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Physical characterisation and a biologically focused classification of "seamounts" in the New Zealand region

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Abstract The physical, biological, and oceanographic characteristics of seamounts of the New Zealand region of the South Pacific Ocean are poorly known. The aim of this study was to present a synopsis of the physical characteristics of seamounts within the region, and to present a preliminary classification using biologically meaningful variables. Data for up to 16 environmental variables were collated and used to describe the distribution and characteristics of the c. 800 known seamounts in the New Zealand region. Seamounts span a wide range of sizes, depths, elevation, geological associations and origins, and occur over the latitudinal range of the region, lying in different water masses of varying productivity, and both near shore and off shore. As such, it was difficult to generally describe New Zealand seamounts, as there is no "typical" feature. Thirteen environmental variables were included in a multivariate cluster analysis to identify 12 seamount similarity groupings, for a subset of over half the known seamounts. The groupings generally displayed an appreciable geographic distribution throughout the region, and were largely characterised by a combination of four variables (depth at peak, depth at base, elevation, and distance from continental shelf). In the future, the findings of the present study can be tested to determine the validity and usefulness of the approach for directing future biodiversity research and informing management of seamount habitat.

Keywords characterisation; classification; New Zealand; seamounts

INTRODUCTION

Seamounts have become a high-profile habitat type in recent years, as they have been increasingly recognised as important areas for biodiversity, sites of localised high biological productivity, and are often the focus of commercial fishing for valuable fish species (see review by Rogers 1994). The number of seamounts in the world's oceans is unknown because large areas of sea floor remain unmapped in sufficient detail to identify such features. However, the global number is likely to be very large as more than 30 000 seamounts are thought to exist in the Pacific Ocean alone (Smith & Jordon 1988). An increasingly extensive literature exists on aspects of seamount geology, oceanography, and biology from research carried out mainly on seamounts in the North Pacific Ocean (see reviews by Keating et al. 1987; Rogers 1994). The physical, biological, and oceanographic characteristics of seamounts of the New Zealand region of the South Pacific Ocean are poorly known. The New Zealand region, because of its geological setting and history, has a complex seafloor relief. Tectonism and volcanism since 300 million years, and crucially within the last 80-100 million years, have formed a sea-floor bathymetry in which isolated submarine rises feature prominently (CANZ 1997). The major physiographic features were known by the early 1970s (e.g., Brodie 1964; Wanoa & Lewis 1972; Thompson 1991), but with the advent of GPS satellite navigation, use of multibeam swath-mapping, and declassification of satellite altimetry data (Sandwell & Smith 1997), the last 10 years have seen a significant increase in knowledge of the distribution of seamounts around New Zealand (Ramillien & Wright 2000). Such data have produced detailed bathymetry of seamounts in some areas (e.g., Lewis et al. 1997; Wright et al. in press), but most have not been mapped in detail. Biological research published in the primary

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literature on seamounts of the New Zealand region is limited, and reflects the fishery or fishing impact issues (Probert et al. 1997; Clark 1999; Clark & O'Driscoll 2003; Tracey et al. 2004). Only since 1999 has research been focused on assessing the diversity and ecology of seamount benthic macroinvertebrate fauna (Clark et al. 1999a). Determining the identities of species sampled from such previously unexplored habitats is very time-consuming and the results of such research effort have only recently begun to be published in preliminary/ interim reports (Clark & O'Shea 2001; Rowden et al. 2002, 2003, 2004). Nonetheless, the importance of conserving seamount habitats (Probert 1999) in the New Zealand region has been recognised with the designation of 19 seamounts with "protected" status (closed to all trawl methods) following a management appraisal (Clark et al. 2000; Brodie & Clark 2004).

The effectiveness of such conservation/management strategies and progress in understanding of the patterns of seamount biodiversity could be improved by a biologically meaningful description/classification scheme for seamounts (Stocks et al. 2004). The aim of this study was to present a synopsis of the physical characteristics of seamounts within the "New Zealand region" (taken here as the area bounded by 24°S, 167°W, 57°S, and 157°E), which extends an earlier characterisation (Wright 1999), and to present an initial classification using biologically meaningful variables (particularly for benthic organisms).

It is important to clarify, in the present context, the term "seamount". Three main types of submarine elevation, as defined by Eade & Carter (1975), are recognised in the New Zealand region: "seamount"-an isolated elevation rising 1000 m or more from the sea floor and of limited extent across the summit (not flat-topped as a "guyot"); "knoll"an isolated elevation rising less than 1000 m from the sea floor, and of limited extent across the summit; "pinnacle"-a small pillar-like elevation of the sea floor. In recent years, the term seamount has been applied more generally to topographic "hill" elevations regardless of size and relief (e.g., Epp & Smoot 1989; Rogers 1994). Reports on seamounts in the New Zealand region have also used variable definitions, with a vertical extent of 250 m applied by Wright (1999), and 100 m by Clark et al. (1999b) and Clark & O'Driscoll (2003). The New Zealand Ministry of Fisheries (MFish) draft "Seamount Management Strategy" defines seamounts as "protruding irregularities or bottom features that rise

greater than 100 m above the sea floor" (MFish 1999). For the purposes of the present study, we have collated data on features with a vertical elevation of 100 m or greater (thus, the term seamount is used here for discrete bathymetric features with \geq 100 m of relief) but have presented these data in a way that accounts for differing interpretations of the terminology for undersea features of various sizes (see Clement & Mace 2003 for an example of alternative views on what constitutes a seamount).

