

# **Seamounts, Submarine Channels, and New Discoveries**

**Benefits of Continental Shelf  
Surveys Extend Beyond Defining  
the Limits of the Shelf**

**by Andrew Armstrong,  
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## Introduction

Article 76 of the United Nations Convention on the Law of the Sea provides that “the continental shelf of a coastal State comprises the seabed and subsoil of the submarine areas that extend beyond its territorial sea throughout the natural prolongation of its land territory to the outer edge of the continental margin, or to a distance of 200 nautical miles from the baselines from which the breadth of the territorial sea is measured where the outer edge of the continental margin does not extend up to that distance.” The Article further provides formulae and constraints for delineation of a state’s continental margin that include, among others, outer limits based on the location of two bathymetric features – the 2,500-m isobath and the “foot of the continental slope.”

In 2001, the Center for Coastal and Ocean Mapping/Joint Hydrographic Center (CCOM/JHC) at the University of New Hampshire (UNH) was funded by the National Oceanic and Atmospheric Administration (NOAA) to undertake a desktop study to determine where there might be potential for the US to delineate its continental shelf beyond 200 nautical miles, and what additional data might be required to support such delineation. In May 2002, the authors of the study – Mayer, Jakobsson, and Armstrong – identified several areas of potential extended continental shelf (ECS) and recommended a campaign of “modern, high-density, complete coverage” multibeam echo sounder mapping in those areas where potential delineation depends on location of either the foot of the slope or the 2,500-m isobath. Areas in Alaska, the coterminous US and the US Pacific Islands were identified as potential regions of interest.

The US ECS bathymetric mapping effort that followed the UNH desktop study constitutes one of the largest, if not the largest, civil ocean mapping projects ever undertaken. The first multibeam mapping cruise took place in the Bering Sea, north of Alaska’s Aleutian Islands, during the summer of 2003. Since then, NOAA’s Office of Coast Survey and

their academic partners at UNH’s CCOM/JHC have led 24 cruises on 12 different vessels spending more than 700 days at sea and mapping approximately 2.3 million square kilometres of seafloor on the US continental margins. Mapping is continuing with expeditions to the Atlantic margin and Pacific Islands this year (2015), and additional cruises to the Pacific Islands in 2016.

Although the limits of the continental shelf have not yet been determined for any US area, many of the regions that have been mapped certainly have ECS. The presence of ECS in some other areas remains uncertain. But regardless of whether there may be ECS or not, all the projects have yielded stunning maps of the seafloor that include new discoveries, provide a source of enhanced scientific insight, support more accurate nautical charts, and offer a foundation for improved identification and management of living and non-living marine resources. As significant as the potential for delineating extended areas of sovereign rights is, in the long term the additional benefits from the ECS mapping may well exceed those of their primary role in locating Article 76-relevant bathymetric features.

## The Bering Sea

In the Bering Sea, the project team mapped two opposing areas of the margin in 2003 with a Reson 8150 12-kHz multibeam system mounted on the RV *Davidson*. The two areas include the south face of the Beringian margin and the north flank of Bowers Ridge. The Beringian margin (Figure 1) provided the first example from the project of how much more could be seen with modern full-coverage multibeam mapping than was available from the existing compilations of trackline data and satellite-altimetry-derived bathymetry, such as those from W.H.F. Smith and D.T. Sandwell published by the Scripps Institution of Oceanography.

## The Arctic

US bathymetric mapping for ECS purposes in the Arctic Ocean began with a 10-day proof-of-concept cruise aboard the US

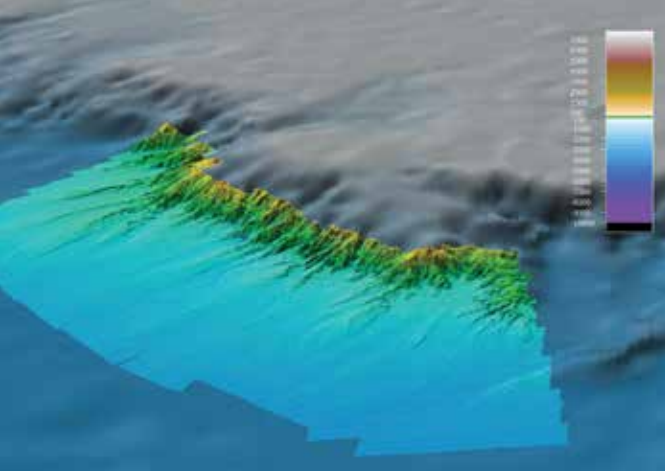


Figure 1: Detailed bathymetry of the Beringian margin – background bathymetry in muted colours from Smith and Sandwell. The background bathymetry shows the resolution and seafloor detail available before the multibeam mapping.

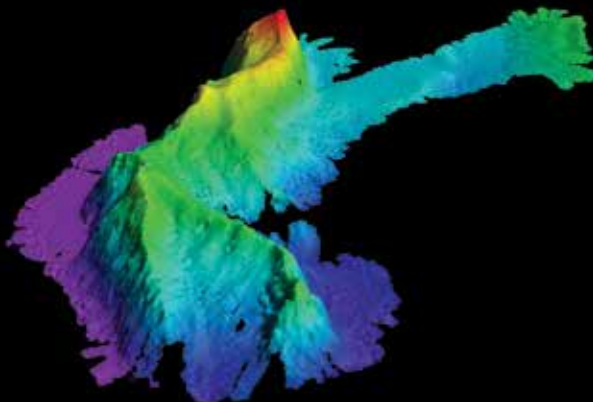
Coast Guard Cutter *Healy*, a medium-duty research icebreaker equipped at the time with a SeaBeam 2112 12-kHz multibeam echo sounder. The goal of this initial cruise was to demonstrate that a multibeam-equipped icebreaker could collect bathymetric data of suitable quality while breaking thick sea ice and maintaining a purposeful track – in this case, a track along the 2,500-m isobath. Since only the general location of the 2,500-m isobath was known in this virtually uncharted region of the ocean, this mission required the survey team to anticipate the trend of the bathymetry and direct the icebreaker's track in real-time. Success of the mission also depended upon the *Healy's* ability to remain on a directed, rather than ice-breaking optimal, track through the ice and for the

multibeam system to acquire useful data in these sonar-challenging conditions. Although other multibeam-equipped icebreakers had collected sounding data previously, these data had typically been collected along whatever track the ship followed.

Despite the short duration of this first Arctic cruise, the existing bathymetric compilation of the Arctic, the International Bathymetric Chart of the Arctic (IBCAO), was significantly improved and a large, previously unknown seamount was discovered and mapped (Figure 2). In honour of the ship and its namesake, Captain Mike Healy of the US Revenue Cutter Service, the new discovery was named Healy Seamount. In the years since 2003, the NOAA/UNH team has led eight additional mapping cruises to the Arctic Ocean, all aboard *Healy*, and has been one of the largest contributors to the constantly improving IBCAO compilation. In 2007, the team mapped a large field of pockmarks (Figure 3) and nearby, a field of ice sheet-derived, mega-scale lineations and bedforms on the Chukchi Plateau.

