differ significantly. Polychaetes, ophiuroids, amphipods and decapods characterised the infauna of both environments.

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APPENDIX 1 – CANYON SPECIES CHECKLIST

This appendix provides a list of benthic macroinvertebrate species recorded from stations within the Otago submarine canyons. It is based on fauna collected at 36 benthic stations: the MV *Alert* stations of 1954–55 A 9, A 13, A 17, A 22, BS 190 and BS 191 (see Dell 1956 for details); 14 RV *Munida* Agassiz trawl stations – those comprising group 'Deep Canyon' in Probert *et al*. (1979) except for station Mu71-299; and 16 additional RV *Munida* stations taken by trawl or dredge. The stations are from water depths of between 420 and 910 m, apart from station Mu67-81 and Mu74-92 which span depths of 330–510 and 320–420 m respectively. The RV *Munida* stations were worked between 1967 and 1974, mainly by E.J. Batham, who was also chiefly responsible for obtaining species identifications from specialists. This list was primarily compiled by P.K. Probert and expanded to include all recorded species to date. References that appear after a species are to published records for Otago canyons. Nomenclature follows the New Zealand Inventory of Biodiversity (NZIB) (Gordon 2009, 2010, 2012) and the World Register of Marine Species (WoRMS) (http://www.marinespecies.org).

Phylum FORAMINIFERA
- Class POLYTHALAMEA
- Order ASTRORHIZIDA
  - RHABDAMMINIDAE
  - *Rhizammina* sp.
- Order LITUOLIDA
  - AMMODISCIDAE
  - *Ammodiscus mestayeri* Cushman, 1919
  - *Ammodiscus tenuis* Brady, 1881

Phylum PORIFERA
- Class DEMOSPONGIAE
- Order SPIROPHORIDA
  - TETILLIDAE
  - *Tetilla australe* Bergquist, 1968
  - *Tetilla* sp.
- Order ASTROPHORIDA
  - ANCORINIDAE
  - *Tethyopsis mortenseni* (Brønsted, 1924)
  - PACHASTRELLIDAE
  - *Thenea novaezealandiae* Bergquist, 1961
- Order HADROMERIDA

POLYMASTIIDAE
Acanthopolymastia acanthoxa (Koltun, 1964)
Polymastia sp.
STYLOCORDYLIDAE
Stylocordyla borealis (Lovén, 1868) (see Bergquist, 1972)
SUBERITIDAE
Suberites australiensis Bergquist, 1968
Suberites microstomus Ridley & Dendy, 1887 (Not in NZIB)
Suberites sp.
TETHYIDAE
Tethya sp.
Order POECILOSCLERIDA
COELOSPHAERIDAE
Coelosphaera globosa Bergquist, 1961 (see Bergquist & Fromont, 1988)
Histodermella australis Dendy, 1924
HYMEDESMIIDAE
Phorbas sp.
MICROCIONIDAE
Ophlitaspongia sp.
MYXILLIDAE
Ectyomyxilla kerguelensis (Hentschel, 1914)
RASPAILIIDAE
Raspailia sp.
TEDANIIDAE
Tedania diversiraphidophora Brønsted, 1923
Order HALICHONDRIDA
HALICHONDRIIDAE
Hymeniacidon sp.
HETEROXYIDAE
Halicnemia sp. (Not in NZIB)

Phylum CNIDARIA
Class ANTHOZOA
Order ALCYONACEA
CLAVULARIIDAE
?*Clavularia* spp.
TAIAROIDAE
Taiaroa tauhou Bayer & Muzik, 1976
(see Bayer & Muzik (1976) type locality)
Order ACTINIARIA
ACTINIIDAE
Bunodactis chrysobathys Parry, 1951
HALCAMPOIDIDAE
?*Calamactinia* sp.
HALOCLAVIDAE
Anemonactis sp.
HORMATHIIDAE
Hormathia sp.

Paracalliactis rosea Hand, 1975
Order ZOANTHIDEA
Zoanthidea spp.
Order SCLERACTINIA
CARYOPHYLLIIDAE
Desmophyllum dianthus (Esper, 1794)
(see Ralph & Squires (1962) as *D. cristagalli* Milne-Edwards and Haime, and Cairns (1995))
Goniocorella dumosa (Alcock, 1902) (see Cairns, 1995)
FLABELLIDAE
Flabellum (*Flabellum*) *knoxi* Ralph & Squires, 1962
(see Cairns, 1995, station Mu74-94)
TURBINOLIIDAE
Peponocyathus dawsoni Cairns, 1995 (see Cairns (1995) station Mu76-139, 660 m, and Ralph & Squires (1962) as *Notocyathus orientalis* (Duncan))
Class SCYPHOZOA
Order CORONATAE
ATORELLIDAE
?*Stephanoscyphus* cf. *simplex* Kirkpatrick, 1874
Class HYDROZOA
Order LEPTOTHECATA
AGLAOPHENIIDAE
Aglaophenia ctenata (Totton, 1930)
Lytocarpia spiralis (Tutton, 1930)
HALECIIDAE
Halecium delicatulum Coughtrey, 1876 (see Ralph, 1958)
Hydrodendron tottoni Rees & Vervoort, 1987
(see Ralph (1958) as *H. armata* (Totton))
HALOPTERIDIDAE
Halopteris campanula (Busk, 1852) (see Ralph 1961b)
LINEOLARIIDAE
Lineolaria flexuosa Bale, 1884 (see Ralph (1958), but not in NZIB)
PLUMULARIIDAE
Nemertesia cymodocea (Busk, 1851) (see Ralph 1961b)
SERTULARIIDAE
Amphisbetia fasciculata (Kirchenpauer, 1864) (see Ralph 1961a)
Salacia bicalycula (Coughtrey, 1876) (see Ralph 1961a)
Sertularella gayi gayi (Lamouroux, 1821) (see Ralph 1961a)
Sertularella integra Allman, 1876
(see (Ralph 1961a) as *S. richardsoni* Ralph)
Symplectoscyphus johnstoni johnstoni (Gray, 1843) (see Ralph 1961a)
Symplectoscyphus subarticulatus (Coughtrey, 1875) (see Ralph 1961a)
Order ANTHOATHECATA
STYLASTERIDAE
Stenohelia conferta Boschma, 1968