METHODS

Data sources and determinations

Physical data on seamounts were collated from existing sources used in the updating of regional bathymetry in 1997 (CANZ 1997), including data held by the National Institute of Water and Atmospheric Research (NIWA), the New Zealand Hydrographic Office, Royal New Zealand Navy, National Geophysical Data Centre (United States), South Pacific Applied Geoscience Commission (Fiji), published scientific papers, and recent multibeam surveys funded by Institut Français de Recherche pour l'Exploitation de la Mer (IFREMER, France). This information was supplemented by detailed data on smaller features from University of Kiel (Germany), Seabed Mapping New Zealand Ltd, and research surveys carried out over the last 20 years by NIWA and MFish (including multibeam surveys in the last 5 years). Many of these surveys were for deep-water fish species such as orange roughy, which often form aggregations over small seamount features on the seabed.

"Position" of a seamount was based on the location of the summit, which was determined from actual bathymetric data wherever possible, or from the central point of the shallowest contour derived from NIWA's regional bathymetric dataset. "Depth at peak" is the shallowest depth record known from the seamount. The "depth at base" of the seamount was generally taken from the deepest most complete depth contour that encircled the entire seamount. In some instances, there was an appreciable difference between sectors of a seamount, where one side is, for example, up-slope of a broader feature like a rise. In these instances the mid-point between the shallow and deep basal depth was taken. "Elevation" was computed as the difference between depth at peak and depth at base. "Area" was estimated from the polygon of the basal depth contour. "Slope" was calculated in two ways. First, actual echo-sounding data from ship tracks over seamounts were analysed and maximum, minimum (usually zero at the peak), and mean slopes computed. For many seamounts, however, data were inadequate for this method, and hence slope was calculated from the seamount trigonometry using elevation and base radius to derive average slope angle. This method tends to underestimate the true slope on the flanks of seamounts, since most seamounts have broadly domed peak regions (i.e., the method tends to average the low gradients near the peak and higher gradients on the flanks).

For the purposes of the present study, the geological "association" of seamounts was broadly categorised as being associated either with the inner New Zealand continental margin (within the enclosing continuous 2000 m isobath) or with various types of ridge and rise systems on the surrounding oceanic sea floor. Most of the known seamounts have received little or no scientific study, and their geological "origin" is not definitive, but over 500 seamounts included in the present study were classified on the basis of geological composition or location, i.e., arc/mid-plate/oceanic plate/hotspot/ rifted margin volcanoes, tectonic ridge, rifted continental block, or continental rise. Less than 10 seamounts in the New Zealand region have any form of direct radiometric age dating (e.g., Wright 1994; Mortimer et al. 1998; Wright unpubl. data), thus most "age" determinations for the present study were based on interpretation of magnetic anomaly and plate reconstructions and a regional assessment of sea-floor volcanism (Sutherland 1999). To date there are no regional studies of seamount "substrates" within the New Zealand region. The only regional compilation of substrate type is for sea-floor sediment composition (Mitchell et al. 1989), which is produced on a scale too coarse to realistically resolve sediment types for a seamount. At smaller spatial scales, modern swath imagery data (typically at an acquisition frequency of c. 12 kHz), although restricted to relatively small areas, can provide important information on general substrate compositions at scales of 100-1000 m. Such swath mapping imagery has been acquired from only a few areas where significant numbers of seamounts exist (southern Kermadec/Colville Ridges and Havre Trough, eastern North Island and Chatham Rise; Coffin et al. 1994; Blackmore & Wright 1995; Lewis et al. 1997, 1999; Barnes et al. 1998). These swath imagery data can differentiate broad areas of sediment and rock substrates (Orpin 2004) and the nature of large-scale degradation and mass-wasting

of seamounts. More recently, as part of detailed geological investigations of specific seamounts along the southern Kermadec arc (Wright 1994, 1996, 2001; Wright & Gamble 1999), higher frequency and higher resolution multibeam systems (at 30 kHz) have been used (Wright et al. in press). From these detailed investigations it is possible to describe substrate heterogeneity at scales of tens to hundreds of metres through integrating data from swath mapping backscatter imagery, sea-floor photography, and/or sea-floor sampling (e.g., Wright et al. 2002). For the present study the distribution of substrate type on the Kermadec arc seamount Rumble III was assessed by interpolating (using Inverse Distance Weighting in MapInfo) measures of % cover of substrate type determined from seabed images recovered by a photographic survey (see Rowden et al. 2002 for details of camera survey method), combined with a visual interpretation of a multibeam backscatter map. This assessment of physical character for a single seamount was conducted to illustrate the level of substrate heterogeneity that seamounts in the New Zealand region can possess.