Pockmarks on the seafloor indicate the vertical escape vents of fluid and/or gas from the sediment. The Chukchi Plateau is known to be continental in origin, and methane is the likely gas that caused these pockmarks. The individual pockmarks have a 200-m diameter and typically are 20- to 40-m deep. They

Figure 2: The Healy Seamount abruptly rises 3,000 m from the ocean floor to about 925 m of depth.



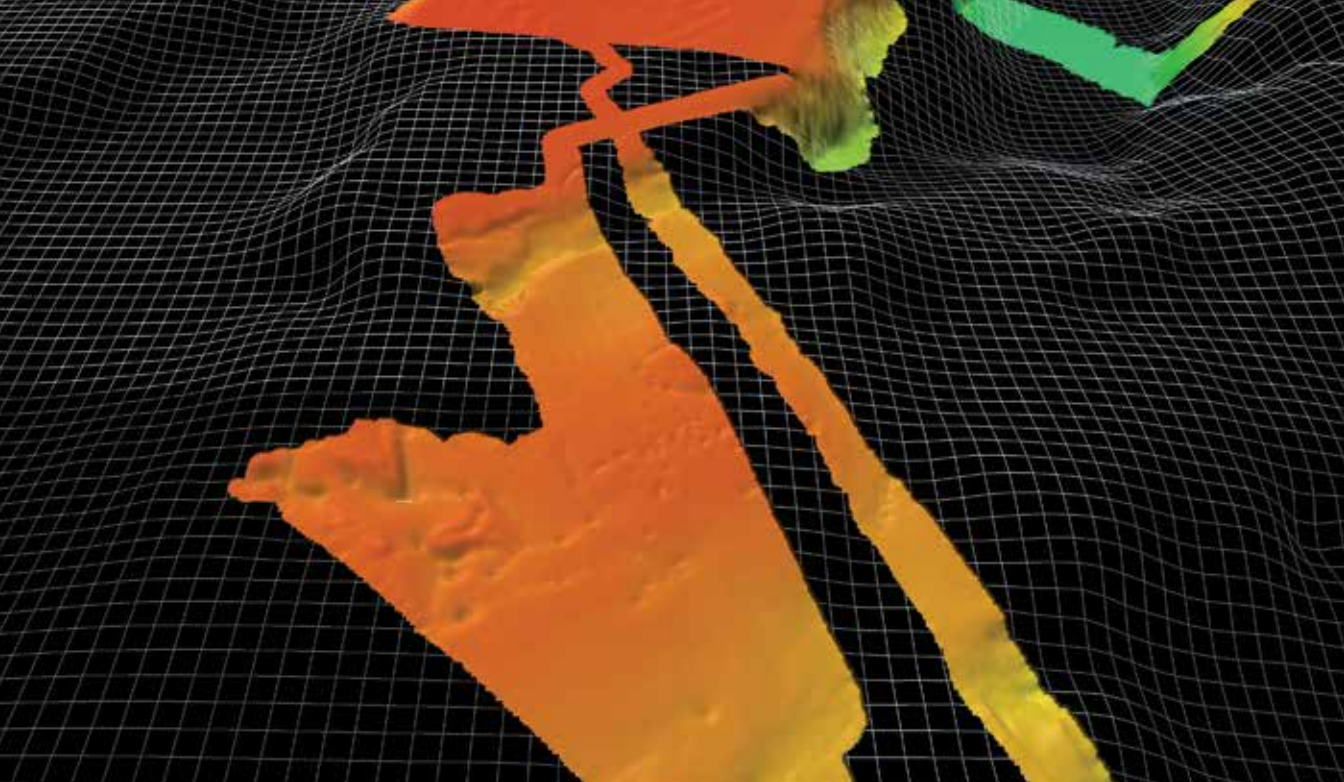


Figure 3: A perspective view, looking north, of gas pockmarks on the surface of Chukchi Plateau. The vertical exaggeration is 5x. Water depth range in the foreground of the image is 380 m to 900 m. IBCAO bathymetry in wireframe.

occur in both random patterns and in linear and circular patterns. Some appear to have coalesced into larger depressions. When the pockmarks were formed, and whether or not they are still active, is yet to be established. The very large field of mega-scale lineations and bedforms is just north of the pockmarks. The mega-scale lineations (Figure 4) are oriented in a southeast to northwest direction and are attributed to formation by an ice sheet rather than icebergs because of their coherent nature. Iceberg scours are typically random in direction and length, whereas these scours are parallel across the entire field, indicating that an ice sheet that was at least 500-m thick once covered and moved across this area 750 km from the present Alaska shoreline. The large bedforms of the field are likely related to flow associated with the ice sheet that caused the mega-scale lineations.

Farther north, on the northern slope of the Chukchi Borderland, between latitude 79° N and 80° N, the mapping team discovered what may be the highest latitude, large, deep-seafloor channel system on Earth (Figure 5).

These data were collected with a Kongsberg EM 122 12-kHz multibeam echo sounder that replaced the SeaBeam system on the *Healy* in 2010. The main channel begins in the western portion of the northern Borderland, and runs eastward for about 160 km, descending 500 m downslope to the Canada Basin abyssal plain. Tributary channels join in several locations, and some tributary channels have hanging walls where joining the main channel, indicating that they have been cut off by the main channel after formation earlier in time.

### The North Atlantic

Eight cruises have been completed along the US Atlantic margin, from offshore of Florida to offshore of Maine. These mapping cruises have been led by the NOAA/UNH team aboard vessels from the US Naval Oceanographic Office, the University National Oceanographic Laboratory System (UNOLS), and NOAA. The vessels were equipped with either a Kongsberg EM120, EM121 or EM122 12-kHz multibeam echo sounder. The Atlantic margin has been much better studied and mapped in the past than most other continental margins in the