Phylum MOLLUSCA
Class APLACOPHORA

NEOMENIIDAE
Neomenia naevata Salvini-Plawen & Paar-Gausch, 2004 (see Salvini-Plawen & Paar-Gausch (2004), type locality, Mu69-71, 380–384 m)
PARARRPOHPALIIDAE
Pararrpohpaliidae sp.
PRONEOMENIIDAE
Dorymenia sp.
Class POLYPLACOPHORA
LEPTOCHITONIDAE
Leptochiton (*Leptochiton*) *deecresswellae* Anseeuw & Terryn, 2002 (see Anseeuw & Terryn, 2002: type locality)
Leptochiton (*L*) *subantarcticus* (Iredale & Hull, 1930) (see Dell, 1956)
Class BIVALVIA
Order SOLEMYOIDA
MANZANELLIDAE
Nucinella maoriana (Hedley, 1904) (see Dell, 1956)
Order NUCULOIDA
MALLETIIDAE
Neilo annectans Powell, 1931 (see Dell (1956, 1962) as *N. rugata* Dell)
Neilo australis (Quoy & Gaimard, 1835) (see Dell, 1956)
Neilo wairoana delli Marshall, 1978
NEILONELLIDAE
Pseudotindaria flemingi (Dell, 1956)
NUCULANIDAE
Jupiteria wolffi Dell, 1956 (see Dell, 1962)
Nuculana bellula (A. Adams, 1856)
Yoldiella finlayi (Powell, 1935) (see Dell, 1956, 1962)
NUCULIDAE
Linucula recens Dell, 1956 (see Dell, 1956, 1962)
Nucula nitidula A. Adams, 1856 (see Dell, 1956)
Order ARCOIDA
ARCIDAE
Bathyarca cybaea Hedley, 1906 (see Dell, 1956, 1962)
GLYCYMERIDIDAE
Tucetona laticostata (Quoy & Gaimard, 1835) (see Dell, 1956)
LIMOPSIDAE
Pectunculina lata (E.A. Smith, 1885) (see Dell, 1962)
PHILOBRYIDAE
Cosa costata (F. Bernard, 1896) (see Dell, 1956)
Lissarca benthicola (Dell, 1956) (see Dell, 1956, 1962 as *Austrosarepta*)
Lissarca trapezina (F. Bernard, 1897) (see Dell, 1956)
Philobrya sculpturalis (Dell, 1956) (see Dell, 1956)
Philobrya sp.
Order MYTILOIDA
MYTILIDAE
Modiolus areolatus Gould, 1850 (see Dell, 1956)
Order PTERIOIDA
ANOMIIDAE

Pododesmus (*Monia*) *zelandicus* (Gray, 1843)
LIMIDAE
Escalima regularis Powell, 1955 (see Dell, 1956, 1962)
Lima zealandica (G.B. Sowerby II, 1876) (see Dell, 1956)
Limatula (*L.*) *maoria* Finlay, 1926 (see Dell, 1956)
Limatula suteri (Dall, 1908) (see Dell, 1956)
PECTINIDAE
Talochlamys dichroa (Suter, 1909)
(see Dell (1956) as *Chlamys taiaroa* Powell)
Talochlamys zelandiae (Gray, 1843)
(see Dell (1956) as *Chlamys celator* Finlay)
Veprichlamys kiwaensis (Powell, 1933) (see Dell, 1956, 1962)
Zygochlamys delicatula (Hutton, 1873) (see Dell, 1956)
PROPEAMUSSIIDAE
Cyclochlamys aupouria (Powell, 1937)
(see Dell, 1956, 1962 as *Cyclopecten*)
Parvamussium maorium Dell, 1956 (see Dell, 1956, 1962)
Order VENEROIDA
CARDIIDAE
Pratulum pulchellum (Gray, 1843) (see Dell, 1956)
CARDITIDAE
Cardita aoteana Finlay, 1926 (see Dell, 1956)
Pleuromeris marshalli (Marwick, 1924) (see Dell, 1956)
Pleuromeris zelandica (Deshayes, 1854) (see Dell, 1956)
Purpurocardia purpurata (Deshayes, 1854) (see Dell, 1956)
CONDYLOCARDIIDAE
Cuna carditelloides Suter, 1911 (see Dell, 1956)
KELLIIDAE
Kellia cycladiformis (Deshayes, 1834)
LUCINIDAE
Lucinoma galatheae Mariwck, 1953 (see Dell, 1956, 1962)
MONTACUTIDAE
Mysella sp.
NEOLEPTONIDAE
?*Marikellia rotunda* (Deshayes, 1856)
(see Dell (1956), but not in NZIB)
Neolepton sublaevigatum (Powell, 1937) (see Dell, 1956, 1962)
SPORTELLIDAE
Anisodonta (*Austrosportella*) *pseudoscintilla* Ponder, 1971
(see Ponder, 1971)
Anisodonta (*Tahunanuia*) *alata alata* (Powell, 1952) (see Dell, 1956)
TELLINIDAE
Elliptotellina urinatoria (Suter, 1913) (see Dell, 1956)
THYASIRIDAE
Genaxinus cookianus Fleming, 1950 (see Dell, 1956)
Genaxinus otagoensis (Suter, 1913) (see Dell, 1956)
Maorithyas marama Fleming, 1950 (see Dell, 1956)
Parathyasira neozelanica Iredale, 1930 (see Dell, 1956, 1962)

