Multibeam Bathymetric Surveys of Submarine Volcanoes and Mega-Pockmarks on the Chatham Rise, New Zealand

John A. Collins
Department of Geology and Geophysics
Woods Hole Oceanographic Institution
Woods Hole, MA 02543

Peter Molnar and Anne F. Sheehan
Department of Geological Sciences, and
Cooperative Institute for Research in Environmental Sciences (CIRES)
University of Colorado at Boulder
Boulder, Colorado 80309-0399

Abstract

Multibeam bathymetric surveys east of the South Island of New Zealand present images of submarine volcanoes and pockmarks west of Urry Knolls on the Chatham Rise, and evidence of submarine erosion on the southern margin of the Chatham Rise. Among numerous volcanic cones, diameters of the largest reach ~2000 m, and some stand as high as 400 m above the surrounding seafloor. The tops of most of the volcanic cones are flat, with hints of craters, and some with asymmetric shapes may show flank collapses. There are hints of both northeast-southwest and northwest-southeast alignments of volcanoes, but no associated faulting is apparent. Near and to the west of these volcanoes, huge pockmarks, some more than ~1 km in diameter, disrupt bottom topography. Pockmarks in this region seem to be confined to sea floor shallower than ~1200 m, but we see evidence of deeper pockmarks at water depths of up to 2100 m on profiles crossing the Bounty Trough. The pockmark field on the Chatham Rise seems to be bounded on the south by a trough near 1200 m depth; like others, we presume that contour currents have eroded the margin and created the trough.

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Introduction

Crust much thicker than that beneath deep ocean basins underlies two regions with relatively shallow water (< 1000 m) east of the South Island of New Zealand, the Chatham Rise and Campbell Plateau (e.g., Davy & Wood 1994; Grobys et al. 2008, 2009) (Fig. 1). When these crustal fragments rifted away from Antarctica in the late Cretaceous, they also separated from one another along a rift that never grew wide (Carter & Carter 1987; Carter et al. 1994). Between the Chatham Rise and Campbell Plateau, sea floor deepens in the Bounty Trough, and Grobys et al. (2007) interpreted their marine geophysical investigations to reveal evidence of such rifting, also in the Cretaceous. As much as 1–2 km of sediment, derived from erosion of the South Island, has subsequently accumulated in the Bounty Trough (e.g., Uenzelmann-Neben et al. 2009). According to this interpretation, the Chatham Rise, Bounty Trough and Campbell Plateau are all essentially tectonically dead. Yet, as others have shown and we document further below, the seafloor seems to be active in a number of ways, with volcanism, subsurface gas flow, and submarine erosion all altering the bathymetry.

On recent cruises to deploy and recover ocean-bottom seismographs deployed around New Zealand (Collins et al. 2009, 2010), we carried out multibeam surveys of the bathymetry in regions of special interest and suggested to us by geologists from New Zealand. These surveys focused on an area with different, largely unrelated features: volcanic topography near the Urry Knolls, pockmarked bathymetry just west of the region of widespread volcanism, and a sharp boundary to the Chatham Rise that seems to be the result of sub-bottom erosion (Fig. 1). Our purpose here is to make these bathymetric data available to others and to offer simple interpretations of them. As these studies address different topics and stand alone, we present them separately, including also single line multibeam swaths crossing the region (Fig. 2).

Volcanism

Although Cenozoic volcanism is widespread in and around New Zealand, such volcanism seems to be concentrated either in large volcanic centers, like those on the Banks Peninsula (e.g., Hoernle et al. 2006; Timm et al. 2009), or in isolated small sites, like Antipodes Island (Cullen 1969) or on Chatham Island (Hoernle et al. 2006).

Isolated single channel (Herzer et al. 1989) and multibeam (Timm et al. 2010) coverage reveals other volcanism, but the sparse bathymetric coverage of the region surrounding New Zealand allows for the possibility of more extensive volcanism. We present evidence below of a field of volcanoes near the Urry Knolls and unlike any hitherto mapped in New Zealand and its surroundings.

Pockmarks

In regions of the sea floor where natural gas apparently has escaped, the bathymetry commonly shows pits or holes into which surface sediment has collapsed so that the depressions resemble pockmarks on scarred facial tissue (e.g., King & MacLean 1970; Hovland 1981; Hovland & Judd 1988; Judd & Hovland 2007). Such "pockmarks" have now been found in many tens of regions globally, but largely in regions of known natural gas reserves (e.g., Judd & Hovland 2007; Pilcher & Argent 2007). Recently, Davy et al. (2010) recognized pockmarked seafloor topography near the Urry Knolls on Chatham Rise (Figs. 1, 3) from the similarity of their topographic signatures on a few multibeam swaths and high-resolution sub-bottom profiles to pockmarks recognized elsewhere. These pockmarks raise the questions of whether they are isolated features or widespread, and hence whether they might indicate extensive gas reserves in New Zealand waters. We show below that indeed pockmarks are widespread.

Deep Submarine Erosion on the Chatham Rise

Davy et al. (2010) noted that the pockmarks on the Chatham Rise seem to be confined to sea floor shallower than ~1200 m, where the south side of the Rise is bounded by a steep slope. Such a steep slope could result from strong contour currents, but as we discuss below, physical oceanographic measurements do not offer convincing evidence of strong present-day currents. We show that west of where Davy et al. (2010) noted a steep slope, a trough, with a steep slope on its north side, follows closely the ~1200 m contour and seems to result from erosion by a contour current, which we presume to flow eastward.

Multibeam Methods

The bulk of the multibeam data shown here were acquired with Kongsberg Simrad EM 300 (Cruise TN229, January–February 2009) and EM122 (Cruise RR1002, January–February 2010) multi-beam echo sounding systems. Sounding velocities were computed from daily (or more frequent) expendable bathythermograph (XBT) profiles. The data shown here have not been corrected for tides. Some single-swath profiles shown in Fig. 2 were acquired on historical cruises and were retrieved from the U.S. National Geophysical Data Center (NGDC).

Submarine Volcanoes Near The Urry Knolls

From scattered dredge hauls, single-channel seismic reflection profiling, and bathymetry from wide-beam echo sounding, Herzer et al. (1989) showed evidence of relatively young volcanism on the Chatham Rise over the Urry Knolls (Fig. 1). This region lies hundreds of kilometers east of the volcanism on the North Island of New Zealand, which is associated with ongoing subduction of the Pacific plate, but rather lies within the Pacific plate itself. Thus, its occurrence might have been somewhat surprising, if widespread late Cenozoic volcanism had not occurred elsewhere in New Zealand and on surrounding islands (e.g., Hoernle et al. 2006; Timm et al. 2010).

Herzer et al. (1989) found that samples from these submarine volcanoes were too altered to allow them to be dated, but they suspected that the volcanism was late Cenozoic in age. Basalts from the east coast of the South Island yield ages from 16 to 10 Ma near Dunedin and 12 to 6 Ma from the Banks Peninsula (Hoernle et al. 2006; Timm et al. 2009, 2010). Between these locations, Matthews & Curtis (1966) measured 2.5 ± 0.7 Ma from basalt near Timaru. Wood & Davy (1994) reported late Cenozoic volcanism on the Hikurangi Plateau north of the Chatham Rise, and Hoernle et al. (2006) also reported ages near 6–7 Ma from Chatham Island. Cullen (1969) gave two K-Ar ages of 0.25 ± 0.2 Ma and 0.50 ± 0.4 Ma from Antipodes Island. With less evidence of volcanism, Adams (1981) inferred an eastward progression of volcanism, but these dates reveal no obvious progression across the region. Subsequent detailed analysis by Timm et al. (2010) has shown widespread volcanism across the Chatham Rise and Campbell Plateau with ages ranging from ~65 M to <1 Ma, but with no obvious progression across the region or systematic temporal variations in composition with age. Consistent with these observations, Uenzelmann-Neben et al. (2009, p. 149) inferred that deformation of sedimentary sequence in the Bounty Trough to the east-southeast of the Urry Knolls is related to Miocene and subsequent magmatic activity. Despite the evidence of late Cenozoic volcanism on the Chatham Rise and Campbell Plateau, active volcanism does not occur today on or even near the South Island.