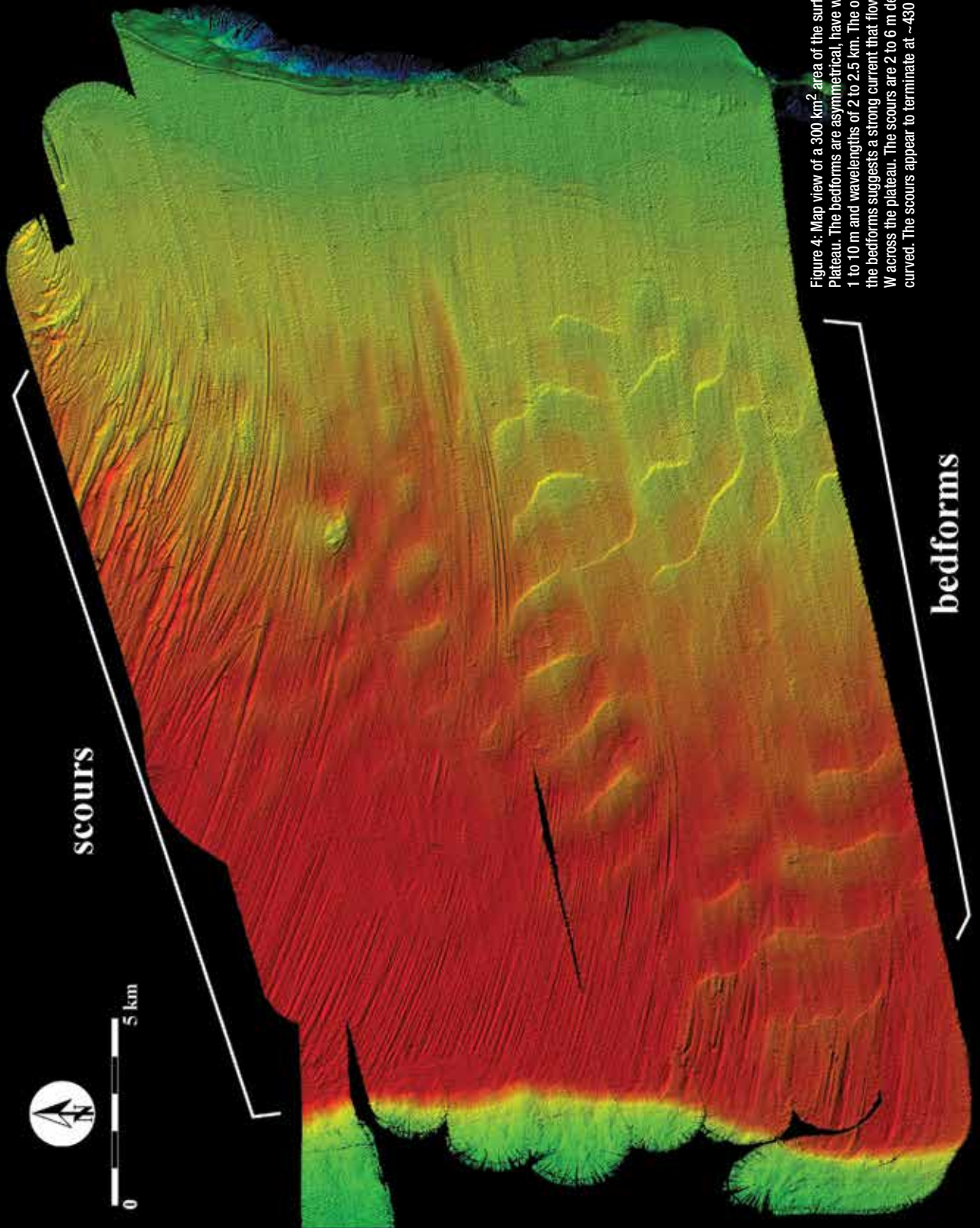


Figure 4: Map view of a 300 km<sup>2</sup> area of the surface of Chukchi Plateau. The bedforms are asymmetrical, have wave heights of 1 to 10 m and wavelengths of 2 to 2.5 km. The orientation of the bedforms suggests a strong current that flowed from E to W across the plateau. The scours are 2 to 6 m deep and slightly curved. The scours appear to terminate at ~430 m water depth.

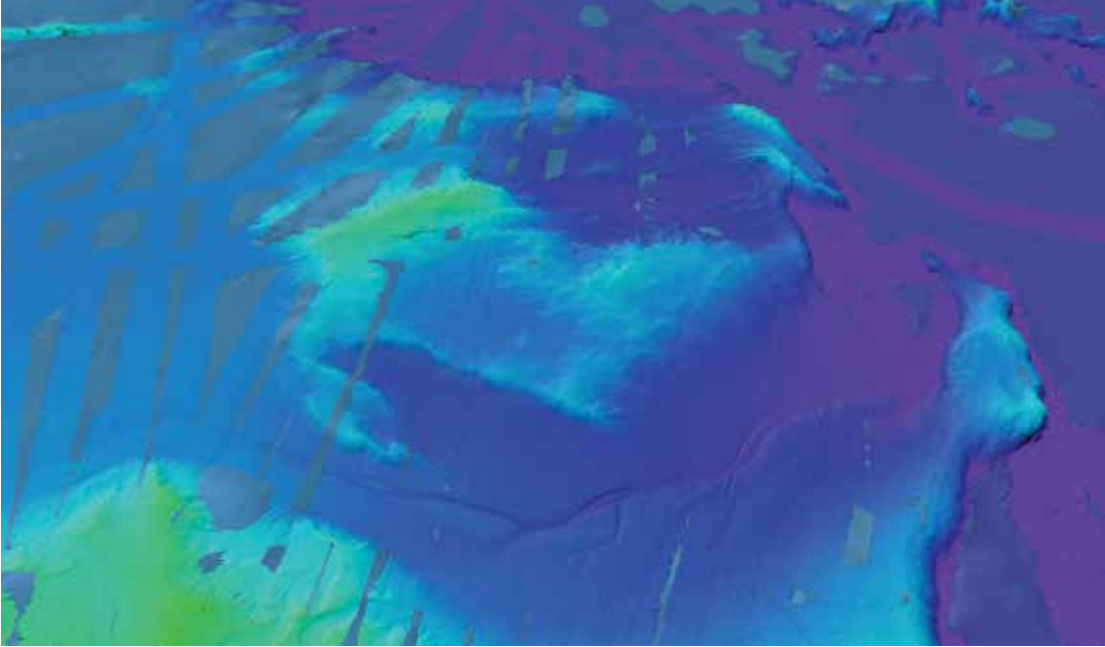


Figure 5: The channel in northern Chukchi Borderland is 160-km long, 300- to 1,500-m wide, and as much as 40-m deep in water depths of 3,300 to 3,800 m. Perspective view, looking north. The image is centred at latitude 80° N, longitude 160° W.

world. Nonetheless, the contrast between pre-existing seafloor maps and the maps produced in this project is substantial, with new data that provides valuable information for multiple uses.

The mapping completed for ECS evaluation was primarily on the continental slope seaward of the 2,000m isobath. However, an innovative coordinated partnership involving the NOAA Ocean Exploration Program, Deep Sea Coral Program, Ocean Service, and Fisheries Service; the Bureau of Ocean Energy Management; the US Geological Survey; and academic partners resulted in extension of the survey to include the outer continental shelf and upper continental slope, and resulted in complete, high-resolution maps of the slope and rise from the shelf break to the abyssal plain. The new maps show, in great detail, the Atlantic canyon heads and upper reaches, and their downslope channels along with associated submarine landslide scarps, slide deposits and debris flow lobes. These data have been used in tsunami risk assessments for the US East Coast and as supporting data that contributed to the US Mid-Atlantic Fishery Management Council's recommendation for new bottom-fishing exclusion zones to protect the fragile cold-water coral habitat within the submarine

canyons and continental slope from bottom-tending fishing gear (Figure 6).

The ECS mapping of the western New England Seamounts provided motivation for additional mapping of those features by NOAA's Office of Ocean Exploration with the NOAA Ship *Okeanos Explorer* using a Kongsberg EM302 30-kHz multibeam. The combined mapping project provides new high-resolution maps of the western section of the New England Seamount Chain (Figure 7). The Office of Ocean Exploration notes that "the New England Seamounts are 'islands' of hard rock substrate on an otherwise sediment-covered abyssal plain. They are exposed to upwelling as ocean currents move over and around them. These physical characteristics result in unique and isolated habitats for a wide variety of marine species. Of particular note is the abundance and diversity of deep sea corals on the seamounts."