Although limited data can be used to indicate substrate type on specific seamounts in the New Zealand region, such a restricted coverage of substrate type and heterogeneity precludes them from the present regional classification of seamount characteristics. Such an omission from the present classification is unfortunate, since substrate type and heterogeneity are known to influence the composition of seamount benthic assemblages (e.g., Raymore 1982; Kaufmann et al. 1989). Even without substrate information the remainder of physical data (13 of the 16 assessed variables; age and position also omitted) compiled for New Zealand region seamounts can be used to produce a biologically meaningful classification. These 13 variables are: association and origin, which effectively represent the geological history of a seamount and thus the potential composition of at least part of the substrate, and other factors that could influence the colonisation of a seamount by benthic fauna (Wilson & Kaufmann 1987); depth at peak, depth at base and elevation, for the position (and extent) of the seamount relative to the water column/surrounding seabed influences the types of organisms which exist in association with the habitat (e.g., Wisher et al. 1990); slope, for slope affects local current regime which in turn can influence the diversity and abundance of suspension-feeding taxa (e.g., Genin et al. 1986); area, because seamounts can be considered marine islands (sensu Hubbs 1959) and therefore, according to island-biogeography theory (sensu MacArthur & Wilson 1963), it can be expected that larger seamounts will support more species than smaller areas. In addition to these physical data, other biologically meaningful data were obtained, and values calculated for each known seamount within the New Zealand region, for inclusion in the analysis. Estimates of "chlorophyll a" (Chl. a) were derived from the mean of SeaWiFS (Hooker et al. 1992) observations at c. 9 km resolution between 1997 (day 244 of year) and 2002 (day 212 of year). Remotely sensed Chl. a data are generally related to the relative occurrence of phytoplankton in surface waters, and given reasonable assumptions are proxies for phytoplankton biomass in the ocean above the seamount (Martin 2004). The amount of phytoplankton (or primary productivity) associated with seamounts is likely to influence the diversity of pelagic and subsequently the benthic faunal assemblages (Piepenburg & Müller 2004). The shortest "distance a seamount is from the continental shelf" was calculated using ArcGIS, where seamount distances from the 250 m depth contour (which approximates the continental shelf edge) were calculated at a resolution of ± 1 km, based on an azimuthal equidistant projection (Central Meridian 171°E, Latitude of Origin 41°S, Datum WGS84). The composition of faunal assemblages on seamounts (which are generally features of the slope or deep-sea) is expected to be in part influenced by the degree to which faunal colonisation has been possible from the shallow water of the shelf (Leal & Bouchet 1991; Gillet & Dauvin 2000). Thus, a measure of the shortest distance from the shelf edge is expected to be a reasonable proxy for the likely extent of seamount colonisation by shallow-water species. Distance from the shelf edge is also a reasonable proxy for the existence of localised, biologically meaningful, hydrodynamic processes. The intensity of the current flow field near a seamount decreases with distance from continental margins (Smith et al. 1989), which concomitantly impacts the development of hydrographic features (e.g., localised upwelling, Taylor columns) that can influence primary productivity overlying seamounts (e.g., Comeau et al. 1995). The absolute geographical location of the seamounts can also be described by latitude and longitude, however, these were not included in the classification for they are not biologically meaningful per se. Latitude and longitude can be used as proxies for the variable sea surface temperature and/or to establish position in

relation to distinct water masses. In the present study, remotely-sensed data were available to directly measure sea surface temperature and derive data that gave temporally and spatially continuous variables that characterise different water masses. Data for sea surface temperature (SST) variables "wintertime SST", "annual amplitude of SST", "spatial SST gradient", and "summertime SST anomaly" were calculated from NIWA's archived SST climatology data set. Procedures for collecting satellite radiometer data, detecting cloud and retrieving SST data are described by Uddstrom & Oien (1999), and the calculation of the specified variables for the New Zealand region (at 1 km resolution) are detailed in Hadfield et al. (2002). Patterns in wintertime SST are a proxy for water mass (which is related to nutrient availability); variations in the annual amplitude of SST are owing to differences in stratification and wind mixing, that together produce the mixed layer across the region; spatial SST gradient recognises fronts in oceanic water masses (and is expected to correlate with variation in primary productivity); summertime SST anomaly is expected to recognise anomalies in temperature that are owing to hydrodynamic forcing, such as upwelling and vigorous mixing from eddies (areas with high values of this variable are expected to correlate with high primary productivity). All of these aforementioned parameters derived from SST data, possibly influence the composition of pelagic and benthic assemblages (see Longhurst 1998).

Data analysis

Descriptive analysis

All seamounts identified from the compiled data sources were included in a basic analysis that served, through simple graph and map plotting of physical variables, to describe the characteristics and distribution of the seamounts in the New Zealand region.