We surveyed an area near Urry Knolls with a multibeam bathymetric system, and indeed a field of volcanoes is clear (Figs. 3–6). Between approximately 44°41'S and 44°58'S and between 174°30'E and 175°E, volcanic cones abound. Some stand less than 100 m above the sea floor and are less than 300 m in diameter. The height of the tallest, however, exceeds 400 m, and typical radii for tall cones are ~1000 m (Fig. 7). They are spaced 5–10 km apart, with numerous smaller cones between them. Between clusters of cones are expanses with little topography; for example, note the nearly flat topography punctuated by only small cone-like structures, some apparently with moats around them in the northwest part of the region in Figs. 3, 4 (between 44°41'S and 44°45'S between 174°31'E and 174°41'E), and in the southeast part (between 44°48'S and 44°52'S between 174°46'E and 174°56'E). Most cones show radial symmetry, but some include an asymmetry easily interpreted as due to major eruptions with failures of one side, or flank collapses. For instance, a tall cone near "a" (Figs. 4–6) seems to be missing its eastern flank, as if an eruption took that part away (like what occurred in the 1980 Mount St. Helens eruption in the western USA). Another nearby to its northeast, ("b", Figs. 4–6), seems to show most of a crater, but the rough topography just east of the crater raises the possibility that it might be debris lost from its eastern flank. Some tall cones seem to have craters at their tops (e.g., "c", Figs. 4–6). In some we might be seeing resurgent domes within the craters, such as at "c" and "f" (Figs. 4–6). Surrounding some small cones are circular moats (e.g., "g", Figs. 4, 6). In some cases large depressions with steep sides hint of collapsed calderas (e.g., "h", Figs. 4–6), though the possibility exists that other processes have formed such crater-like depressions.

There seems to be a set of linear trends in the topography with east-northeast and west-northwest orientations (Figs. 3–6). Cones line up with these orientations, but these patterns are subtle.

As noted above, Timm et al. (2010) dated many seamounts on the Chatham Rise and Campbell Plateau. Using $^{40}Ar/^{39}Ar$, they obtained a date of 14.45 ± 0.22 Ma for one seamount (Fig. 4), at the southeast end of profile A–A' (Fig. 7). They also reported a date of 2.6 ± 0.6 Ma from a nearby seamount (Timm et al. 2010, Fig. 2).

Our survey documents the presence but not the processes responsible for the Urry Knolls volcanic field. The petrology and alkaline content of both surrounding volcanic rock and a few samples from the field that we surveyed suggest that small degrees of melting occurred at relatively large depths within the lower lithosphere (e.g., Finn et al. 2005; Hoernle et al. 2006; Timm et al. 2009, 2010) and/or just beneath it. Hoernle et al. (2006) and Timm et al. (2009, 2010) associated volcanism near New Zealand with removal of mantle lithosphere and partial melting of some of it. In support of this view, Hoke et al. (2000) reported $^{3}He/^{4}He$ ratios consistent with upper mantle sources, but not enrichment associated with hotspots or plumes from the deep mantle. The occurrence of volcanism 200–300 km from the most intense deformation, along the Alpine Fault and its continuation into the Marlborough fault zone, might indicate ongoing deformation spread over a much wider zone than seems to be seismically active.

Mega-Pockmarks On The Chatham Rise

Brief Summary of Pockmark Characteristics

Since King & MacLean (1970) apparently first recognized pockmarks on the sea floor, studies in a variety of settings have shown a spectrum of associated submarine topography. At least when young, pockmarks tend to be cone-shaped, with walls sloping with constant dips of as much as 10° down to the centers where floors commonly are flat (e.g., Pilcher & Argent 2007; Uchupi et al. 1996). Older pockmarks seem to have flatter bottoms (e.g., Paull et al. 2002), and Hovland (1981) described some as “dish-shaped.” The majority of those reported in the literature seem to be circular in planform, but asymmetrical pockmarks are common (e.g., Hovland 1982; Sultan et al. 2010), and connections of them can create a variety of topographic forms, as bathymetric charts of Pilcher & Argent (2007) and Sultan et al. (2010) illustrate well.

Most associate centers of pockmarks with loci of escaped, or escaping, gas or liquids (e.g., Hovland 1981, 1982; Hovland & Somerville 1985; Hustoft et al. 2009; King & MacLean 1970; Loncke et al. 2004; Solheim & Elverhøi 1993; Sultan et al. 2010; Uchupi et al. 1996). Many such pockmarks seem to be inactive, but rising gas above some of them supports the deduction that they form when gas escapes (e.g., Hovland & Judd 1988; Hovland & Somerville 1985; Hovland et al. 1984; Loncke et al. 2004). Some believe that they form in short periods, perhaps episodically (Hustoft et al. 2009) or even catastrophically (Hovland et al. 2005). Many pockmarks are underlain by Bottom-Simulating Reflectors (BSR) (Judd & Hovland, 2007; Hovland et al. 2005), which are attributed to low-density, low-speed gas-rich layers trapped below impermeable hydrate caps. Where mapped in detail, such reflectors have been disrupted beneath the pockmarks, again consistent with a role for escaped gases (e.g., Hustoft et al. 2009; Judd and Hovland 2007). Although some pockmarks are aligned along faults where liquids and gases can escape more quickly than beneath laterally homogeneous layers (e.g., Dimitrov & Woodside 2003; Judd & Hovland 2007; Loncke et al. 2004), by no means are all associated with obvious faults.

Lateral dimensions of pockmarks range from tens of meters to several kilometers (e.g., Davy et al. 2010; Loncke et al. 2004; Pilcher & Argent 2007). Hovland & Judd (1988, p. 116) stated that there is no dependence of sizes of pockmarks on water depths. Pilcher & Argent (2007), however, show from a compilation of 57 sets of pockmarks that their depths below the surrounding terrain (their relief) are commonly roughly one tenth of the diameters of the pockmarks. Although they plotted depths versus diameter on a log-log plot, for which there is much scatter, this scaling works quite well over four orders of magnitude in both dimensions.

Pockmarks on the Chatham Rise

On the south side of the Chatham Rise, west of the Urry Knolls and south of the Mernoo Bank, where depths of seafloor range from ~750 m to 1400 m, we traversed disrupted sea floor with a wide range of dimensions, from as small as a few hundred meters to several kilometers in diameter, that resemble pockmarks (Figs. 8, 9). Walls of pockmarks are quite steep, up to 10°–12°, suggesting that they are young. Conical shapes are common but by no means ubiquitous (Figs. 8, 9). Some small cones seem to be quite symmetrical, but most are clearly asymmetrical. Some groups seem to define alignments, but no consistent alignment stands out.

In the eastern part of the mapped area (Figs. 3, 4), not only do pockmarks seem to be present, but so also is the volcanic terrain described above. Volcanism overlaps part of the region with pockmarks but not all of it.