### The Gulf of Alaska

The Gulf of Alaska off the west coast of North America is another region where the ECS mapping project, with two cruises aboard the University of Hawaii's RV *Kilo Moana*, used a Kongsberg 12-kHz system to reveal seafloor channels in striking detail. Canyons and canyon channels of the deep seafloor are a ubiquitous

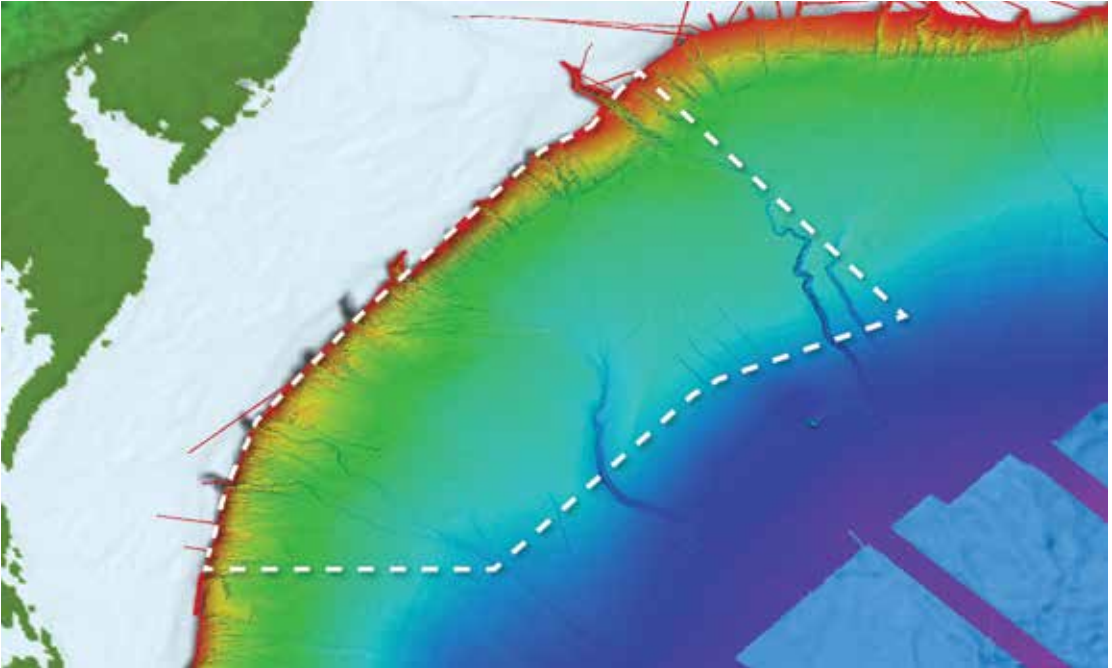


Figure 6: Mid Atlantic canyons and channels on continental slope; this image shows the approximate region of areas proposed for bottom-fishing limitation (dashed white polygon). Steep-sloped canyon faces are considered prime cold-water coral habitat. Background bathymetry from Smith and Sandwell.

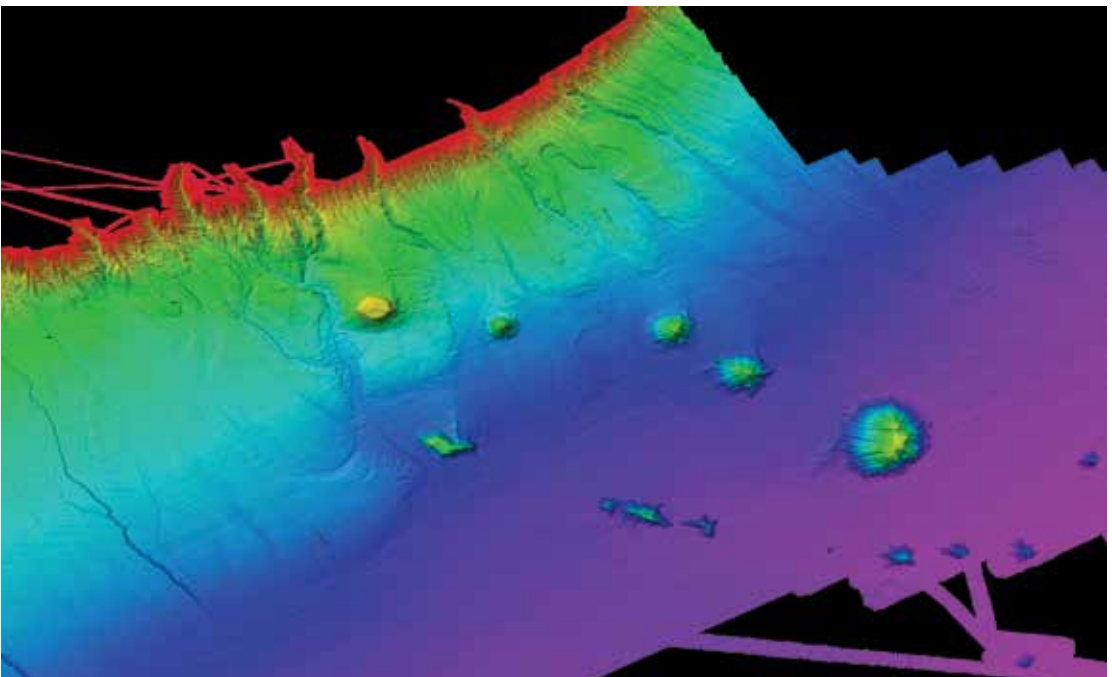


Figure 7: New England seamounts, canyons and channels, downslope flow, landslide scarps, and debris flows. Water depths in this image range from 100 m to 5,000 m.

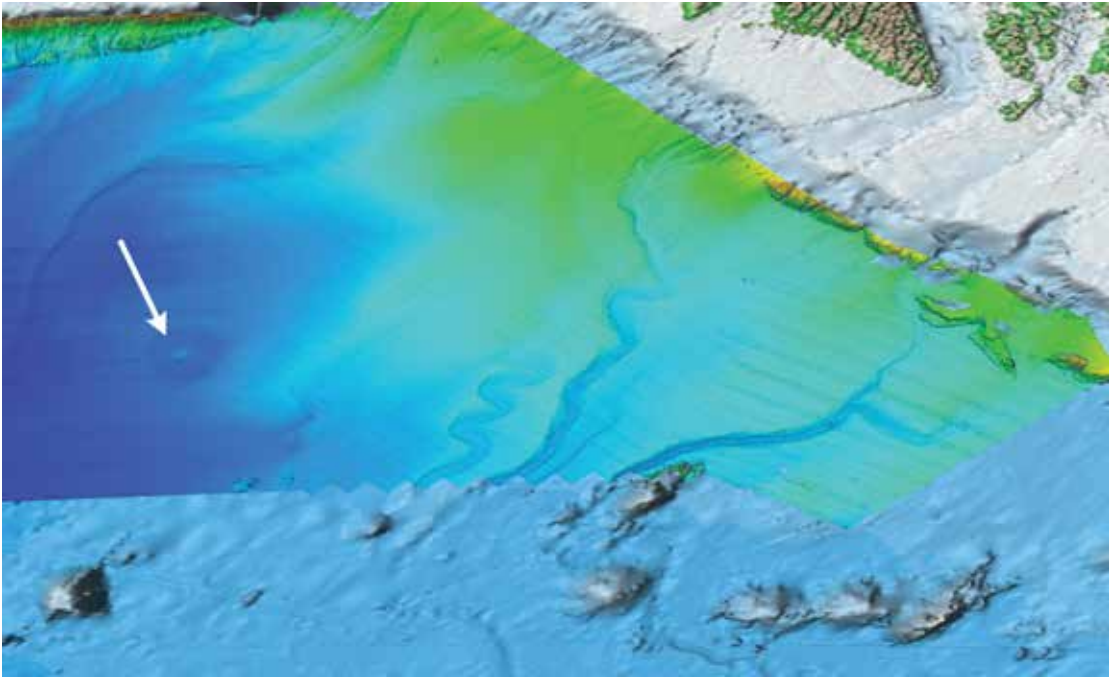


Figure 8: The Baranof Fan and associated channels in the western Gulf of Alaska. High resolution multibeam data contrast with previously available general seafloor compilation from Smith and Sandwell. White arrow points to moat that surrounds mostly buried seamount.