Thyasira peregrina (Iredale, 1930)
(see Dell (1956, 1962) as *T. peroniana peregrina* (Iredale))
UNGULINIDAE
Diplodonta (*Zemysina*) *globus* (Finlay, 1926) (see Dell, 1956)
VENERIDAE
Notocallista (*Striacallista*) *multistriata* (G.B. Sowerby II,1851)
(see Dell, 1956)
Plurigens phenax Finlay, 1930 (see Dell, 1956)
Ruditapes largillierti (Philippi, 1849)
Tawera spissa (Deshayes, 1835)
Order MYOIDA
HIATELLIDAE
Hiatella arctica (Linnaeus, 1767)
Hiatella australis (Linnaeus, 1818) (see Dell (1956), but not in NZIB)
Panopea smithae Powell, 1950 (see Dell, 1956)
PHOLADIDAE
Pholadidea acherontea Beu & Climo, 1974 (see Beu & Climo, 1974)
Pholadidea suteri Lamy, 1926
(see Dell (1956 as *P. spathulata*)
Order ANOMALODESMATA
CUSPIDARIIDAE
Cardiomya bruuni Dell, 1956
Cardiomya rectimarginata Dell, 1962 (see Dell (1962), type locality)
Cuspidaria fairchildi Suter, 1908 (see Dell, 1956, 1962)
Cuspidaria morelandi Dell, 1956 (see Dell, 1956)
EUCIROIDAE
Euciroa galatheae (Dell, 1956)
MYOCHAMIDAE
Hunkydora novozelandica (Reeve, 1859) (see Dell, 1956)
Myadora antipodum E.A. Smith, 1880 (see Dell, 1956)
Myadora novaezelandiae E.A. Smith, 1880 (see Dell, 1956)
Myadora subrostrata E.A. Smith, 1880 (see Dell, 1956)
PARILIMYIDAE
Panacca tasmanica (Hedley & May, 1914)
Parilimya maoria (Dell, 1963)
THRACIIDAE
Parvithracia (*Parvithracia*) *suteri* Finlay, 1927 (see Dell, 1956)
Thracia sp.
VERTICORDIIDAE
Haliris (*Setaliris*) *setosa* (Hedley, 1907) (see Dell, 1956)
Order POROMYOIDA
POROMYIDAE
Poromya neozelanica (Dell, 1956) (see Dell, 1956)

Class SCAPHOPODA
Order GADILIDA
GADILIDAE
Cadulus teliger Finlay, 1926 (see Dell, 1956)

Class GASTROPODA

Subclass PROSOBRANCHIA
Order DOCOGLOSSA
LEPETIDAE
Maoricrater explorata (Dell, 1935) (see Dell, 1956)
Order COCCULINIFORMIA
LEPETELLIDAE
Tecticrater compressa (Suter, 1908) (see Dell, 1956, 1962)
Tecticrater sp.
Tectisumen clypidellaeformis (Suter, 1908) (see Dell, 1956, 1962)
Order VETIGASTROPODA
ANATOMIDAE
Anatoma regia (Mestayer, 1916) (see Dell, 1956)
CALLIOSTOMIDAE
Calliostoma (*Maurea*) *foveauxanum* (Dell, 1950) (see Dell, 1956)
Calliostoma (*M.*) *pellucidum* (Valenciennes, 1846) (see Dell, 1956)
Calliostoma (*Otukaia*) *alertae* (B. Marshall, 1995)
(see Dell (1962) as *Alertalex blacki* Dell)
CHILODONTIDAE
Brookula (*B.*) *benthicola* (Dell, 1956) (see Dell, 1956)
COLLONIIDAE
Argalista fluctuata (Hutton, 1883) (see Dell, 1956)
FISSURELLIDAE
Emarginula (*E.*) *striatula* (Quoy & Gaimard, 1834)
(see Beu & Climo, 1974)
Monodilepas sp.
SKENEIDAE
Lissotesta ambigua (Dell, 1956) (see Dell, 1956)
Lissotesta decipiens (Powell, 1940) (see Dell, 1956)
Lissotesta errata (Finlay, 1927) (see Dell, 1956)
Lissotesta otagoensis (Dell 1956) (see Dell, 1956)
Lissotestella rissoaformis (Powell, 1931) (see Dell, 1956)
Lissotestella tenuilirata (Powell, 1931) (see Dell, 1956)
Powellisetia porcellana (Suter, 1908)
(see Ponder (1965) for *Notosetia stewartiana* (Suter) in Dell (1956))
Putilla neozelanica (Suter, 1898) (see Dell, 1956)
SOLARIELLIDAE
Archminolia meridiana (Dell, 1953)
(see Dell (1956, 1962 as *Zeminolia*)
TROCHIDAE
Antisolarium egenum (Gould, 1849) (see Dell, 1956)
Micrelenchus (*Plumbelenchus*) *caelatus* (Hutton, 1884) (see Dell, 1956)
Thoristella chathamensis (Hutton, 1873) (see Dell, 1956)
Order NEOTAENOGLOSSA
ANABATHRIDAE
Pisinna micronema micronema (Suter, 1898)
(see Dell (1956) as *Estea sculpturata* (Suter))
Pisinna rufoapicata (Suter, 1908) (see Dell, 1956)
CALYPTRAEIDAE