The largest pockmarks that we mapped are among the largest that we have seen reported in the literature, though still smaller than some of those shown by Davy et al. (2010) near this region or by Loncke et al. (2004) from the Nile Delta. For example, the diameter of one along profile F–F' (Fig. 8) is ~2 km. If the large one at site "g" (Fig. 8), apparently with two volcanoes in it, is a pockmark, its diameter is >5 km. A series of others near site "h" (Fig. 8) have diameters of ~3 km. Pilcher & Argent (2007) reported the diameter of the largest in their compilation to be 1300 m, but they seemed to have been unaware of the work of Loncke et al. (2004) showing larger ones. Pilcher & Argent (2007) did note that Cole et al. (2000) reported larger pockmarks, up to 4000 m in diameter that had formed in Paleogene time and have subsequently been buried. Pilcher & Argent (2007) also emphasized, however, that these large pockmarks seem to have formed by a coalescence of smaller ones. The multiple scarps of some, like those crossed by line A–A' (Fig. 8) near 173°37'E, may imply such coalescence, but simpler ones, like that crossed by line B–B', may have formed as single features in single events. (Michaud et al. (2005) also reported large crater-like features suggesting collapse of the seafloor on the Carnegie Ridge, west of Ecuador, but they, in fact, inferred that these features are not pockmarks like those described above or shown in Figs. 3, 8.) None of those reported in published literature that we have read, or that we found, seem to be as large as those discussed by Davy et al. (2010), who show some exceeding 10 km in diameter from the region east of our study area but at shallower depths.

There is a tendency for the western sides of pockmarks in Figs. 3, 8 to be steeper than the eastern sides, which gives the pattern an asymmetry. Hovland (1982) noted a similarly consistent asymmetry, albeit in smaller pockmarks, off the west coast of Norway. We also observe many pockmarks that are not circular at all, such as those between 44°48'S and 44°50'S and between 174°35' and 174°55'. Similarly Pilcher & Argent (2007) showed troughs that might have formed by a coalescence of pockmarks where the regional topography slopes down the continental shelf. An area of linear or slightly curved pockmarks in Fig. 8 is also found where the seabed slopes, in this case toward the south.

Although the pockmarks that we mapped do not show features that have not been reported elsewhere, they do seem to be atypically large examples, comparable to those found by Pilcher & Argent (2007). We show examples of profiles across them in Fig. 9. Slopes as great as 10° do not characterize all pockmarks but many of them.

Possible Pockmarks in the Bounty Tough

Multibeam swath bathymetry profiles from the Bounty Trough collected by us and by others show what appear to be pockmarks in water depths of up to 2100 m (Figs. 10–11). The walls of some of these features have slopes of ~20°, steeper than the pockmarks that we imaged on the Chatham Rise. Pockmarks from similar depths, but of smaller diameter, have been reported from the Mediterranean (Dimitrov & Woodside 2003).

Assuming that these deep pockmarks formed by the release of gas hydrates, these depths pose a potential problem. Because the stability field of gas hydrates deepens as pressure increases, stable gas hydrates in deep water should both lie deeper beneath the sea floor than those at shallow depths, and hence they should be more immune to changes in pressure and temperature. Davy et al. (2010) argued that the pockmarks at depths of 800–1200 m and near the Urry Knolls formed by the loss of gas in peak glacial times because of depressurization during low sea level and/or during periods when bottom waters may have been warmer by 1°C. At depths of up to 2100 m, the effect of sea level change should be less important than at 1200 m, and bottom water changes are likely to have been smaller than at 1200 m. These deeper pockmarks, however, need not have formed at the same time as those shallower than 1200 m. Thus, the explanation offered by Davy et al. (2010) may not apply to the deeper pockmarks, and perhaps, the deeper pockmarks are much older than the shallower ones.

Summary and Discussion of Mega-pockmarks

Pockmarked topography characterizes the southern margin of the Chatham Rise west of the Urry Knolls. Such topography presumably reflects the exhalation of natural gas and collapse of the overlying sediment into depressions created by this loss. Although Davy et al. (2010) argued that such gas loss for pockmarks in water depths > 800 m likely occurred during peak stages of glacial periods, when sea level was lower by ~100 m, we are not aware of evidence that gas is not escaping at present, or that the pockmarks are not actively forming.

Hovland & Somerville (1985) noted two possible sources of gas. Some is biochemically produced in place from decay of organic material, and until exhalation remained where it was produced. In addition and alternatively, warming of organic material not only can accelerate decay and formation of gas, but also facilitate its migration and concentration at shallow depths. Pockmarks with this thermogenic origin seem to be much more common than those of purely biogenic origin (Cole et al. 2000; Hovland & Somerville 1985; Maestro et al. 2002; Solheim & Elverhøi 1993; Uchupi et al. 1996). The close proximity of many of the pockmarks to the volcanic terrain of Urry Knolls (Figs. 3, 6) makes a thermogenic source seem the more likely.

We refrain from speculating on what the pockmarks mean for potential gas reserves in this part of the Chatham Rise, or any of the region surrounding New Zealand, but obviously the large dimensions of them might mean that much gas has already been lost and/or that much gas remains to be found.

Deep Submarine Erosion On The Chatham Rise

The multibeam bathymetric charts in Figs. 3, 8 reveal a steep southward slope and a slightly deepened region that follows approximately the 1200 m contour. Davy et al. (2010) had recognized an erosive slope farther east, but did not report a trough. Like them, we presume this steep slope and trough to be a region of intense contour currents that have eroded sediment, or that prevented its deposition.

The deepest region on the multibeam bathymetric chart in Figs. 3, 8 is defined by a narrow zone 3–4 km wide and trending east-southeast from the southern edge of the chart near 44.95°S, 174.10°E to 44.85°S, 173.75°E. Although disrupted by pockmarks, it continues west and then west-southwestward to form an arcuate trough that becomes shallower to the west and reaches the edge of the chart near 44.95°S, 173.30°E. Although this trough does not follow contours precisely, clear disruptions by pockmarks make it likely that gas exhalation has disrupted it. Perhaps more important, the notably shallower depths north of this trough, of 1000 m and shallower, compared with those south of the trough (>1100 m) give the impression that the trough and steep slope to its north have been cut into the southern edge of the Chatham Rise at nearly a constant depth near 1200 m, as Davy et al. (2010) noted. Following their interpretation, we infer that deep-sea currents that follow contours (contour currents) have carved this trough. Of course, if this interpretation is correct, it allows for the trough to be actively forming. In contrast, Davy et al. (2010) inferred the steep slope to have formed principally by strong currents during glacial times. In the latter case, present-day ocean currents might be irrelevant to the formation of the trough.

Not surprisingly the Chatham Rise profoundly affects ocean circulation. Chiswell (2002) associated the location of the Subtropical Front, which separates Subtropical Water on the equatorial side to the north from Subantarctic Water, with the Chatham Rise. The Subtropical Front marks a sharp contrast in temperature and salinity, and also in density (Chiswell 2002; Sutton 2001). With the Subtropical Front interrupted by the islands of New Zealand, however, eastward geostrophic flow seems to be supplied by a current, the Southland Current, that flows northward along the east side of the

South Island and carries as much as 9.3 Sv (1 Sverdrup = 1 x 10^6 m^3/s) of water (Sutton 2003). All of this work, however, focused on currents shallower than 500–600 m and concentrated in the upper 300 m. Morris et al. (2001), for instance, showed 5 Sv of eastward flow in the upper 300 m along the southern Chatham Rise. Thus, the Southland Current and geostrophic flow associated with the Subtropical Front might be irrelevant for the sea-floor topographic features at depths near 1000 m, which we discuss here.

The pattern of flow implied by the Southland Current and geostrophic flow associated with the Subtropical Front is essentially opposite to that described by Carter & Wilkin (1999), who exploited oceanographic data from sections in the New Zealand area and a numerical ocean circulation model to infer a pattern of subbottom flow. For the southern side of the Chatham Rise, they reported westward flow along the bottom at depths < 2500 m, and essentially along contours. As well as we can resolve from their Fig. 5, Carter & Wilkin (1999) showed westward flow in the depth range of ~1000 m, but not with high speed (~1 cm/s). Their map, however, does not reach far enough to the west for us to be confident that the westward flow applies to the region in Figures 3 and 8. The focus on depths greater than 2500 m in the study by Carter & Wilkin (1999), the dependence on model simulations to fill in regions where data are sparse, and the low rates of flow make us dubious of the significance of this flow for features that we discuss.