feature of continental margins that are only fully revealed with high-resolution full-bottom mapping. Although global seafloor compilations such as the ETOPO series and the Smith and Sandwell satellite altimetry-derived bathymetry hint at the presence of channels, they lack detail. In the Gulf of Alaska, multiple channels spill off the shelf off Baranof Island and Chatham Strait to the deep sea (Figure 8). Glacially-scoured sediment from the continent has built a complex network of interacting fans, channels, and levees on the margin. In the Baranof Fan area, a large, very sinuous channel has been created by flow that has cut into the levee of an adjacent, probably older, channel. Farther offshore and to the west at the fringes of the fan system, a moat has formed around a seamount mostly buried by sediment from the continent.

### The Mariana Islands

The Mariana Islands area comprises the US Territory of Guam and the Commonwealth of the Northern Mariana Islands. Guam and the Northern Marianas are volcanic islands that rise from the Mariana Arc. The Mariana Trench borders the eastern and southern

margin of the Mariana Arc, and the Mariana Trough and West Mariana Ridge lie to the west. Four cruises of 30 days each were devoted to the Mariana Islands region, two focused on the West Mariana Ridge, one on the eastern margin and trench, and one on the southern margin and trench. For these cruises, the NOAA/UNH team worked with the US Naval Oceanographic Office and carried out the mapping from US Navy-owned T-AGS 60 class oceanographic vessels equipped with EM 121 or EM 122 12-kHz multibeam echo sounders. Twelve-kHz multibeam sounders are marketed as “full-ocean depth” systems, and that characterization was tested on this project. The greatest depth in the ocean lies in the Challenger Deep of the Mariana Trench (Figure 9), and in mapping the entire Trench, a new value of 10,984 m +/- 25 m for the deepest depth in the ocean was established. Along both the eastern and southern portion of the Mariana Trench, seamounts and guyots on the Pacific tectonic plate are being accreted to the Mariana margin or subducted into the Mariana Trench as the Pacific Plate



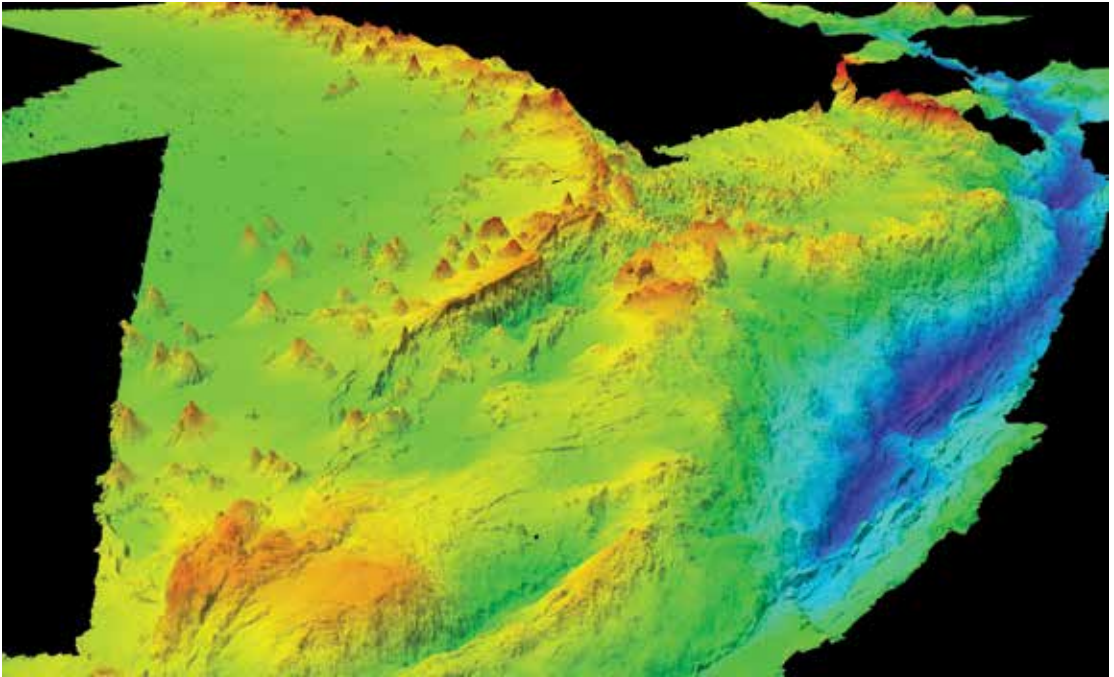


Figure 9: Perspective view from the southwest of the Challenger Deep (violet tint) and southern end of the Mariana Trough and West Mariana Ridge. Depths in image range from 50 m to 10,984 m.

slowly subducts beneath the Philippine Plate on which the Mariana Islands reside. The subduction process creates a series of faults through the subducting Pacific Plate and seamounts. These faults are clearly visible and can be accurately plotted and traced in the multibeam data set.

The Western Mariana Ridge also appears to have been tectonically and perhaps volcanically active in the recent geologic past. A large fault scarp with 3,500 m of vertical relief defines the southern end of the ridge, and the flat seafloor at the top of the scarp, like the entire western ridge, is topped with scores of conical volcanic seamounts. The steep slopes of these seamounts and their proximity to the surface indicate fairly recent formation. Some of these seamounts rise to within 30 m of the sea surface and constitute significant hazards to surface and submarine navigation. The Mariana ECS surveys have been applied to the nautical charts of the area, replacing data from a variety of sources of uncertain reliability, and greatly improving the safety of navigation for the region.

The West Mariana Ridge is also an area characterized by a complex channel system that has distributed sediment eroding from the volcanic seamounts to the deep sea (Figure 10). These channels, like others mapped in the ECS project, incise an extensive apron of sediment fans and downslope debris flows.