Classification analysis

Of the total number of seamounts identified by the descriptive analysis, complete data for biologically meaningful variables (association, origin, depth at peak, depth at base, elevation, slope, area, Chl. *a*, distance to continental shelf, wintertime SST, annual amplitude of SST, spatial SST gradient, summertime SST anomaly) were available for 475 seamounts. Thus, only this subset of the New Zealand region seamounts was included in the classification analysis. The classification analysis was undertaken using the statistical software package PRIMER version 5.2

(Clarke & Gorley 2001) for multivariate analysis (see Clark & Warwick 2001). Before analysis, data for each of the biologically meaningful variables were examined, using pairwise "draftman plots", for conformity to continuous, univariate, normal behaviour (the ideal) and, the extent of correlation with each of the other variables. Variables not conforming to the ideal distribution were transformed (natural log area, $\sqrt{\text{slope}}, \sqrt{\text{Chl. }a}$. Correlation coefficients between variables did not exceed 0.90, and thus all data were retained for analysis. Since variables were measured in different units it was essential to normalise data for each variable (by subtracting the mean and dividing by the standard deviation). After normalisation, each variable had the tendency to contribute equally to the subsequent distance matrix (something which was not necessarily desirable but largely unavoidable with mixed units). The variables origin and association are categorical, so for the analysis categories were treated as dummy variables (i.e., 0/1 variable for each category). A similarity matrix for all suitably transformed and normalised variables for the subset of New Zealand region seamounts was then calculated using the Euclidean distance metric. This metric is considered the most suitable measure of similarity for analyses using these types of data (see Valesini et al. 2003). A group average hierarchical clustering/ classification procedure was performed on this similarity matrix using the program CLUSTER. Such an analysis aims to find "natural groupings", such that seamounts within a group are more generally similar to each other than seamounts in different groups. The result of the clustering analysis is represented by a dendrogram, where groups with the same (arbitrary) level of similarity can be identified. Here, a "cut-off" level of similarity was chosen that would produce between 10 and 15 groups whilst still retaining a relatively high level of dissimilarity between groups. The similarity percentages programme SIMPER for Euclidean distances (beta version 6 of PRIMER, supplied by K. R. Clarke) was used to describe the within-group level of similarity and to identify those biologically meaningful variables that contribute most to the similarity of each identified seamount group.

RESULTS

Geographical distribution

A total of 812 seamounts are currently identified within the New Zealand region (Fig. 1). The total area of presently known seamounts within the New Zealand region is c. 250 000 km² of sea floor. About 103 000 km² (410 seamounts) of the total seamount area lies within the New Zealand Exclusive Economic Zone (EEZ) (Table 1). The proportion of seamount sea floor both within and outside the New Zealand EEZ is very similar, being a minimum of c. 2.5% of the total sea-floor area for the region.

The distribution of seamounts within the New Zealand region is uneven, with more seamounts in northern latitudes of $\leq 42^{\circ}$ S. The individual latitude band with the greatest number of seamounts is 44–46°S (Fig. 2A), which includes features associated with the Chatham Rise. Seamount frequency by longitude (Fig. 2B) shows that most of the features lie within the range 174°E to 174°W, with concentrations in the Bay of Plenty (where the Kermadec Ridge approaches slope off North Island of New Zealand) and southeastern Chatham Rise being prominent.

The distribution of seamounts in waters to the north and east of New Zealand means that the majority (over 500) are overlain by subtropical water masses (Fig. 3). About 120 are overlain by subantarctic water, and just under 150 are in the intervening subtropical convergence zone (mostly along the Chatham Rise) between the subtropical and subantarctic waters (with reference to water masses identified by Carter et al. 1998).

Seamount morphology

The area of individual seamounts ranges from <0.5 km² to 34 700 km². The frequency of seamount areas <3000 km² is plotted in Fig. 4, which does not include the very large Gilbert and Bollons seamounts (13 800 and 34 700 km², respectively) that are located in deep water west and southeast of the South Island of New Zealand, respectively. The mean area of all known seamounts is 390 km². Relatively few seamounts have areas >1000 km², with the majority small in area (<20 km²), with between 40 and 50 per 20 km² interval up to a size of 100 km². Thereafter the number of seamounts per area-band progressively decreases. The area of seamounts relative to the total sea floor of the region varies with depth (Table 1). Although area data are not available for all known seamounts, the proportion of the region covered by seamounts is small at depths less than c. 3000 m. Deeper, the proportion increases from 1% or less per depth interval, to 3-4%, and between 4000 m and 5000 m water depth this proportion increases to c. 10%, owing primarily to the very large areas of Gilbert and Bollons seamounts.

Known seamounts range in depth from the surface between 20 m and 6500 m at their peaks (Fig. 5A). There is strong predominance of peak depths of



Fig. 1 The distribution of known seamounts in the New Zealand region. Filled diamonds indicate position of seamount peak.

800 m to 1000 m, which reflects in part the knowledge of sea-floor morphology in the deep-water orange roughy and oreo trawl fisheries. Outside this depth range there is a relatively uniform number of seamounts at between 10 and 20 per 100 m depth bin. However, there are few seamounts at depths >5000 m, which is approaching the abyssal depths for most sea floor surrounding New Zealand (apart from the Kermadec-Tonga Trench). The depth at base of seamounts ranges from 300 m to over



Fig. 2 Frequency of seamount in the New Zealand region by: A, latitude; and B, longitude.



Fig. 3 Distribution of seamounts in the New Zealand region amongst different categories of overlying water mass. Water mass categories after Carter et al. (1998).

7000 m (Fig. 5B). Most seamounts rise from depths of 1000 m to 1300 m, although the distribution is relatively even to depths of 5500 m.