McCave & Carter (1997) and McCave et al. (2008) noted that Antarctic Intermediate Water, which forms by sinking of cold water at the Antarctic Polar Front, moves northward in the depth range of c. 600–1450 m. Elderfield et al. (2010) illustrated well its distribution on a north-south profile through the Chatham Rise. Yet, because these studies focused on the region farther north, their discussion does not inform us well about circulation of the Antarctic Intermediate Water south of the Chatham Rise.

The most important data constraining flow near 1000 m may come from floats, apparently from the Argo program (e.g., http://www.argo.ucsd.edu/About_Argo.html). In their Fig. 2, Morris et al. (2001) showed eastward flow along the 1000 m contour.

They based this largely on trajectories of floats at a depth of ~900 m. Paleoceanographic studies replicated a figure similar to theirs, with an arrow showing eastward flow approximately along the 1000 m contour (e.g., Crundwell et al. 2008; McCave et al., 2008), but those papers do not discuss the arrow.

We deduce that sufficiently rapid eastward flow along the contours near 1000–1200 m during the past few hundred thousand years has created this trough by preventing sedimentation and by eroding older sediment. When that erosion is or was most intense might have been in glacial times as Davy et al. (2010) suggested, but in light of published studies that we have read, we remain agnostic.

Conclusions

New multibeam seafloor mapping offshore the east coast of the South Island of New Zealand reveals a complex pattern of seafloor volcanoes, seafloor depressions (pockmarks), and seafloor erosion. The seafloor volcanoes are far from the nearest plate boundary, suggesting a broad area of plate boundary deformation or a secondary mechanism such as lithospheric removal. The proximity of the seafloor pockmarks, thought to be the result of natural gas escape, to the seafloor volcanic field suggest a thermogenic origin for the pockmarks. On the southern margin of the Chatham Rise, a 3–4 km wide arcuate trough near 1200 m depth may have been eroded by contour currents.

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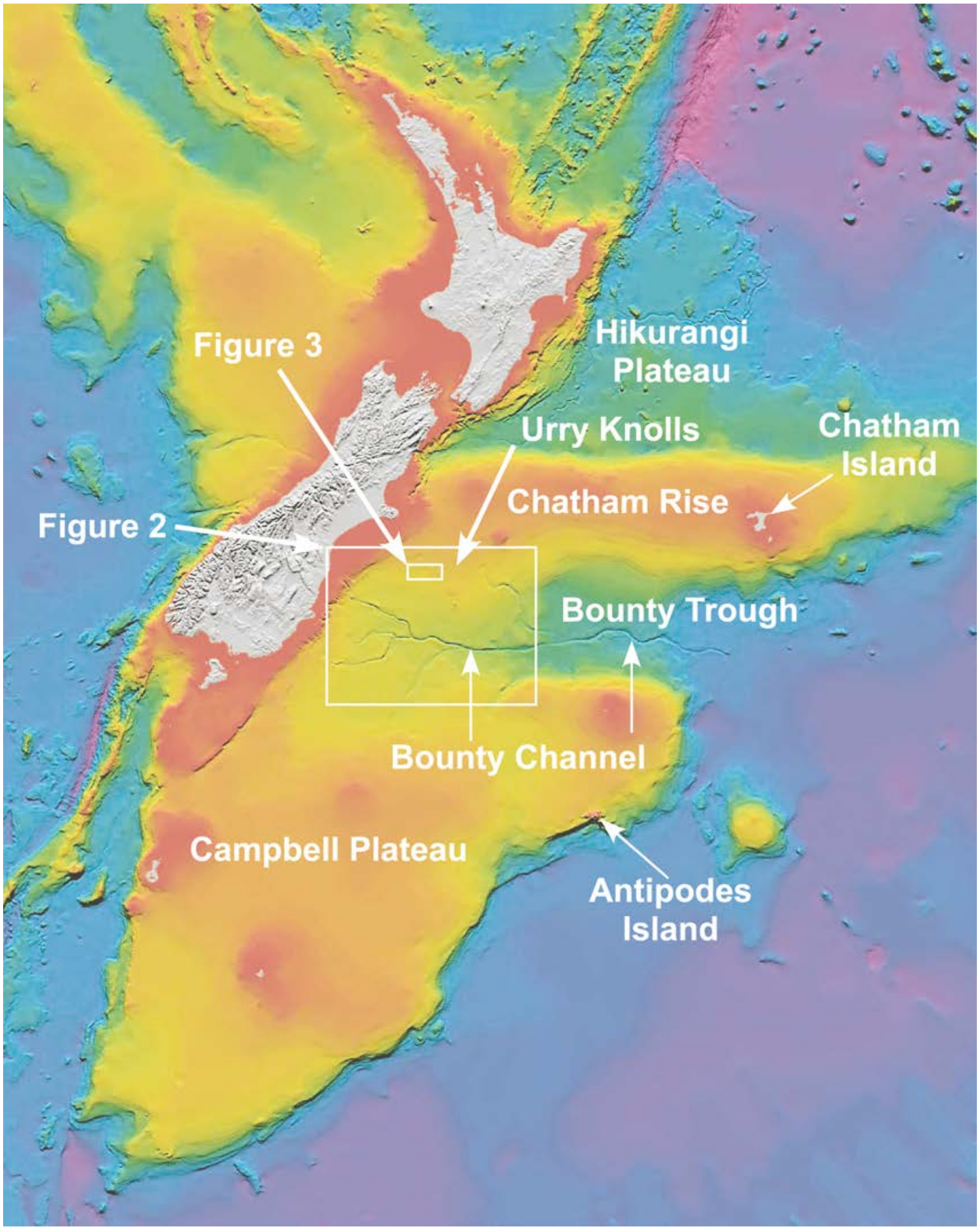

Fig. 1 Regional bathymetric chart of the region surrounding New Zealand showing the locations of the multibeam surveys discussed in the text. Boxes show the areas in Figs. 2-3. This chart (CANZ, 2008) was cropped from one provided by New Zealand's National Institute of Water & Atmospheric Research (NIWA). Content, datasets and imagery are provided by NIWA. Used with permission of NIWA.