### **Mendocino Ridge**

Mendocino Ridge on the US Pacific coast margin is another site of spectacular volcanic seafloor. The ridge extends continuously from the continent many hundreds of kilometres to sea. The ECS project team, in partnership with the NOAA Office of Ocean Exploration, has mapped the ridge out to more than 900 km from shore. Data for this project were acquired from the NOAA Ship *Okeanos Explorer* and the Woods Hole Oceanographic Institution RV *Atlantis*, using Kongsberg EM 302 30-kHz and EM 122 12-kHz multibeam systems, respectively. Beginning with an oversized volcanic structure about 440 km from shore, the north side of the ridge is characterized by a series of “J-structures” (Figure 11) that originate at the ridge

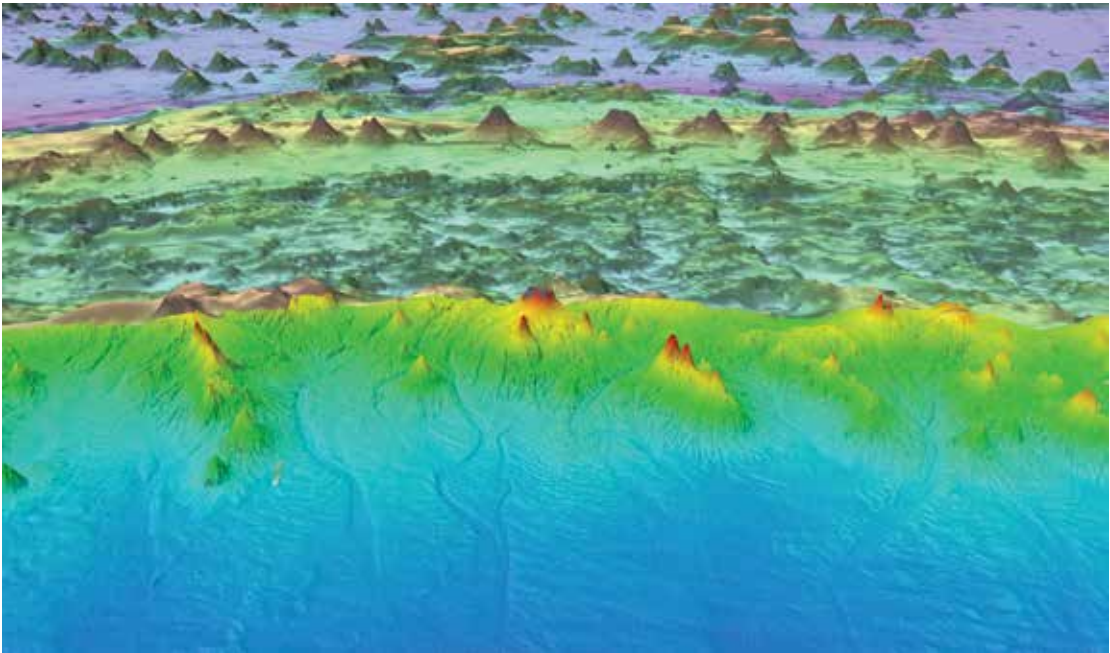


Figure 10: View of West Mariana Ridge bathymetry (bright colours) highlighting seamounts and associated sediment distribution channels. Depths in bright-coloured part of image range from 85 m to 4,800 m. Background bathymetry from Smith and Sandwell.

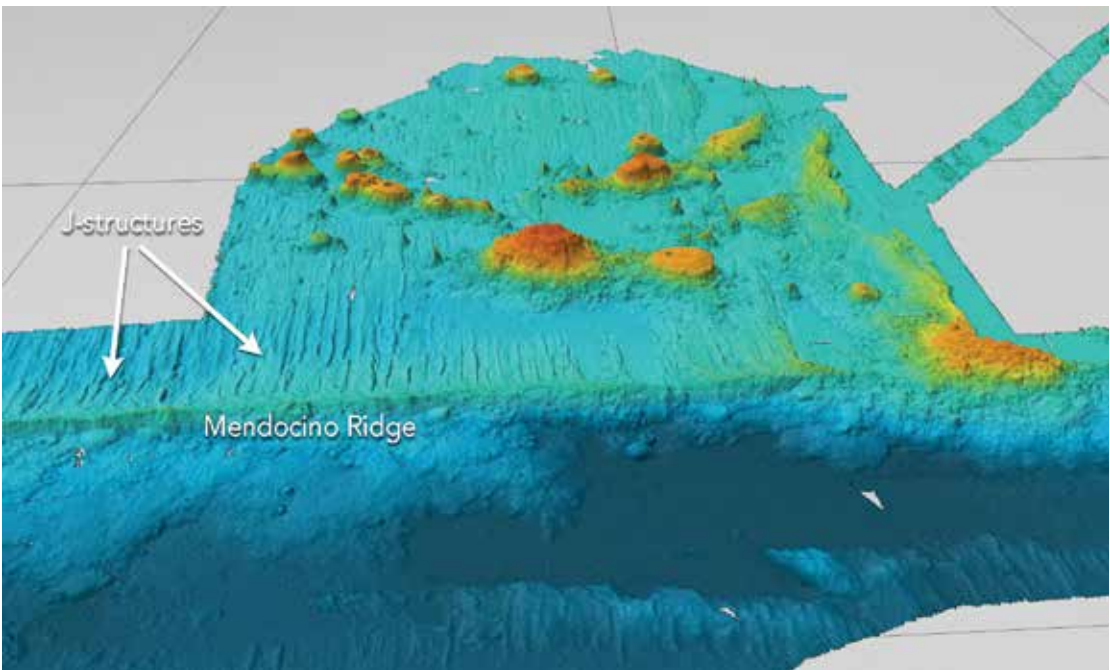


Figure 11: Perspective view of volcanic field and J-structures north of Mendocino Ridge, looking N. Background bathymetry from Smith and Sandwell.

and curve northward and merge into the washboard topography of the deep ocean floor. North and west of the initial oversized J-structure is an extensive field of submarine volcanoes – some quite large – and volcanic

ridges fully mapped for the first time, over an area about 130 km by 180 km. On the south side of Mendocino Ridge in this area, massive overlapping lobes of basalt have extruded onto the seafloor.

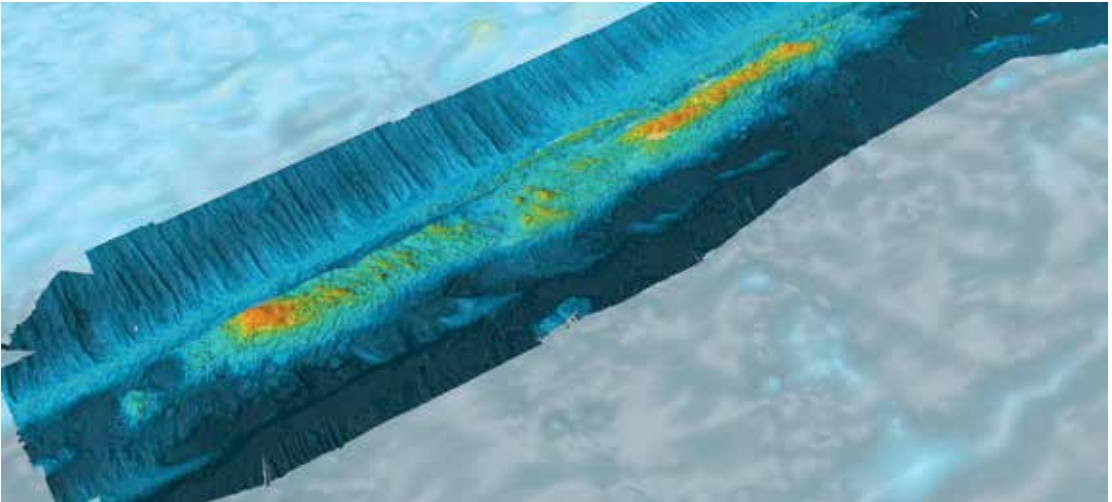


Figure 12: Outermost mapped region of Mendocino Ridge. View from the SW, with large volcanic extrusion area offset from the main ridge axis. Small ridges on the main feature strike northwest to southeast and terminate at a minor fracture line paralleling the primary fracture line.