Maoricrypta monoxyla (Lesson, 1830) (see Dell, 1956)
Sigapatella novaezelandiae (Lesson, 1830) (see Dell, 1956)
Sigapatella tenuis (Gray, 1867) (see Dell, 1956)
CAPULIDAE
Malluvium calcareum (Suter, 1909) (see Dell (1956, 1962) as *Capulus*)
Trichosirius , 1962carinatus (Laws, 1940) (see Dell, 1956)
CASSIDAE
Galeodea triganceae Dell, 1953
CERITHIOPSIDAE
Alipta crenistria (Suter,1907)
Cerithiella nucleoproducta (Dell, 1956)
Mendax subapicina (Dell, 1956)
Retilaskeya (*R.*) *zelandica* B. Marshall, 1978
Seila (*Hebeseila*) *bulbosa* Suter, 1908
Specula retifera (Suter, 1908)
Specula styliformis (Suter, 1908) (see Dell (1956) as *S. dissimilis*)
Zaclys sarissa (R. Murdoch, 1905) (Dell, 1956)
EPITONIIDAE
Cirsotrema (*Tioria*) *forresti* Dell, 1956 (see Dell, 1956, 1962)
EULIMIDAE
Curveulima otakauica (Dell, 1956) (see Dell, 1956)
Melanella alertae (Dell, 1956) (see Dell, 1956)
Melanella puhana (Dell, 1956) (see Dell, 1956)
HIPPONICIDAE
Leptonotis perplexus (Suter, 1907) (see Dell (1962) as *Neojanacus*)
NATICIDAE
Falsilunatia ambigua (Suter, 1913) (see Dell (1956, 1962) as *F. powelli*)
Falsilunatia subperforata Dell, 1956 (see Dell, 1956, 1962)
Friginatica conjuncta Dell, 1953 (see Dell, 1956, 1962)
Globisinum drewi (R. Murdoch, 1899) (see Dell, 1956)
Proxiuber australe (Hutton, 1878)
Tanea zelandica (Quoy & Gaimard, 1832) (see Dell, 1956)
Uberella alacris Dell, 1956 (see Dell, 1956, 1962)
Uberella cf. *barrierensis* (Marwick, 1924)
Uberella vitrea (Hutton, 1873)
RANELLIDAE
Fusitriton magellanicus laudandus Finlay, 1926
(see Dell, 1956; Beu, 1978)
Sassia kampyla kampyla (Watson, 1885) (see Dell, 1956; Beu, 1978)
RISSOIDAE
Alvinia (*Linemera*) *abrupta* (Dell, 1956) (see Dell, 1956)
Alvinia (*L.*) cf. *gradatoides* (Finlay, 1930) (see Dell, 1956)
Attenuata merelina (Dell, 1956) (see Dell, 1956)
Merelina maoriana Powell, 1939 (see Dell, 1956)
Powellisetia porcellana (Suter, 1908)
Powellisetia subtenuis (Powell, 1937)
Pusillina (*Haurakia*) *miniscula* (Powell, 1955) (see Dell, 1956)
Rissoa (*H.*) *otagoensis* (Dell, 1956) (see Dell, 1956)

Rissoa (*H.*) *subsuturalis* Dell, 1956 (see Dell, 1956)
TORNIDAE
Scrupus uniliratus Powell, 1931 (see Dell (1956), but not in NZIB)
TRIPHORIDAE
Cautor luteus (Suter, 1908) (see Dell, 1956)
TRIVIIDAE
Notoficula otagoensis Dell, 1962 (see Dell (1962), type locality)
TURITELLIDAE
Zeacolpus (*Stiracolpus*) *ascensus* Marwick, 1957 (see Dell, 1962)
Zeacolpus (*S.*) *symmetricus* (Hutton, 1873)
VANIKORIDAE
Radinista corrugata (Hedley, 1904) (see Dell, 1956)
VELUTINIDAE
Lamellaria sp.
Order NEOGASTROPODA
BUCCINIDAE
Aeneator elegans (Suter, 1917)
Aeneator recens (Dell, 1951) (see Dell, 1956)
Aeneator valedictus (Watson, 1886)
Austrofusus glans (Röding, 1798) (see Dell, 1956)
Belomitra climacella (Dall, 1895)
(see Ponder (1968) as *Waipaoa munida* Ponder)
Buccinulum flexicostatum Dell, 1956 (see Dell, 1956)
Buccinulum pertinax finlayi Powell, 1929 (see Dell, 1956)
Cominella (*Eucominia*) *alertae* (Dell, 1956)
Cominella (*Eucominia*) *nassoides otakauica* Powell, 1946 (see Dell, 1956)
Cominella (*Eucominia*) *otagoensis* (Finlay, 1926) (see Dell, 1956)
Euthrenopsis venusta Powell, 1929 (see Dell, 1956)
Penion fairfieldae (Powell, 1947) (see Dell, 1956)
CANCELLARIIDAE
Inglisella marwicki (Dell, 1956)
(see Dell (1956, 1962) as *Waipaoa marwicki*)
Zeadmete otagoensis Dell, 1956 (see Dell, 1956, 1962)
Zeadmete ovalis Dell, 1956 (see Dell, 1956)
Zeadmete subantarctica Powell, 1933 (see Dell, 1956)
Zeadmete trailli (Hutton, 1873) (see Dell, 1956)
COLUMBELLIDAE
Liratilia sp.
Macrozafra sp.
Zemitrella benthicola Dell, 1956 (see Dell, 1956, 1962)
Zemitrella circumcincta Dell, 1962 (see Dell (1962), type locality)
Zemitrella laevigata laevigata (Suter, 1908) (see Dell, 1956)
CONIDAE
Antiguraleus fusiformis Dell, 1956 (see Dell, 1956, 1962)
Antiguraleus cf. *pulcherrimus* Dell, 1956
Asperdaphne expeditionis Dell, 1956 (see Dell, 1962)
Asperadaphne ula (Watson, 1881) (see Dell, 1956, 1962)
Bathytoma (*Riuguhdrillia*) *parengonius* (Dell, 1956)