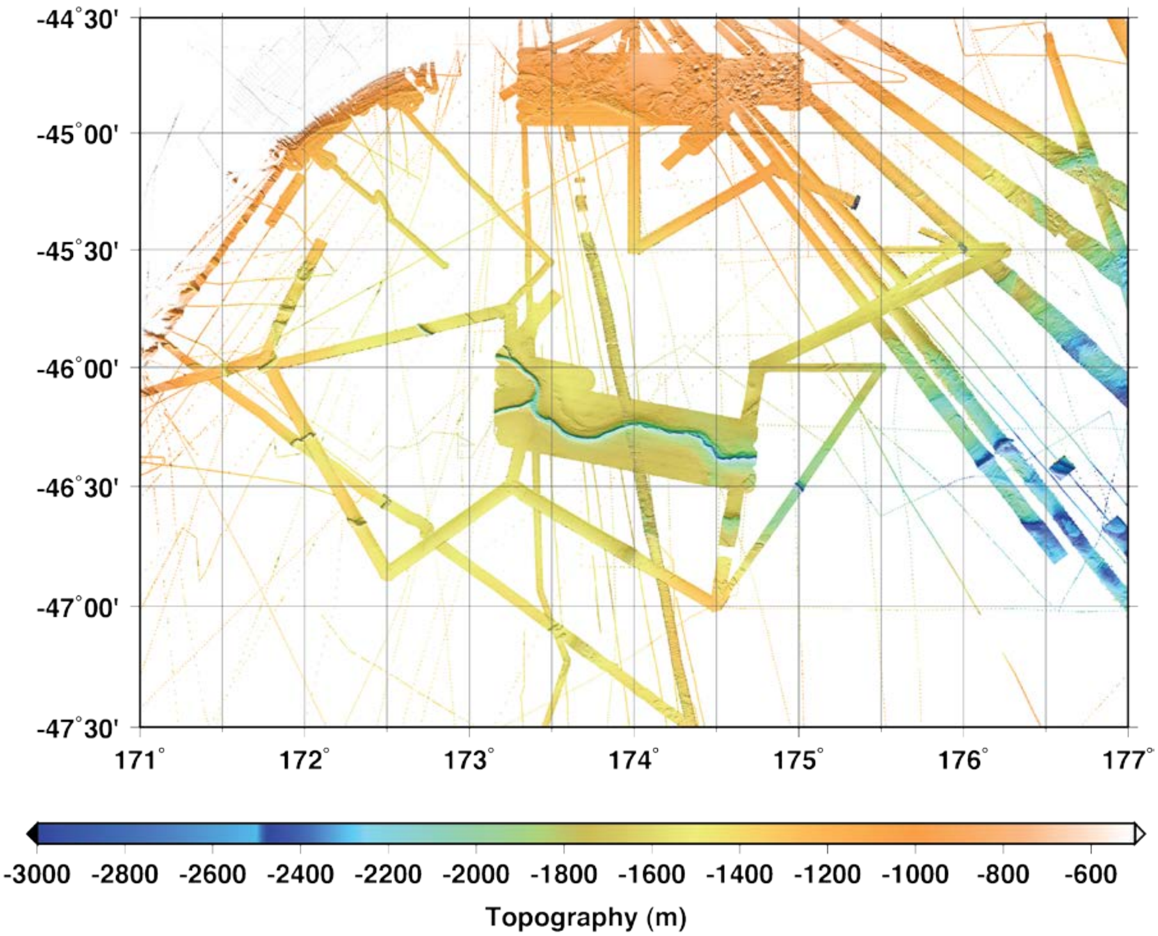

Fig. 2 Map showing all multibeam profiles, including those in Figs. 3-6, 8, 10, and others gathered in previous cruises.

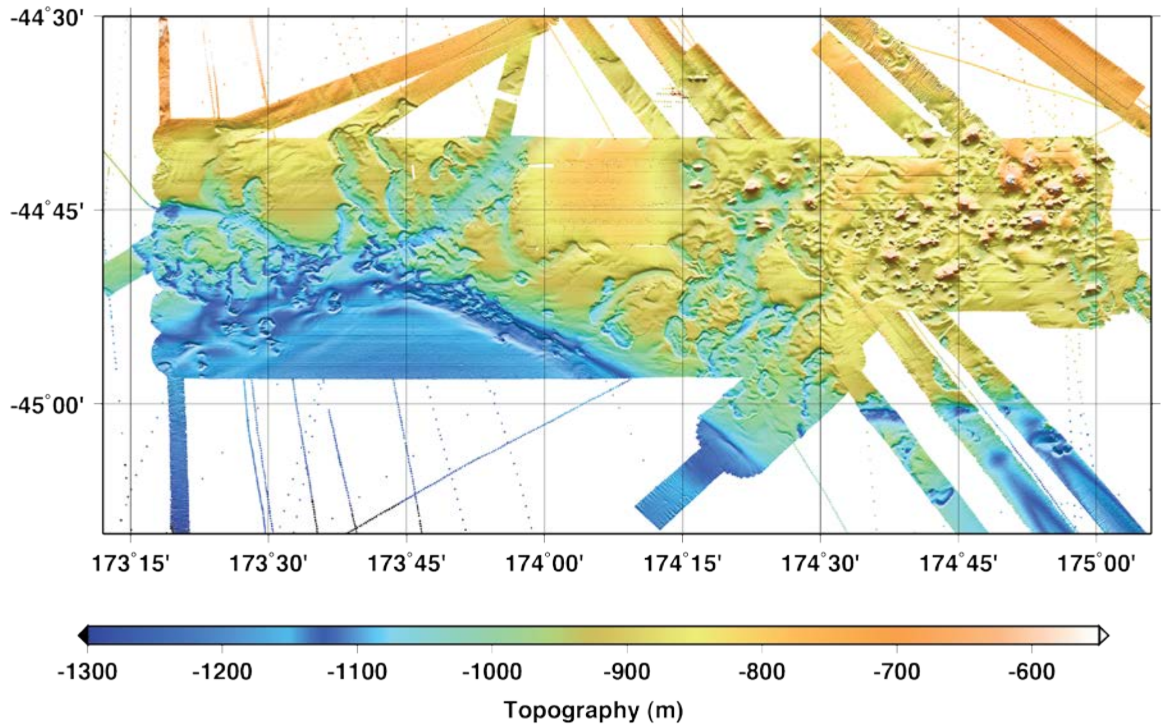

Fig. 3 Multibeam bathymetry of a portion of the Chatham Rise showing pockmarked and volcanic terrain. These data were collected largely during the MOANA deployment (cruise TN229) and recovery cruises (cruise RR1002), with some lines from other historical cruises.

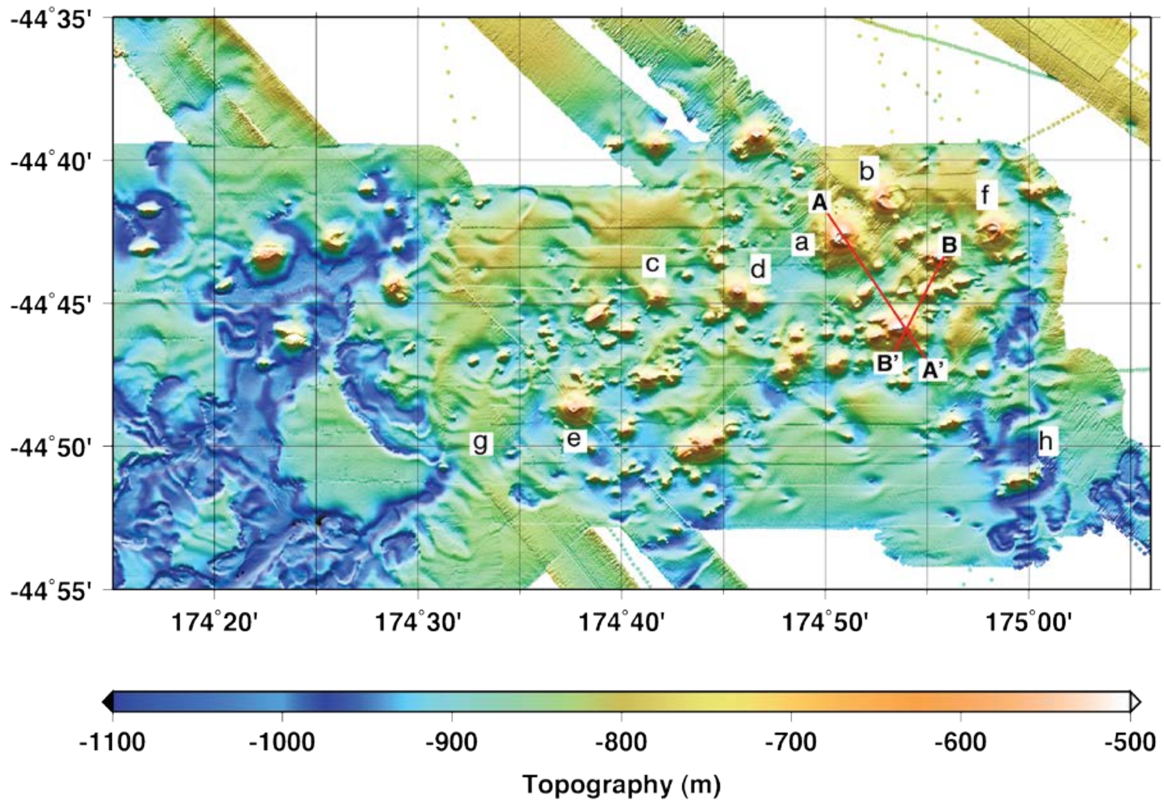

Fig. 4 Shaded relief and bathymetric chart of the volcanic field near Urry Knolls. Cross-sections along the profiles A–A' and B–B' are shown in Fig. 7. Specific bathymetric features discussed in the text are labeled with lower case letters.