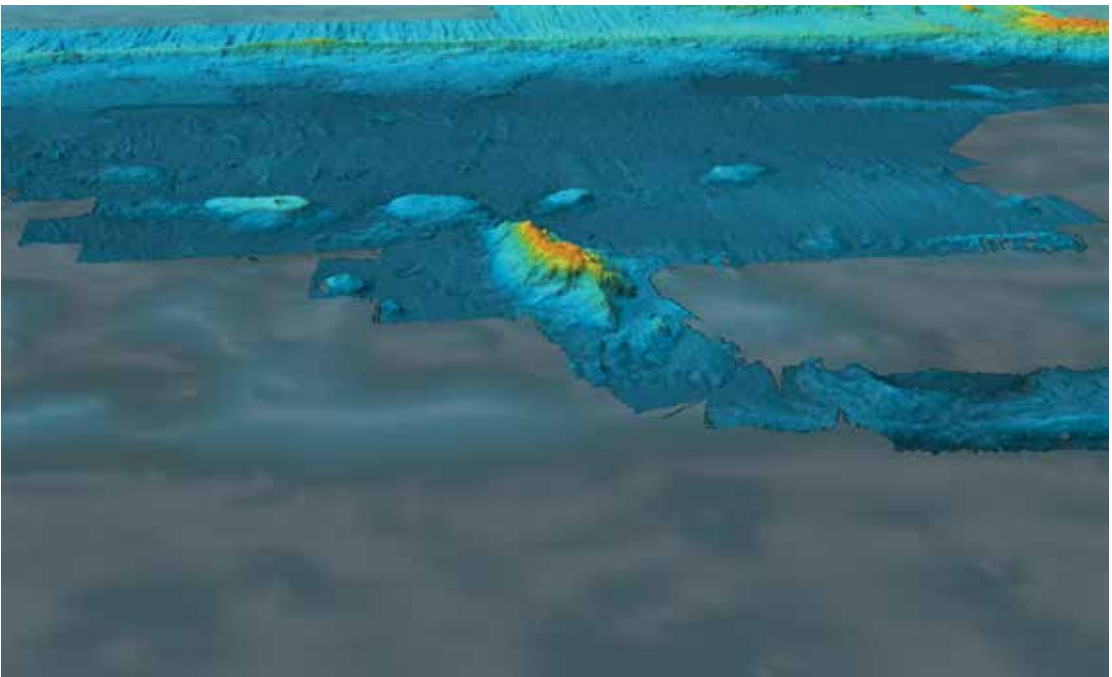


Figure 13: Boutelle Seamount, view from the southwest. Mendocino Ridge is mapped to the north, and Pioneer Ridge is to the south. Background bathymetry from Smith and Sandwell.

Further seaward, from about 750 km to 950 km offshore, the source of the volcanic flows appears to have split off from the main axis of the ridge. Volcanic activity has created an elongated east-west oriented region with obliquely oriented volcanic structures just to the south of the ridge axis (Figure 12).

Pioneer Ridge runs parallel to Mendocino Ridge, about 180 km to the south. Between the two ridges, and likely associated volcanically with Pioneer Ridge, Boutelle Seamount (Figure 13) abruptly rises from the seafloor. The base of Boutelle Seamount is at 4,570 m depth, the summit is 1,889 m below the sea surface, a

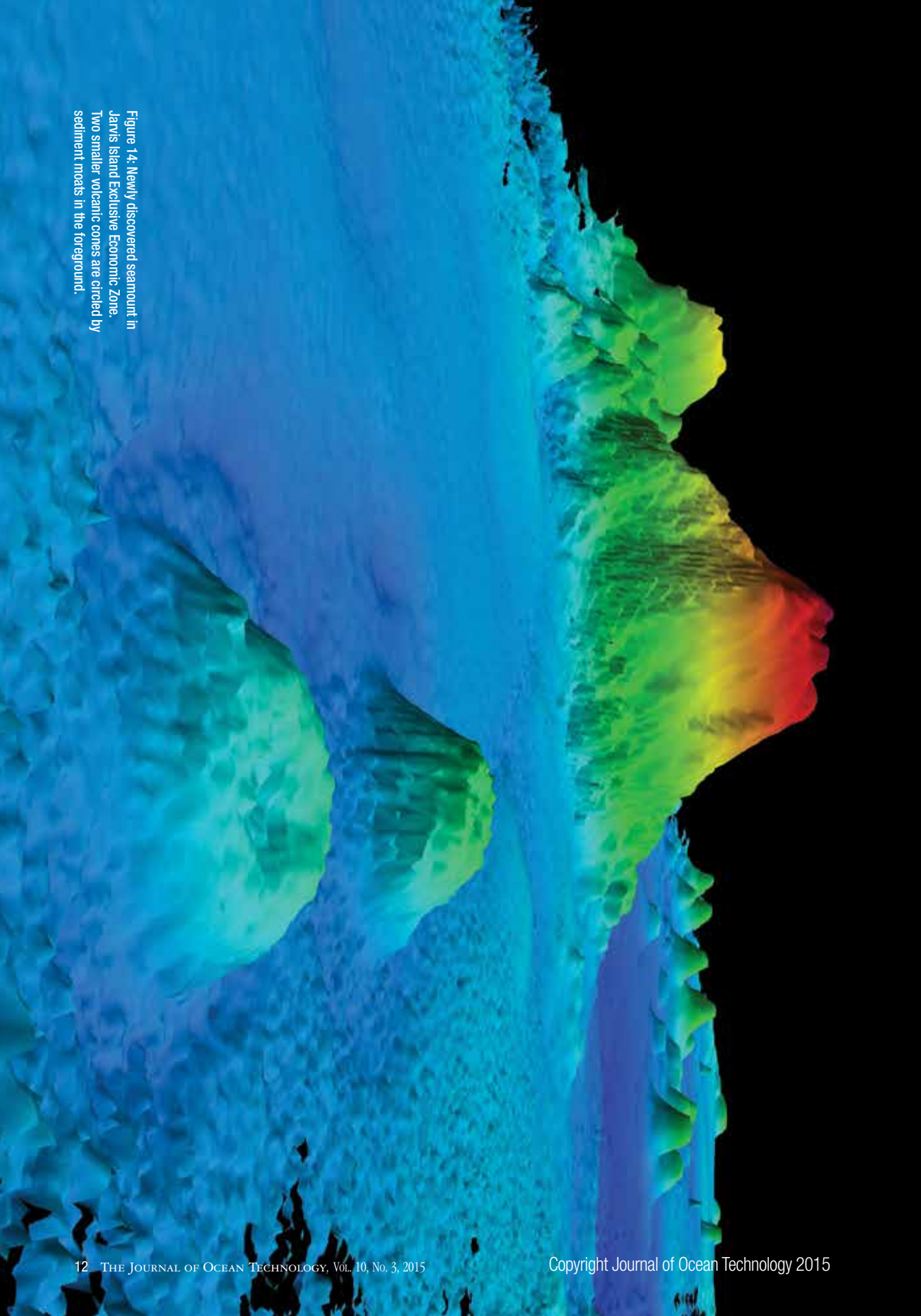


Figure 14: Newly discovered seamount in Jarvis Island Exclusive Economic Zone. Two smaller volcanic cones are circled by sediment moats in the foreground.

vertical change in elevation of 2,681 m in just 12 km horizontally. This seamount is shown on nautical charts with depth and location based on a variety of vintage sources; data from these surveys will provide significantly more-accurate charted soundings.