(see Dell (1962) as *Micantapex*)
Liracraea odhneri benthicola Dell, 1956 (see Dell, 1956)
Liracraea otakauica Powell, 1942 (see Dell, 1956)
Mitromorpha (*Mitrolumna*) *benthicola* (Dell, 1962)
(see Dell (1962) as *Itia benthicola*, type locality)
Mitromorpha sp.
Taranis benthicola (Dell, 1956) (see Dell (1956) as *Fenestrosyrinx*)
Taranis imporcata (Dell, 1962)
(see Dell (1962) as *Fenestrosyrinx imporcata*, type locality)
Taranis spirulata (Dell, 1962)
see Dell (1962) as *Fenestrosyrinx spirulata*, type locality)
COSTELLARIIDAE
Austromitra lawsi Finlay, 1930 (see Dell, 1956)
Austromitra rubiginosa (Hutton, 1873)
DRILLIIDAE
Splendrillia (*Hauturua*) *vivens* (Powell, 1942) (see Dell, 1956, 1962)
Splendrillia (*Splendrillia*) *aoteana* Finlay, 1930
Splendrillia (*S.*) *benthicola* Dell, 1956 (see Dell, 1956)
Splendrillia (*S.*) *jacula* Dell 1956 (see Dell, 1956)
Splendrillia (*S.*) *otagoensis* Powell, 1942 (see Dell, 1956, 1962)
Splendrillia (*S.*) *roseacincta* Dell, 1956
FASCIOLARIIDAE
Glaphyrina caudata (Quoy & Gaimard, 1833)
(see Dell (1956) as *G. vulpicolor*)
Microfulgur carinatus Ponder, 1970
Pleia cryptocarinata Dell, 1956
MARGINELLIDAE
Dentimargo fusuloides (Dell, 1956) (see Dell, 1956, 1962 as *Marginella*)
Dentimargo subfusula (Powell, 1932) (see Dell, 1956)
Mesoginella cracens (Dell, 1956) (see Dell, 1956, 1962 as *Marginella*)
Mesoginella otagoensis (Dell, 1956) (see Dell, 1956)
Ovaginella profunda (Suter, 1909) (see Dell, 1956)
MURICIDAE
Comptella devia (Suter, 1908) (see Dell, 1956)
Poirieria kopua Dell, 1956
Poirieria zelandica (Quoy & Gaimard, 1833) (see Dell, 1962)
Terefundus (*Terefundus*) *anomalus* Dell, 1956 (see Dell, 1956)
Terefundus (*T.*) *axirugosus* Dell, 1956 (see Dell, 1956, 1962)
Xymene aucklandicus (E.A. Smith, 1902)
Xymene convexus (Suter, 1909) (see Dell, 1956)
Xymene huttoni (R. Murdoch, 1900)
(see Dell (1956) as *Zeatrophon tmetus* Finlay)
Xymene pulcherrimus (Finlay, 1930) (see Dell, 1956)
Xymene pumilus (Suter, 1909)
NASSARIIDAE
Nassarius (*Cryptonassarius*) *ephamillus* (Watson, 1882) (see Dell, 1962)
OLIVIDAE
Amalda (*Baryspira*) *bathamae* (Dell, 1956) (see Dell, 1956)

Amalda (*Gracilispira*) *benthicola* (Dell, 1956) (see Dell, 1956, 1962)
PTYCHATRACTIDAE
Metzgeria problematica (Ponder, 1968)
TURBINELLIDAE
Coluzea mariae Powell, 1952 (see Dell, 1956)
Egestas waitei (Suter, 1909) (see Dell, 1956)
Exilia expeditionis (Dell, 1956)
TURRIDAE
Aoteadrillia wanganuiensis (Hutton, 1873) (see Dell, 1956)
Comitas onokeana vivens Dell, 1956 (see Dell, 1956, 1962)
Comitas trailli (Hutton, 1873) (see Dell, 1956)
Leucosyrinx canyonensis (Dell, 1956) (see Dell (1962) as *Antimelatoma*)
VOLUTIDAE
Alcithoe flemingi Dell, 1978
Alcithoe knoxi (Dell, 1956)
Alcithoe wilsonae (Powell, 1933)
Alcithoe sp.
Provocator mirabilis (Finlay, 1926)
(see Dell (1956) as *Iredalina aurantia* Powell)
VOLUTOMITRIDAE
Volutomitra banski (Dell, 1951)

Subclass HETEROBRANCHIA
Order HETEROSTROPHA
PYRAMIDELLIDAE
Agatha georgiana (Hutton, 1885) (see Dell, 1956, 1962)
Evalea propria Laws, 1941 (see Dell, 1956)
Linopyrga rugata rugata (Hutton, 1886) (see Dell, 1956)
Odostomia parvacutangula Laws, 1939 (see Dell, 1956)
Planpyrgiscus lawsi Dell, 1956 (see Dell, 1956)
Terelimella benthicola Dell, 1956 (see Dell, 1956)

Subclass OPISTHOBRANCHIA
Order INCERTAE SEDIS
ACTEONIDAE
Neactaeonina inexpectata Dell, 1956 (see Dell, 1956, 1962)
RINGICULIDAE
Ringicula (*Ringicula*) *delecta* R. Murdoch & Suter, 1906
(see Dell, 1956, 1962)

Order CEPHALASPIDEA
CYLICHNIDAE
Scaphander otagoensis Dell, 1956 (see Dell, 1956, 1962)
PHILINIDAE
Philine constricta R. Murdoch & Suter, 1906 (see Dell, 1956)
Philine powelli Rudman, 1970
Philine umbilicata Murdoch & Suter, 1906 (see Dell, 1956)
RETUSIDAE
Cylichnina striata (Hutton, 1873) (see Dell, 1956)
Retusa oruaensis (Webster, 1908) (see Dell, 1956)
Retusa aff. *suteri* Finlay (see Dell (1956, 1962), but not in NZIB)

Relichna pachys (Watson, 1883) (see Dell, 1956, 1962)
Relichna) aff. *pachys* (Watson, 1883) (see Dell, 1956)
Volvulella truncata Dell, 1956 (see Dell, 1956, 1962)
Order NUDIBRANCHIA
DORIDIDAE
Aphelodoris luctuosa (Cheeseman, 1882)
Class CEPHALOPODA
Subclass COLEOIDEA
Order SEPIIDA
SEPIADARIIDAE
Sepioloidea pacifica (Kirk, 1882) (see Dell, 1956)
Order OCTOPODA
OCTOPODIDAE
?*Octopus huttoni* Benham, 1943
(see Dell (1956) as *Robsonella australis* (Hoyle)

Phylum BRACHIOPODA
Class RHYNCHONELLATA
Order TEREBRATULIDA
TEREBRATULIDAE
Liotheyrella neozelanica Thomson, 1918
TEREBRATELLIDAE
Aerothyris macquariensis (Thomson, 1918)
Neothyris lenticularis (Dehayes, 1839)