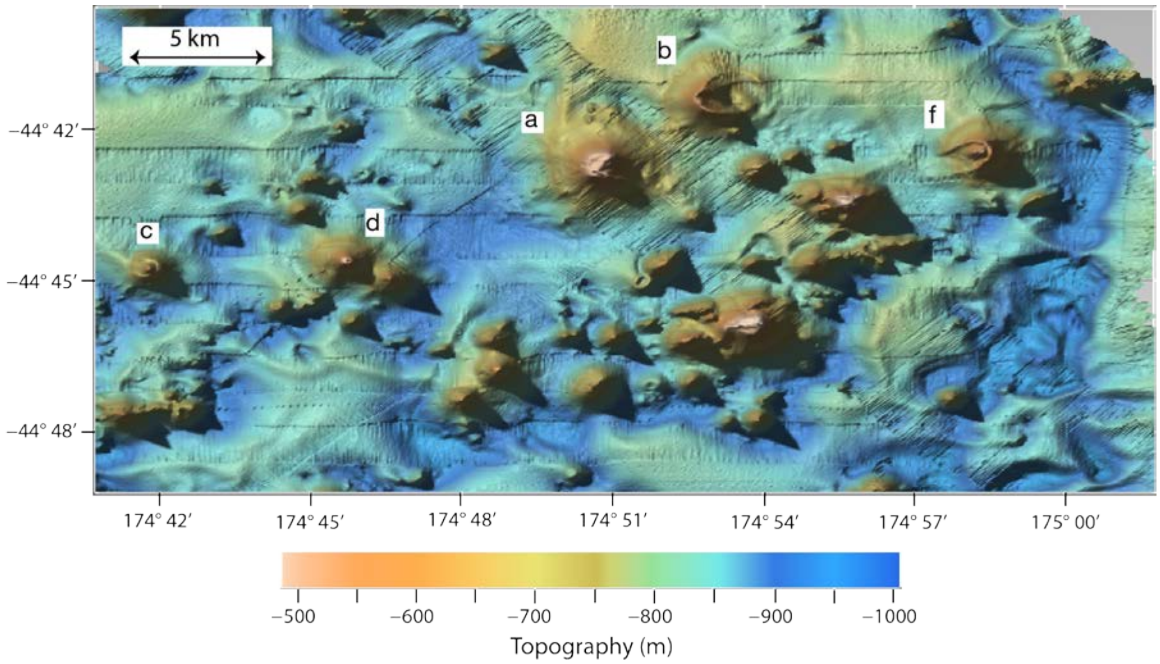

Fig. 5 Plan view of volcanic cones located in the north-east of our surveyed area. Note the apparent flank collapse features on at least three of the cones. Volcanic features discussed in the text are labeled with lower case letters.

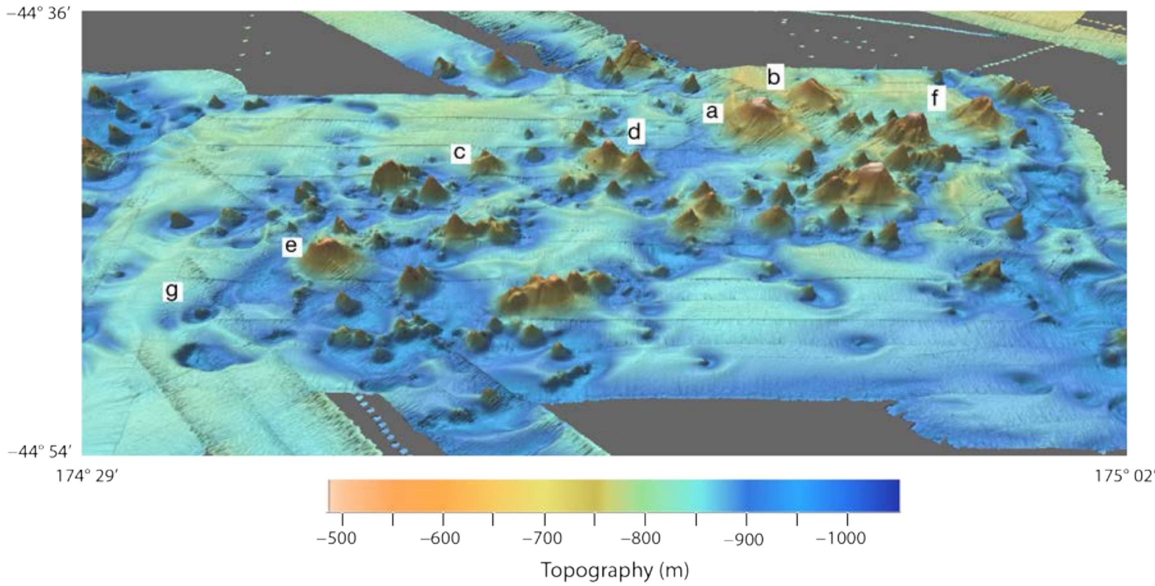

Fig. 6 Oblique view, looking north, at a vertically exaggerated (x6) relief map of the volcanic field near Urry Knolls. Volcanic features discussed in the text are labeled with lower case letters.