Seamount elevation (the height relief from the deepest complete depth contour to the peak) ranges from c. 100 m to over 5000 m (Fig. 6). Almost 70% of seamounts with known elevation are <1000 m, with 100–150 m being the most frequent grouping. A further 21% lie between 1000 m and 2000 m. The average elevation of all seamounts is 930 m. Fig. 7 shows seamount elevation by four groupings (<250 m, 250–500 m, 500–1000 m, >1000 m) which illustrates that seamounts with elevations <500 m tend to be found inshore or on the flanks of more

Table 1 Seamount area by depth interval for seamounts within the New Zealand Exclusive Economic Zone (EEZ). nArea is the number of seamounts in the depth interval with known area; nTotal is the total number of known seamounts within the depth interval; pArea is the proportion of the depth interval covered by the seamounts with known area.

Depth interval (m)	Seamount nArea	Seamount nTotal	Seamount area (km ²)	EEZ area (km ²)	pArea
0-250	0	0	0	277 076	0.000
250-500	4	4	55	200 300	0.000
500-750	10	10	4064	350 668	0.012
750-1000	27	46	224	246 518	0.001
1000-1500	102	125	3086	482 748	0.006
1500-2000	43	47	2229	311 029	0.007
2000-2500	46	47	4505	295 588	0.015
2500-3000	32	32	3942	290 705	0.014
3000-3500	34	34	8872	234 478	0.038
3500-4000	16	16	7302	237 434	0.031
4000-4500	25	25	24 498	293 676	0.083
4500-5000	9	9	39 095	337 265	0.116
>5000	15	15	4938	542 000	0.009
Total	363	410	102 810	4 099 485	0.025



Fig. 4 Frequency of seamount area (km²), in 100 km² groupings, for those seamounts less than 3000 km² in the New Zealand region.

general rises and plateaux like the Chatham Rise (Fig. 7A,B) whereas seamounts over 500 m are typically 200 km or more from the coastline, and associated with major bathymetric features like the Louisville Ridge, Colville and Kermadec Ridges, Three Kings Ridge, Macquarie Ridge, and Lord Howe Rise (Fig. 7C,D).

Seamounts are often visualised as steep-sided features, typically using $a \times 3$ exaggeration of the vertical scale. However, at true vertical scale many have gradual or shallow slopes. Both methods used here to calculate slope show similar results (Fig. 8). The mean slope of most seamounts is <20°, with the most frequent slope being between 5° and 10°. Few slopes exceed 30°, although calculated mean slope can be over 50°. The distribution of maximum slopes is fairly unimodal centred on c. 20°, and extending to over 45°. Cross-sectional profiles of representative seamounts are shown in Fig. 9, which demonstrates the variability of size, shape, slope, and elevation of New Zealand seamounts. Mount Taranaki and One Tree Hill are also plotted to enable easy comparison with familiar New Zealand terrestrial forms.

Seamount geology

There are approximately equal numbers of seamounts with continental and oceanic association (Fig. 10A). Continental seamounts are generally close to the coast, or around the edges of the extended shelf-slope, and include the Challenger Plateau, Lord Howe Rise, and Chatham Rise. Oceanic seamounts, such as those of the Louisville Ridge, are offshore from the coast, and surrounded by deep water. Over 100 seamounts are linked with elevated ridges (e.g., Macquarie Ridge, Kermadec Ridge).

Those seamounts that tend to have a continental association include continental rises, rifted continental blocks, and rifted margin volcanoes. Oceanic seamount features include hotspot volcanoes, oceanic plateau volcanoes, some mid-plate volcanoes, and arc volcanoes. Bollons and Gilbert seamounts are examples of large seamount blocks rifted from the main continental mass whilst the Louisville seamount chain is a series of hotspot volcanoes. An assessment of the number of seamounts for each of these geological origins is given in Fig. 10 B. Most have volcanic origin, with over 50% being mid-plate (e.g., Chatham Rise seamounts) seamounts, and over 100 seamounts formed by arc volcanism (e.g., Brothers, Rumble III) along the present-day Pacific-Australian plate boundary.

Data for seamount age are limited, but broadly speaking, seamounts within the New Zealand region have formed between: c. 100 and c. 80 million years ago (Ma), and associated with mid-plate or hot-spot volcanism of the deeper ocean floor; c. 90 and c. 70 Ma, and associated with break-up volcanism and tectonism of the New Zealand continental plateau (e.g., Bollons and Gilbert seamounts); and post 40 Ma, and associated with the evolving plate boundary, including arc volcanism, rifting, and oblique subduction.



Surveys of seamounts associated with the southern Kermadec volcanic arc show good correspondence between the general backscatter from multibeam mapping, and the sediment type revealed by sea-floor photography (e.g., Rumble III seamount, Fig. 11). "Dark" backscatter represents areas of high acoustic impedance, which indicates hard rock substrate, whilst "light" backscatter imagery shows areas of low acoustic impedance and indicates the distribution of soft sediment.