Phylum BRYOZOA
Class GYMONAEMATA
Order CHEILOSTOMATA
Suborder INOVICELLINA
AETEIDAE
Aetea sp.
Suborder MALACOSTEGINA
MEMBRANIPORIDAE
Jellyella tuberculata (Bosc, 1802)
Suborder NEOCHEILOSTOMATA
Infraorder FLUSTRINA
BUGULIDAE
Bugula sp.
CALLOPORIDAE
Valdemunitella pyrula (Hincks, 1881)
CANDIDAE
Caberea zelandica (Gray, 1843)
CELLARIIDAE
Cellaria immersa (Tenison-Woods, 1880)
Cellaria tenuirostris (Busk, 1852)
Melicerita angustiloba Tenison-Woods, 1862 (see Powell, 1969)
CHAPERIIDAE
Chaperia cf. *acanthina* (Lamouroux, 1825)

Chaperiopsis (*Chaperiopsi*) *rubida* (Hincks, 1881)
FOVEOLARIIDAE
Foveolaria elliptica Busk, 1884
MICROPORIDAE
Micropora spp.
Odontionella cyclops (Busk, 1854)
OTIONELLIDAE
Otionella squamosa (Tenison-Woods, 1880)
STEGINOPORELLIDAE
Steginoporella magnifica Harmer, 1900

Infraorder ASCOPHORINA
ADEONIDAE
Adeonellopsis
ARACHNOPUSIIDAE
*Arachnopusia unicorn*is (Hutton, 1873)
CALWELLIIDAE
Callwellia sp.
CATENICELLIDAE
Orthoscuticella ventricosa (Busk, 1852)
CELLEPORIDAE
Celleporina spp.
CREPIDACANTHIDAE
Crepidacantha crinispina Levinsen, 1909
Crepidacantha zelanica Canu & Bassler, 1929
CRIBRILINIDAE
Figularia carinata (Waters, 1923)
Figularia huttoni Brown, 1952
ESCHARINIDAE
Chiastosella enigma Brown, 1954
Chiastosella sp.
EUTHYROIDIDAE
Euthyroides episcopalis Busk, 1852
Euthyroides sp.
HIPPOPODINIDAE
Hippomenella vellicata (Hutton, 1873)
HIPPOTHOIDAE
Hippothoidae sp.
LACERNIDAE
Arthropoma sp.
Phonicosia oviseparata (Brown, 1952)
LEPRALIELLIDAE
Celleporaria spp.
MICROPORELLIDAE
Calloporina angustipora (Hincks, 1885)
Fenestrulina thyreophora (Busk, 1857)
Fenestrulina sp.
Microporella aff. *ciliata* (Pallas, 1766)

PETRELIELLIDAE
Riscodopa cotyla (Cook & Chimonides, 1981)
(see Cook & Chimonides (1981) as *Mucropetraliella*, type locality)
PORINIDAE
Porina sp.
ROMANCHEINIDAE
Escharella spinosissima (Hincks, 1881)
Escharoides excavata (MacGillivray, 1860)
Exochella conjuncta Brown, 1952
Exocella tricuspis (Hincks, 1881)
SCHIZOPORELLIDAE
'*Schizoporella*' sp.
SMITTINIDAE
Parasmittina aotea (Brown, 1952)
Smittina spp.
UMBONULIDAE
?*Umbonula* sp.

Class STENOLAEMATA
Order CYCLOSTOMATA
CINCTIPORIDAE
Cinctipora elegans Hutton, 1873
FASCIGERIDAE
Fasciculipora cf. *fruticosa* MacGillivray, 1884
IDMONEIDAE
Idmonea sp.

Phylum SIPUNCULA
Class SIPUNCULIDEA
Order SIPUNCULIFORMES
SIPUNCULIDAE
Sipunculus sp.
Order GOLFINGIIFORMES
GOLFINGIIDAE
Nephasoma diaphanes diaphenes (Gerould, 1913)
(see Edmonds (1976) as *Golfingia* (*Phascoloides*) *improvisa* (Théel))
PHASCOLIONIDAE
Phascolion strombus (Montagu, 1804)
(see Edmonds (1976) described as *Phascolion tortum* n. sp.)

Phylum ANNELIDA
Class POLYCHAETA
AMPHINOMIDA
AMPHINOMIDAE
Chloeia cf. *inermis* Quatrefages, 1865
?*Pareurythoe* sp.
Pherecardia sp.
EUNICIDA
DORVILLEIDAE

Schistomeringos incerta (Schmarda, 1861)
EUNICIDAE
Eunice australis Quatrefages, 1865
Eunice spp.
LUMBRINERIDAE
Lumbrineris sp.
ONUPHIDAE
Hyalinoecia tubicola longibranchiata McIntosh, 1885
Kinbergonuphis proalopus (Chamberlin, 1919)
Nothria cf *conchylega* Sars, 1835
Rhamphobrachium (*Spinigerium*) *averincevi* Kucheruk, 1979
(see Paxton, 1986)
PHYLLODOCIDA
GLYCERIDAE
Glycera sp.
NEREIDIDAE
Cheilonereis peristomialis Benham, 1916
SIGALIONIDAE
Sthenelais novaezealandiae Monro, 1936
CANALIPALPATA
SERPULIDAE
Filograna implexa Berkeley, 1835
Serpula crenata (Ehlers, 1908)
(see Dell (1956, 1962) as *Dentalium tiwhana* Dell)
Spirobranchus latiscapus (Marenzeller, 1885)
(see Fleming (1971) as *Temporaria inexpectata* (Mestayer))
[POGONOPHORA]
[OLIGOBRACHIDAE]
Oligobrachia kernohanae Batham, 1973
(see Batham (1973), type locality)
SIBOGLINIDAE
Siboglinum sp.
SPIONIDA
CHAETOPTERIDAE
Phyllochaetopterus socialis Claparède, 1870
TEREBELLIDA
AMPHARETIDAE
Amphicteis gunneri (Sars, 1835)
TRICHOBRANCHIDAE
Terebellides cf. *stroemii* Sars, 1835
Class CLITELLATA
Clitellata spp.