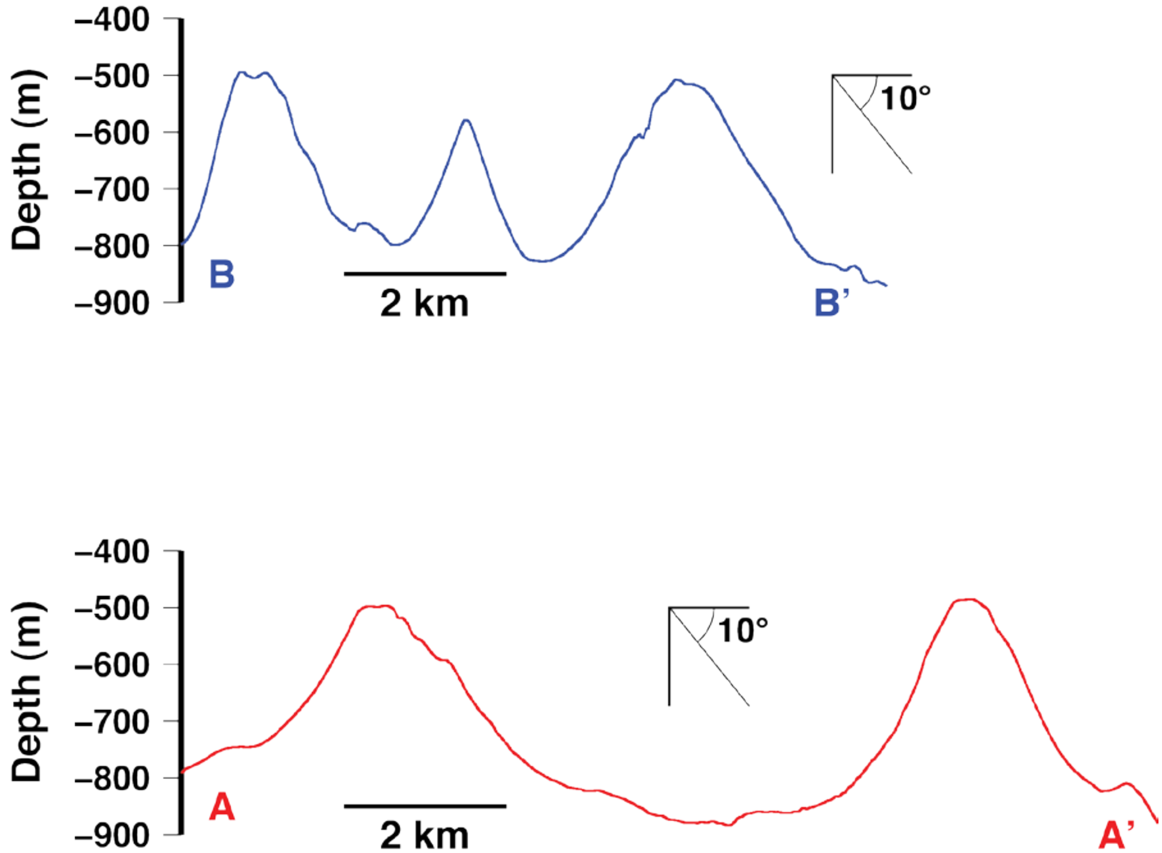

Fig. 7 Profiles across volcanoes near Urry Knolls. Profile locations are shown in Fig. 4.

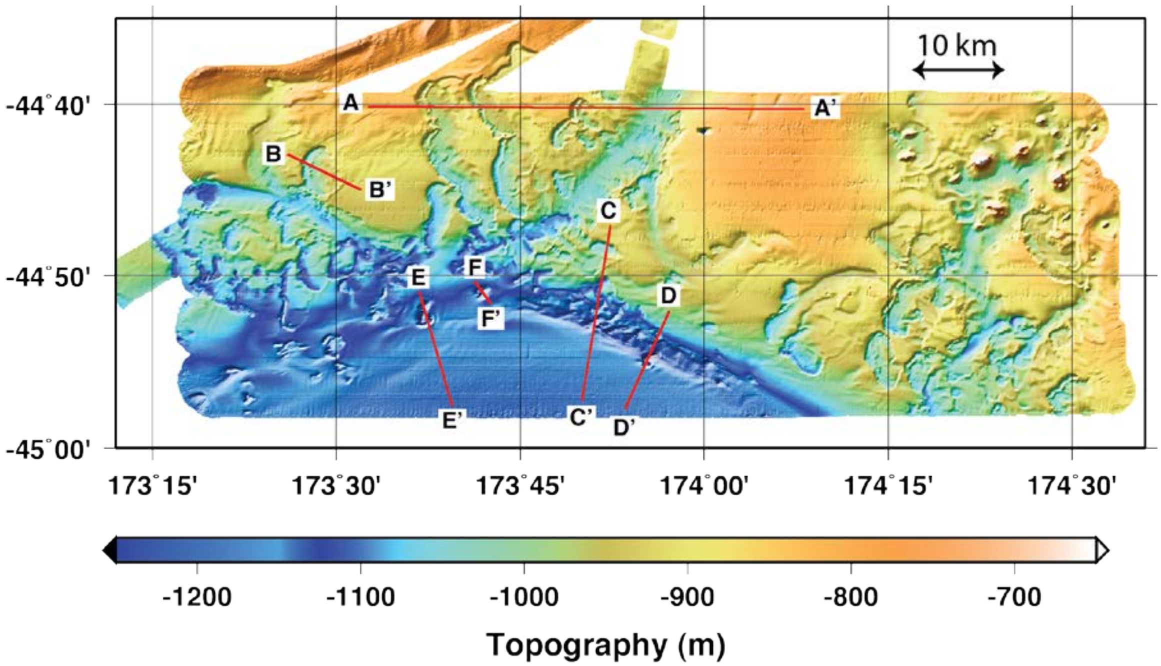

Fig. 8 Close-up view of multibeam bathymetry in Fig. 3 showing pockmarked terrain and the locations of the profiles shown in Fig. 9. Pockmark features discussed in the text are labeled "h" and "g".

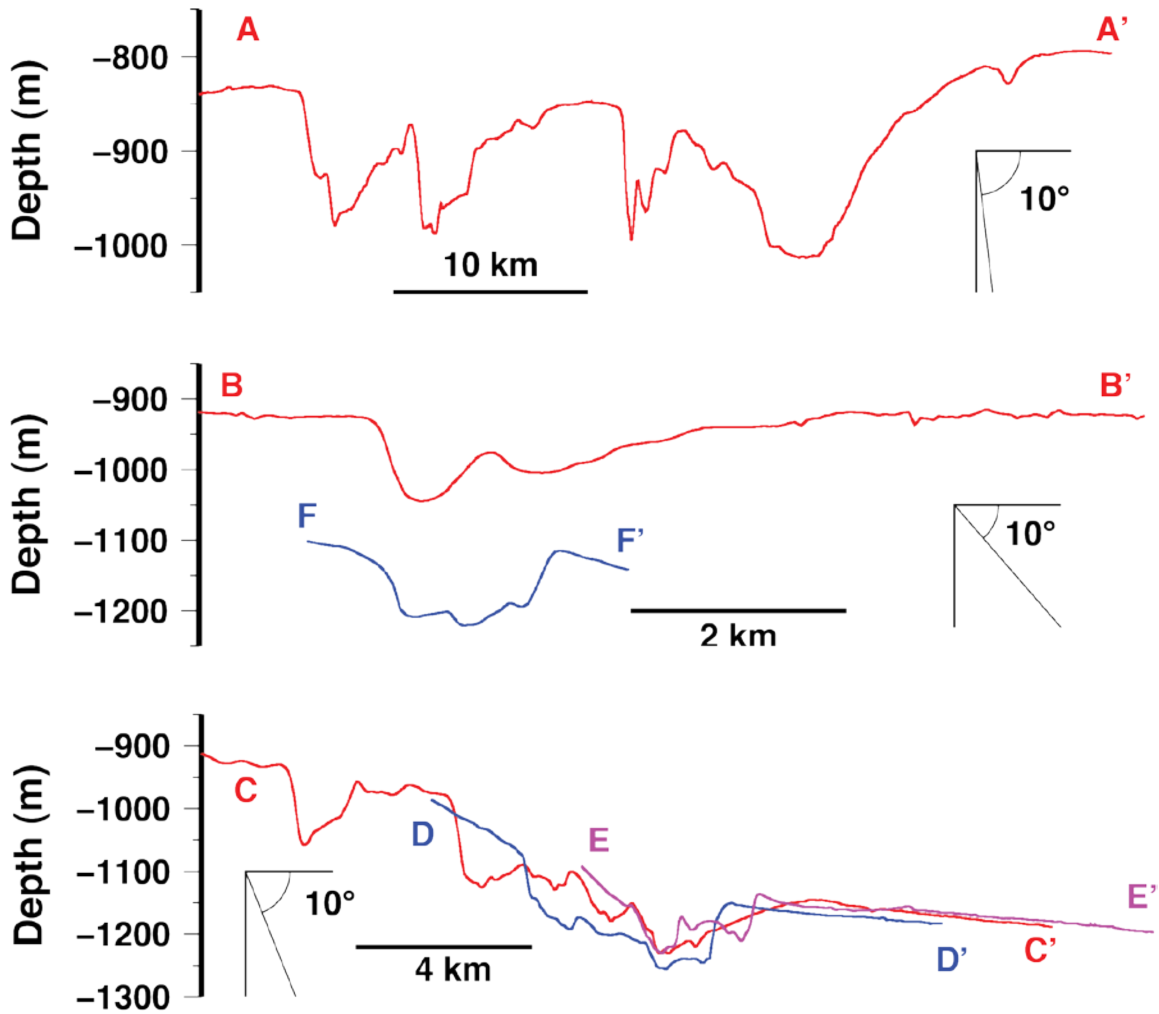

Fig. 9 Profiles across selected pockmarks showing slopes, shapes of bottoms, and both symmetry for some and asymmetry for others. Profile locations are shown in Fig. 8.