Seamount classification

The results of the cluster analysis, illustrated as a dendrogram, indicate that 12 groupings of seamounts (n = 475) can be identified at the Euclidean distance measure of six (Fig. 12). Three seamounts were not classified at the level of similarity chosen to identify seamount groupings. The geographic distribution of the seamounts belonging to the identified classification groupings is shown in Fig. 13. The majority of the classified seamounts (n = 136) belong



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to Group 11 and are widely distributed throughout the New Zealand region in deep basins. Group 12 seamounts, the second largest grouping (n = 115), are associated with the Kermadec, Colville, and Three Kings Ridges in the north of the region. Group 10 seamounts (n = 23) are almost entirely restricted in distribution to the Hikurangi Plateau, whereas those of Group 9 seamounts are associated with the slopes of the Chatham Rise (n = 70), Bay of Plenty (n = 10), and Challenger Plateau (n = 4). Seamounts of Group 8 (n = 26) are more widely dispersed, occurring in relatively deep water north and south of the eastern end of the Chatham Rise (n = 15), in a trough on the western edge of the Lord Howe Rise (n = 2), at the head of the New Caledonia Trough (Telecom, Aotea seamounts), and on the slope of the Campbell Plateau near Auckland Island (n = 7). Group 7 seamounts are either closely associated with the Louisville Ridge (n = 18) or the Lord Howe Rise (n = 8) in the north of the region, whereas Group 5 (n = 16) and Group 2 (n = 6) are both associated with the Macquarie Ridge in the south of the region. Group 6 contains four seamounts along the Resolution Ridge System, four features clustered together on the slope at the southern end of the East Coast Ridge, the region's two largest seamounts (Bollons and Gilbert), two seamounts north of Gilbert seamount in the Tasman Basin, and other single isolated seamounts at the southern end of the Colville Ridge (Colville Knoll), on the Hikuranki Margin (Ritchie Hill), on the Northland Plateau (Cavalli seamount), and on the West Norfolk Ridge

(seamount No. 447). Groups that contain only a small number of seamounts are situated in the Emerald Basin (Groups 4 and 3) and the slope of the Campbell Plateau (Group 1) in the extreme south of the region.

The Euclidean distance similarities of the seamount groups and the biologically meaningful variables that contribute the most to such similarities are detailed in Table 2. The similarity values for the identified seamount groups ranged considerably, with seamounts belonging to Group 9 and Group 6 being the most and least similar, respectively. The variables depth at base, depth at peak, elevation, and distance from continental shelf were consistently ranked as the top four contributing variables to the similarity observed for each seamount group. The contribution to the within-group similarity by any other of the variables used in the analysis was always negligible (<0.01%). Depth at base was the variable that in the majority contributed the most to the observed within-group similarity (for Groups 12, 9, 8, 6, 5, 2, and 1), otherwise it generally ranked third in overall contribution (5.86-54.22%). Although the variable depth at peak was deemed the most important variable for four of the seamount groupings (Groups 11, 10, 7, and 3), generally this variable was the second in its overall contribution (15.95-49.57 %) to the observed similarity. The variable elevation, which contributed between 3.6% and 63.41%, was either the third or second (6 and 5 instances out of 12, respectively) highest contributor, only once contributing the most to the observed within-group

Fig. 6 Frequency of seamount elevation in the New Zealand region.

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Fig. 7 Distribution in the New Zealand region of seamounts by elevation (4 categories: <250 m; 250–499 m; 500–999 m; ≥1000 m). Filled diamonds indicate position of seamount peak.



Fig. 8 Frequency of seamount slopes in the New Zealand region. A, mean slope calculated from area and elevation; and B, maximum slope measured from the detailed bathymetry.

similarity (for Group 4). Of the four most important variables, distance from the continental shelf always contributed the least (0.01–4.72%) to the observed within-group similarity.

DISCUSSION

The results of the present study clearly demonstrate that c. 800 known seamounts in the New Zealand region have very diverse physical characteristics. Seamounts span a wide range of sizes, depths, elevation, geological associations and origins, and occur over the latitudinal range of the region, lying in different water masses of varying productivity, and both near shore and off shore. As such, it is difficult to generally describe New Zealand seamounts, as there is no typical feature. Thus, seamounts provide a wide variety of habitats, and this is potentially important for structuring the diversity of the faunal assemblages associated with the seamounts of the region.

The number of known seamounts considered by the present study is almost certainly an underestimate for smaller seamounts that are in the order of 100-500 m high. Recent multibeam swath-mapping of regions of the Kermadec Ridge (northeast of the North Island) indicates that seamounts as large as 10-20 km basal diameter can remain undiscovered (Wright et al. in press). Thus it should be noted that the sea-floor area of currently unknown features may increase the present estimate of seamount area considerably (only c. 7 % of the region is mapped with multibeam surveys). For larger seamounts a comparison of regional bathymetric data (CANZ 1997) and satellite altimetry data (Smith & Sandwell 1994, 1997; Ramillien & Wright 2000) suggests that most are identified. The present assessment of seamount distribution is in part an artifact of the latitudinal/longitudinal distribution of bathymetric data (Smith 1993), some of which reflects fisheryrelated research effort (e.g., seamounts on the Chatham Rise which are commercially fished for orange roughy and oreo), but is in part real owing to a greater number of seamounts associated with boundary or hotspot volcanism to the north.