Phylum NEMERTEA
Nemertea spp.

Phylum ECHINODERMATA
Class CRINOIDEA

Order COMATULIDA
ANTEDONIDAE
Florometra austini A.M. Clark, 1966
Class ASTEROIDEA
Order PAXILLOSIDA
ASTROPECTINIDAE
Astropecten primigenius (Mortensen, 1925) (see Fell, 1958)
Dipsacaster magnificus (H.L. Clark, 1916)
Proserpinaster neozelanicus (Mortensen, 1925)
Psilaster acuminatus Sladen, 1889
Order NOTOMYOTIDA
BENTHOPECTINIDAE
Benthopecten munidae H.E.S. Clark, 1969 (see Clark (1969), type locality)
Order VALVATIDA
GONIASTERIDAE
Mediaster sladeni Benham, 1909 (see Fell, 1958)
Pentagonaster pulchellus Gray, 1840
(but recorded only to 215 m in Clark & McKnight (2001 p. 93)
ODONTASTERIDAE
Odontaster benhami Mortensen, 1925 (see Fell, 1958)
Order VELATIDA
KORETHRASTERIDAE
Peribolaster lictor Fell, 1958
PTERASTERIDAE
Pteraster (*Apterodon*) *bathamae* Fell, 1958
Order SPINULOSIDA
Henricia sp.
Order FORCIPULATIDA
ZOROASTERIDAE
Zoroaster spinulosus Fisher, 1906
(but recorded depth range in NZ of 1000–4500 m (McKnight, 2006))
Class OPHIUROIDEA
Order OPHIURIDA
AMPHIURIDAE
Amphipholis squamata (Delle Chiaje, 1829) (see Fell, 1958)
Amphiura (*Amphiura*) *aster* Farquhar, 1901 (see Fell, 1958)
Amphiura (*A.*) *heraldica* Fell, 1952 (see Fell, 1958)
Amphiura (*A.*) *magellanica* Ljungman, 1867
Amphiura (*A.*) *praefecta* Koehler, 1907
Amphiura (*A.*) *psilopora* H.L. Clark, 1911 (see Baker, 1977)
Amphiura (*A.*) *pusilla* Farquhar, 1897 (see Fell, 1958)
Amphiura (Ophiopeltis) dikellancantha Baker, 1974
OPHIACANTHIDAE
Ophiacantha otagoensis Fell, 1958 (see Fell, 1958)
Ophicantha rosea Lyman, 1878 (see Fell, 1958)
Ophiocamax brevicetra Baker, 1974 (see Baker, 1974, type locality)
OPHIACTIDAE
Ophiactis hirta Lyman, 1879

Ophiactis profundi Lütken & Mortensen, 1899
OPHIOCOMIDAE
Clarkcoma bollonsi (Farquhar, 1908) (see Fell, 1958)
OPHIOMYXIDAE
Ophiomyxa brevirima H.L. Clark, 1915 (see Fell, 1958)
Ophiomyxa sp.
OPHIURIDAE
Ophiozonella stellamaris Fell, 1952 (see Baker, 1977)
Ophizonella stellata (Lyman, 1878)
(see Fell (1958) as *Ophiomastus admiral* Fell)
Ophiura (*Ophiura*) *ooplax* (H.L. Clark, 1911)
Ophiura (*Ophiuroglypha*) *irrorata* (Lyman, 1878)
Class ECHINOIDEA
Order CIDAROIDA
CIDARIDAE
Goniocidaris parasol Fell, 1958
Order TEMNOPLEUROIDA
TEMNOPLEURIDAE
Pseudechinus flemingi Fell, 1958
Pseudechinus huttoni Benham, 1908
Order SPATANGOIDA
SPATANGIDAE
Paramaretia multituberculata Mortensen, 1950 (Not in NZIB)
Class HOLOTHURIOIDEA
Order DENDROCHIROTIDA
CUCUMARIIDAE
Amphicyclus thomsoni (Hutton, 1878)
Psolidocnus sacculus (Pawson, 1983)
(see Pawson (1983), as *Ocnus sacculus*, type locality)
PSOLIDAE
Psolus neozelanicus Mortensen, 1925
Order DACTYLOCHIROTIDA
YPSILOTHURIDAE
Ypsilothuria bitentaculata (Ludwig, 1893) (see Pawson, 1970)
Order ASPIDOCHIROTIDA
SYNALLACTIDAE
Bathyplotes natas (Sars, 1868)

Phylum TUNICATA
Class ASCIDIACEA\
Order ENTEROGONA
CLAVELINIDAE
Clavelina michaelseni Millar, 1982 (see Millar, 1982, type locality)
DIDEMNIDAE
Leptoclinides duminus Millar, 1982 (see Millar, 1982, type locality)
POLYCLINIDAE
Aplidium chthamalum Millar, 1982 (see Millar, 1982)
Aplidium novaezealandiae Brewin, 1952

Synoicum otagoensis Millar, 1982 (see Millar, 1982, type locality)
Synoicum stewartense (Michaelsen, 1924)
Polyclinidae spp.
PSEUDODISTOMIDAE
?*Pseudodistoma* cereum Michaelsen, 1924 (see Millar, 1982)
RITTERRELLIDAE
Pharyngodictyon elongatum Millar, 1982 (see Millar, 1982, type locality)
Order PLEUROGONA
MOLGULIDAE
Molgula bathamae Millar, 1982 (see Millar, 1982, type locality)
STYELIDAE
Cnemidocarpa stewartensis Michaelsen, 1922
Polycarpa zetata Millar, 1982 (see Millar, 1982, type locality)