### **The Central Pacific Islands**

A cruise of opportunity aboard the RV *Kilo Moana* took the NOAA/UNH mapping team to the Central Pacific to collect a swath of multibeam soundings through the US EEZ around Jarvis Island and survey some gaps in Keli and Karin Ridges in the Johnston Atoll EEZ. The Central and South Pacific are probably the most sparsely mapped regions of the world. Relatively few ships transit these waters, so even the trackline soundings that populate charts of the North Pacific and Atlantic are lacking here. The President of the United States recently issued an Executive Order that expanded the boundaries of the Pacific Remote Islands National Monument, and extended the monument status to the limit of the EEZ of several US Pacific Islands, including both Jarvis Island and Johnston Atoll. One of the reasons for expanding these boundaries was to protect the unique and unspoiled habitat associated with seamounts in the region. On the single track to Johnston Atoll that passed through the Jarvis Island EEZ, a new seamount was discovered and mapped in detail (Figure 14), validating the rationale for the monument extension. Finding a seamount in the Pacific is not an extraordinary discovery; what is noteworthy is that although we know hundreds of these seamounts exist, we have yet to locate and map most of them.

### **Conclusion**

Modern, full-coverage multibeam echo sounding has been a transformative technology for mapping our oceans. Earlier mapping technology, from lead line and wire sounding machine to single-beam echo sounding and side scan sonar have provided considerable information about the shape and character of the seafloor, but only with

the full-coverage, high resolution technology provided by multibeam and similar swath mapping systems can we discover, interpret, and most importantly, share knowledge of the seafloor and its underlying geology and natural history. There are, however, important conditions without which the value of multibeam echo sounder data is greatly reduced. The US ECS bathymetric project and their partners took care to use multibeam systems that were correctly integrated with supporting sensors such as high-quality global navigation satellite systems, top-quality inertial motion units, and continuous surface sound speed monitors. System tests were run and validated at the start of each cruise. Patch test calibrations were run for each cruise or project and necessary bias corrections carefully applied. Data acquisition was directed, conducted, and documented by expert operators and watch standers. Sound speed profiles, using conductivity-temperature-depth sensors, tethered and expendable sound speed profilers, and expendable bathythermographs, were obtained and applied frequently to avoid refraction and sound speed artifacts. The acquired sounding data were processed and cleaned aboard ship and quality-assured with additional processing ashore after the cruises using state-of-the-art multibeam data processing software. Without these rigorous procedures and quality control, multibeam data can be distorted by systematic and random errors and artifacts. Interpreting poor data can lead to missed discoveries and unfounded conclusions. And, perhaps most significantly, all the data were archived at the NOAA National Centers for Environmental Information (formerly the National Geophysical Data Center) and made publicly available within six months of data acquisition. US ECS bathymetry has been used in numerous scientific studies and publications by both project scientists and other authors, and has prompted several additional mapping projects and scientific investigations. Seafloor mapping data is most valuable when it is quickly and fully available for use by everyone. ~



Andrew Armstrong is Co-Director of the NOAA-UNH Joint Hydrographic Center at the University of New Hampshire. He directs NOAA's role in the research, mapping, and educational programs of the Center, and is the bathymetry team leader for the Interagency US Extended Continental Shelf Project. He has served as chief scientist

or co-chief scientist on ECS mapping cruises to the Arctic, the Marianas, the western Pacific, and the Atlantic. He is past president of the Hydrographic Society of America and a member and past chair of the International Advisory Board on Standards of Competence for Hydrographic Surveyors and Nautical Cartographers. Mr. Armstrong has over 40 years of hydrographic and ocean mapping experience with NOAA, including positions as officer in charge of hydrographic field parties, commanding officer of NOAA *Ship Whiting*, and chief of NOAA's Hydrographic Surveys Division.



Larry Mayer is a Professor and the Director of the School of Marine Science and Ocean Engineering and the Director of the Center for Coastal and Ocean Mapping at the University of New Hampshire. He received a PhD from the Scripps Institution of Oceanography in Marine Geophysics in 1979.

After being selected as an astronaut candidate finalist for NASA's first class of mission specialists, Dr. Mayer went on to a post-doctorate at the School of Oceanography at the University of Rhode Island and then became an Assistant Professor in the Department of Oceanography at Dalhousie University. In 1991, he moved to the University of New Brunswick to take up the NSERC Industrial Research Chair in Ocean Mapping and in 2000 Dr. Mayer became the founding director of the Center for Coastal and Ocean Mapping at the University of New Hampshire. He has participated in more than 90 cruises and has been chief or co-chief scientist of numerous expeditions including two legs of the Ocean Drilling Program and seven mapping expeditions in the ice covered regions of the high Arctic. He is the recipient of the Keen Medal for Marine Geology and an Honorary Doctorate from the University of Stockholm. He has chaired National Academies of Science committees on national needs for coastal and ocean mapping and on the impact of the *Deepwater Horizon*

oil spill on ecosystem services in the Gulf of Mexico and is currently the Chair of the Academy's Ocean Studies Board. Dr. Mayer's current research deals with sonar imaging and remote characterization of the seafloor as well as advanced applications of 3D visualization to ocean mapping problems and applications of mapping to Law of the Sea issues, particularly in the Arctic.



James V. Gardner is Project Chief for the US Law of the Sea Bathymetric Mapping and a Research Professor of earth sciences at the Center for Coastal and Ocean Mapping, University of New Hampshire. Dr. Gardner earned his PhD from the Lamont Earth Observatory, Columbia University, in 1973. From

1975 to 2003, he was a Research Marine Geologist with the US Geological Survey (USGS), Menlo Park, CA, specializing in deep sea sedimentary processes and the collection, processing, and visualization of high-resolution multibeam sonar data. He retired from the USGS as Chief, Pacific Seafloor Mapping. He has mapped in the Coral Sea, along the California margin, in the Bering Sea, along the insular slopes of Hawaii, central San Francisco Bay, outer shelf and basin margins of the Gulf of Mexico, the entire US Atlantic margin, the US Gulf of Alaska margin, the Mariana Trench and West Mariana Ridge, Necker and Mendocino Ridges as well as several island areas in the Pacific and Lake Tahoe and Crater Lake. Dr. Gardner has participated in four Deep Sea Drilling Project Cruises, one as co-chief scientist, and has participated in more than 50 research cruises in the north and south Atlantic, north and south Pacific Oceans, the Mediterranean, Caribbean, and Bering Seas; and has published more than 200 papers on marine geology. He has won several awards, including being the first USGS Mendenhall Lecturer. In 2012, he was awarded the Francis P. Shepard Medal for Excellence in Marine Geology by the Society of Sedimentary Geology/SEPM.