Data on substrate type for seamounts in the region are very limited. However, the apparent agreement between the distribution of substrate interpreted from the backscatter and pattern of sediment and rock substrate derived from the seabed photographs (for Rumble III) provide clear evidence for the existence of highly heterogeneous substrate composition over spatial scales of 10-1000 m for at least the Kermadec arc seamounts. Extrapolation of results from multibeam/camera substrate surveys of active seamount volcanoes to New Zealand-wide seamounts is currently difficult to assess. However, a new technique provides a promising avenue to directly derive objective substrate maps from backscatter data (Le Gonidec et al. in press) and thereby improve understanding of substrate distribution on/between seamounts.

Although some data indicate that physical characteristics can be important in influencing the composition of the fish fauna of some New Zealand seamounts (Clark & Field 1998; Tracey & Fenaughty 1997; Clark et al. 2001; Tracey et al. 2004), there are currently no comparable studies for benthic macroinvertebrates. Studies are under way to quantify the diversity of benthic fauna for New Zealand seamounts and to examine the spatial



Fig. 9 Profiles of selected seamounts of the New Zealand region (and terrestrial features Mt. Taranaki and One Tree Hill for comparison).

pattern of assemblage composition, both within and between seamounts of the region (Clark et al. 1999a). However, presently such an analysis will be fairly restricted (so far 40 seamounts have been specifically sampled with a limited number of direct sampling gear deployments on each feature) and is likely to be incomplete for some time (complete identification of certain taxa will take many years). Considering the need to more efficiently document the biodiversity of seamounts, which are costly to sample, and the need for such information to underpin issues of conservation and sustainable use of the seamount environment (e.g., fishing, mining) (Johnston & Santillo 2004; Morato & Pauly 2004), it seems prudent to produce a biologically meaningful classification of New Zealand's seamounts. Such a classification is consistent with recent recommendations from the seamount scientific community (Stocks et al. 2004).

The adoption of simple classification procedures, and the resultant interpretations, potentially provide a greater scientific underpinning for environmental management (e.g., Valesini et al. 2003). The results of this classification analysis indicate that New Zealand region seamounts can be placed into 12



Fig. 10 Geological association of seamounts in the New Zealand region with: **A**, continental or oceanic systems; **B**, and frequency of seamount classes based on interpreted geological origin.



Fig. 11 A, Multibeam backscatter map of Rumble III seamount (white rectangle indicates area in which seabed photographic survey undertaken); **B**, seabed photograph of soft sediment—rippled medium—coarse sand with no visible granule—cobble sized clasts; **C**, seabed photograph of hard substrate—coarse volcanic breccia including pillow-lava breccias with clasts dominantly greater than granule in size (photographs taken c. 2–3 m above seabed; approximate field of view is 2×3 m); **D**, interpolated distribution of soft sediment; **E**, interpolated distribution of hard substrate (coloured squares are 130×130 m; red = high and blue = low % cover of substrate type; black crosses = position where seabed photographs taken, white circle = position of photographs illustrated; black bathymetric contour lines are drawn at 250 m intervals).



Fig. 12 Dendrogram of the biologically meaningful data for 475 seamounts of the New Zealand region resulting from cluster analysis. Seamount groupings (1–12) identified at the Euclidian distance value of six (dashed line).

 Table 2
 Results of the SIMPER analysis for variables that best characterised the seamount groups identified by the classification procedure (figures in bold indicate greatest contributory value).

	% contribution of variables to observed within-group similarity					
Seamount group and level of similarity (average squared Euclidean distance)	Depth at base	Depth at peak	Elevation	Distance from continental shelf		
12 : 1.65E+06	36.88	27.67	33.85	1.60		
11:1.55E+06	23.98	42.52	33.5	4.72		
10:6.11E+05	19.16	49.57	29.73	1.54		
9:1.60E+05	43.88	29.48	22.27	4.37		
8:3.63E+06	51.89	32.18	14.83	1.10		
7 : 4.01E+06	23.74	38.64	35.01	2.61		
6 : 4.11E+06	54.22	28.72	16.47	0.59		
5:3.69E+06	52.95	43.33	3.60	0.12		
4:9.93E+05	5.86	30.72	63.41	0.01		
3:5.80E+05	46.51	47.89	5.11	0.49		
2:4.63E+05	52.6	15.95	31.3	0.15		
1:3.30E+06	51.28	38.77	9.83	0.11		



Fig. 13 Distribution of seamounts belonging to groups identified by classification analysis (see key). Lettered seamounts are those seamounts currently closed to trawling: a, seamount No. 140; b, seamount No. 148; c, Cavalli; d, seamount No. 447; e, Telecom; f, Aotea; g, Rumble III; h, Brothers; i, Morgue; j, Pyre; k, Gothic; l, Diamond Head; m, seamount No. 328; n, Pinnie; o, seamount No. 358; p, seamount No. 375; q, Christable; r, Bollons; s, seamount No. 401.