Phylum ARTHROPODA
Subphylum CHELICERATA
Class PYCONOGONIDA
Order PANTOPODA
AMMOTHELLIDAE
Cilunculus sewelli Calman, 1938
COLOSSENDEIDAE
Colossendeis macerrima Wilson, 1881
Colossendeis megalonyx Hoek, 1881
PALLENOPSIDAE
Pallenopsis kupei Clark, 1971 (see Clark, 1971)
Pallenopsis obliqua Thomson, 1884
RHYNCHOTHORACIDAE
Rhynchothorax articulatus Stock, 1968 (see Clark, 1976)
Subphylum CRUSTACEA
Class MAXILLOPODA
Order IBLIFORMES
IDIOBLIDAE
Idioibla idiotica (Batham, 1945) (see Foster, 1978)
Order SCALPELLIFORMES
CALANTICIDAE
Smilium acutum (Hoek, 1883) (see Foster, 1978)
SCALPELLIDAE
Amigdoscalpellum costellatum (Withers, 1935) (see Foster, 1978)
Arcoscalpellum pertosum Foster, 1978 (see Foster, 1978)
Arcoscalpellum trochelatum Foster, 1978
Class MALACOSTRACA
Order LEPTOSTRACA
PARANEBALIIDAE
Levinebalia fortunata (Wakabara, 1976)
(see Wakabara, 1976, type locality)
Order AMPHIPODA
AMPELISCIDAE
Ampelisca chiltoni Stebbing, 1888

Byblis sp.
AORIDAE
Aora maculata (Thomson, 1879)
Camacho bathyplous Stebbing, 1888
Lembos sp.
CHEVALIIDAE
Chevalia sp.
EPIMERIIDAE
Epimeria ?*bruuni* Barnard, 1961
ISCHYROCERIDAE
Runanga wairoa McCain, 1969
LILJEBORGIIDAE
Liljeborgia barhami Hurley, 1954
LYSIANASSIDAE
Parawaldeckia sp.
Tryphosites sp.
OEDICEROTIDAE
Monoculodes sp.
Oediceroides sp.
PHOTIDAE
Photis sp.
PHOXOCEPHALIDAE
Paraphoxus sp.
Proharpinia sp.
PODOCERIDAE
Podocerus sp.
STEGOCEPHALIDAE
Andaniotes corpulentus (Thomson, 1882)
STILIPEDIDAE
Stilipes sanguineus (Hurley, 1954)
(see Hurley, 1954 as *Cacao*, type locality)
SYNOPIIDAE
Tiron sp.
URISTIDAE
Uristes gigas Dana, 1849 (Not in NZIB)
UROTHOIDAE
Urothoe sp
Order ISOPODA
SEROLIDAE
Brucerolis ?*hurleyi* Storey & Poore, 2009
Order TANAIDACEA
NOTOTANAIDAE
Nototanais sp.
Order CUMACEA
LAMPROPIDAE
Hemilamprops pellucidus Zimmer, 1908
Order DECAPODA
Suborder DENDROBRANCHIATA

SERGESTIDAE
Sergestes arcticus Kröyer, 1855 (see Yaldwyn, 1957)
Infraorder CARIDEA
CAMPYLONOTIDAE
Campylonotus rathbunae Schmitt, 1926
CRANGONIDAE
Metacrangon knoxi (Yaldwyn, 1960)
Philocheras acutirostratus (Yaldwyn, 1960)
HIPPOLYTIDAE
Bathyhippolyte yaldwyni Hayashi & Miyake, 1970
(see Hayashi & Miyake, 1970)
Nauticaris marionis (Bate, 1888)
PALAEMONIDAE
Periclimenes sp.
PASIPHAEIDAE
Pasiphaea notosivado Yaldwyn, 1971
Suborder PLEOCYEMATA
Infraorder AXIIDEA
AXIIDAE
Axiopsis sp.
Infraorder POLYCHELIDA
POLYCHELIDAE
Stereomastis suhmi Bate, 1878
Infraorder ANOMURA
CHIROSTYLIDAE
Gastroptychus novaezelandiae Baba, 1974
Uroptychus scambus Benedict, 1902
*Uroptychus tomemtos*us Baba, 1975
Uroptychus spp.
DIOGENIDAE
Paguristes subpilosus Henderson, 1888
GALATHEIDAE
Munida gregaria (Fabricius, 1793)
Munida spp.
Phylladiorhynchus cf. *pusillus* (Henderson, 1885)
PAGURIDAE
Lophopagurus (*Australeremus*) *stewarti* (Filhol, 1883)
(see Forest et al., 2000)
Lophopagurus (*Lophopagurus*) *lacertosus* (Henderson, 1888)
(see Forest et al., 2000)
Paguridae sp.
PARAPAGURIDAE
Sympagurus dimorphus (Studer, 1883)
(see Forest et al., 2000)
PYLOCHELIDAE
Trizocheles spinosus (Henderson, 1888)
(see McLaughlin & Lemaitre, 2009)
Infraorder BRACHYURA

ATELECYCLIDAE
Pteropeltarion novaezelandiae Dell, 1972 (see Dell, 1972)
Trichopeltarion fantasticum Richardson & Dell, 1964
CYMONOMIDAE
Cymonomus bathamae Dell, 1971 (see Dell (1971), type locality)
HOMOLIDAE
Dagnaudus petterdi (Grant, 1905)
INACHIDAE
Dorhynchus ramusculus (Baker, 1906)
MAJIDAE
Jacquinotia edwardsi (Jacquinot, 1853) (see Dell, 1963; Griffin, 1966)
Leptomithrax garricki Griffin, 1966
Leptomithrax longimanus Miers, 1876 (see Griffin, 1966)
Leptomithrax longipes (Thomson, 1902) (see Dell, 1963)
Prismatopus filholi (A. Milne Edwards, 1876)
(see Griffin (1966) as *Chlorinoides*)
Teratomaia richardsoni (Dell, 1960)
PORTUNIDAE
Nectocarcinus antarcticus (Jacquinot, 1853)

Phylum PRIAPULIDA
Order PRIAPULOMORPHA
PRIAPULIDAE
Priapulopsis australis (de Guerne, 1886)

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