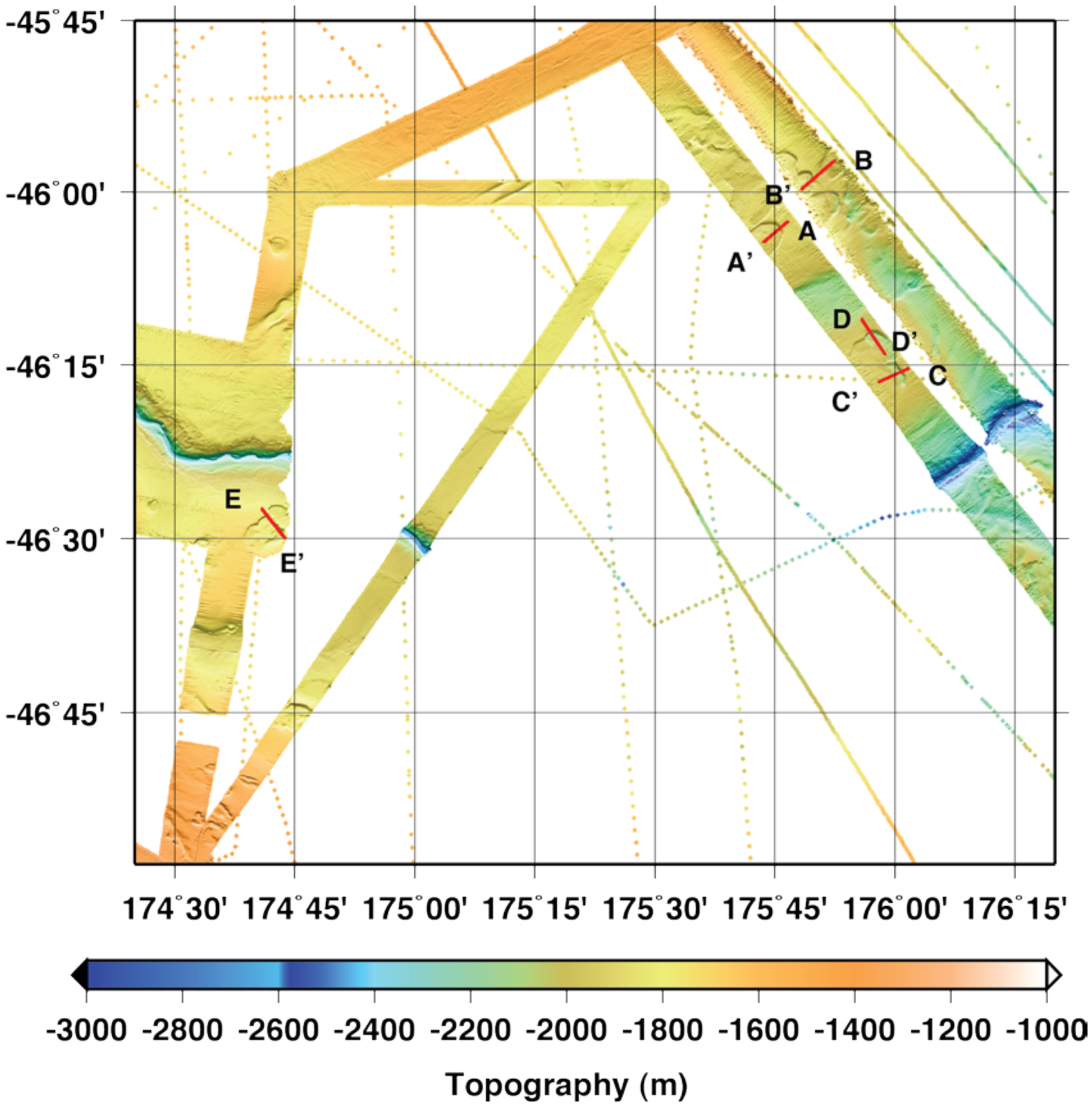

Fig. 10 Multibeam data from the Bounty Trough acquired during cruises TN229, RR1002, and earlier cruises. The locations of the profiles shown in Fig. 11 are indicated by the red lines.

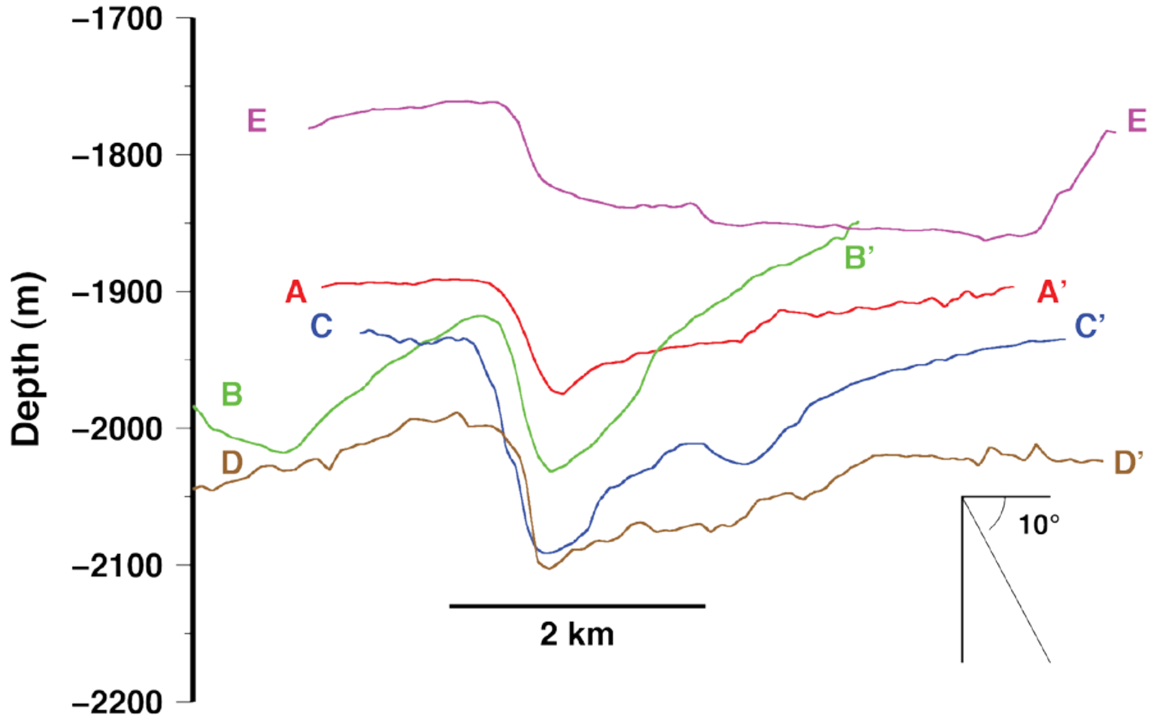

Fig. 11 Profiles across selected possible pockmarks in the Bounty Trough. Locations of profiles are shown in Fig. 10.