groups. These seamount groups could be characterised by the properties of 13 variables that were interpreted to influence the composition of benthic assemblages. The classification groupings generally display a readily appreciable geographic distribution throughout the New Zealand region, and all groups

are largely characterised by a combination of four variables. These variables, in increasing order of apparent importance (in the percentage contribution to the measured similarity across all groups), were distance from the continental shelf, elevation, depth at peak, and depth at base. Clearly, apart from the first of these variables which contributed a relatively small amount to the characterisation of seamount groupings (on average 1.5%), it is the physical location variables that describe the seamount's relationship to the adjacent sea floor and the overlying water column that are best able to characterise the different types of New Zealand region seamounts. These three variables, like all the variables included in the classification analysis, are expected to influence the assemblage composition of benthic fauna associated with seamounts. Here, it would appear that although the three variables do not directly correlate with any environmental variable other than pressure, environmental factors which measures of depth (and range) reflect-such as temperature, light, surface water-derived particulate matter, available oxygen (e.g., Wishner et al. 1990), and depth-associated evolutionary factors (Jacobs & Lindberg 1998)-could influence biodiversity such that the composition of benthic assemblages of the different seamount groups are likely to be different. Whether this proposition is true can be tested by comparing the biodiversity of seamounts that "belong" to the different groups identified by the present analysis. Sampling to date (in the New Zealand EEZ) allows a comparison of tens of seamounts distributed among only five of the seamount groups (Groups 6, 8, 9, 10, 12). Ideally, before such an analysis is undertaken, more seamounts from each of these groups need to receive additional sampling. Specific sampling of seamounts from the remaining groups currently unsampled is also required. Such a test would serve to extend appreciation of the factors that influence the biodiversity of seamount habitats and validate, or suggest refinement of, the present classification scheme. If the biological meaningfulness of the classification is established it will constitute a credible basis for the resource management of New Zealand seamounts.

Clark et al. (2000) assessed the then available physical and archived biological data for New Zealand seamounts for a range of criteria (representativeness, comprehensiveness, ecological uniqueness and importance, productivity, vulnerability, naturalness) specified in the draft MFish Seamount Management Strategy to select appropriate seamounts for protection from commercial fishing (MFish 1999). Subsequently 19 seamounts, widely distributed throughout the New Zealand region according to a "biogeographic area" structure, were closed to bottom trawling (Anon. 2001; Brodie & Clark 2004). Clark et al. (2000) recognised that the selection process was the initial step in the selection and management of seamounts. For this reason it is important to comment on the significance of the groupings to which the present classification allocates these 19 protected seamounts. The protected "Northern area" seamounts are assigned, in the majority, to one group, i.e., Brothers, Rumble III, No. 140 and No. 148 all belong to Group 12, with only Cavalli belonging to a different group (Group 6). Seamount No. 447, of the "Western area", was also assigned to the same group as Cavalli, whereas its relatively near neighbours (Telecom, Aotea) belong to Group 8. In the "Eastern area", seamount No. 328 is also a member of the latter group, with other seamounts of the Chatham Rise area (Morgue, Pyre, Gothic, Diamond Head, Pinnie) all belonging to Group 9. Seamounts of the "Southern area" were assigned by the classification analysis into a greater number of groups: Bollons and Christable to Group 6; seamounts No. 358 and No. 375 to Groups 11 and 5, respectively; and the most southerly of the protected seamounts, No. 401, was one of only four seamounts belonging to Group 1 (see Fig. 13).

The ability to afford protection to seamounts in the New Zealand region is currently restricted to the EEZs of New Zealand and Australia, and so protected seamounts represent all but two of the 12 groupings identified by the present classification. Groups with no representatives of protected seamounts are located (within the New Zealand EEZ) on the Hikurangi Plateau (Group 10) and the Macquarie Ridge (Group 2).

Some seamounts, included in the present classification analysis, were assigned to three groups that occur exclusively outside the New Zealand EEZ; these are seamounts associated with the Emerald Basin (Groups 3 and 4) and the Lord Howe Rise and Louisville Ridge (Group 7). All five of the seamounts in Group 3 occur within the Australian EEZ that surrounds Macquarie Island, and two seamounts of this group, although not identified for specific protection (as are Australia's Tasmanian seamounts; Department of Environment and Heritage 2004, Tasmanian Seamount Marine Reserve: www.deh.gov.au/coasts/mpa/seamounts (accessed February 2005), are afforded *de facto* protection by being located in the Macquarie Island Marine Park (within the Northern Habitat/Species Management Zone). Similarly, both seamounts that comprise (in total) Group 4 also occur in the Macquarie Island Marine Park (within the Highly Protected Zone). Five of the eight seamounts belonging to Group 7 on the Lord Howe Rise occur within the Australian EEZ around Lord Howe Island, one of which effectively receives protection by being located within the Lord Howe Island Marine Park (within the Habitat Protection Zone). Seamounts of Group 7 on the Louisville Ridge are located in international waters ("high seas") and have no management protection. However, some marine scientists and non-governmental organisations want a moratorium on deep-sea trawling on the high seas, primarily to protect deep-sea coral assemblages (that are frequently associated with seamounts) (see Gianni 2004).

Clearly the present investigation is preliminary in nature. However, the study described is the first of its kind for seamounts in any ocean, and the findings can be tested to determine the validity and usefulness of the approach for directing future biodiversity research and informing management of seamount habitat.

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