Volcanic platforms, ancient reefs, ridges, and seamounts: mapping the Papahānaumokuākea Marine National Monument

Final Project Report for *Falkor* Cruises FK140307 and FK140502

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Introduction and Background

The Papahānaumokuākea Marine National Monument (PMNM) surrounding the Northwestern Hawaiian Islands (NWHI) represents the largest marine protected area under U.S. jurisdiction and one of the largest in the world, encompassing over 366,631 km^2 and spanning close to 2,000 km from the edge of Middle Bank past Kure Atoll (Fig. 1). The PMNM was established in 2006 and just four years later was inscribed by UNESCO as a mixed World Heritage Site (i.e., both natural and cultural), the only one of its kind in the U.S. and the first inscription of a U.S. site in over 15 years.

There are many reasons why PMNM achieved this designation. The monument contains islands, seamounts, atolls, ridges, and submerged banks that constitute the northwestern three quarters of the oldest, longest, and most remote island chain in the world. Within its boundaries exists a diverse and unique collection of marine and terrestrial flora and fauna. With a spectrum of bathymetry and topography ranging from abyssal seafloor at depths greater than 5,000 m, to rugged island hill slopes up to 275 m above sea level, PMNM represents a complete cross section of a Pacific archipelagic ecosystem. Habitats include deep pelagic basins, abyssal plains, submarine escarpments, deep and shallow coral reefs, lagoons, littoral shores, dunes, and dry coastal grasslands.

Ninety-eight percent of PMNM's seafloor (i.e., 355,000 km^2) is below 100 m, the lower range of SCUBA, and therefore has not been extensively investigated. The monument is laced with volcanic platforms terraced with drowned fossil coral reefs that provide a detailed record of the formation of the Hawaiian Archipelago and tracks the movement pattern of the Pacific plate over millions of years (Myr). It's believed that many of the roughly 52 volcanoes in the archipelago are capped by drowned reefs (*e.g.*, Davies et al. 1972, Greene et al. 1980, Grigg 1988, Grigg 1997, Clague et al., 2009) that have recorded the subsidence history of the volcanoes (*e.g.*, Clague et al. 2009). These reefs have also recorded the climatic conditions under which they formed. However many aspects of the archipelago's history west of the Main Hawaiian Islands remain poorly documented (Clague & Dalrymple 1987, Rooney et al. 2008). Even the most accepted conclusion that the volcanoes increase in age to the west and north is not without controversy (Clague 1996, Sharp & Clague 2008). The general age progression along the chain indicates that at least one volcano formed during roughly each Myr for the past 80 Myr. The carbonate caps therefore record climate during the last 80 Myr and specific climatic periods can be studied by selecting the right volcano whose age is clearly understood.

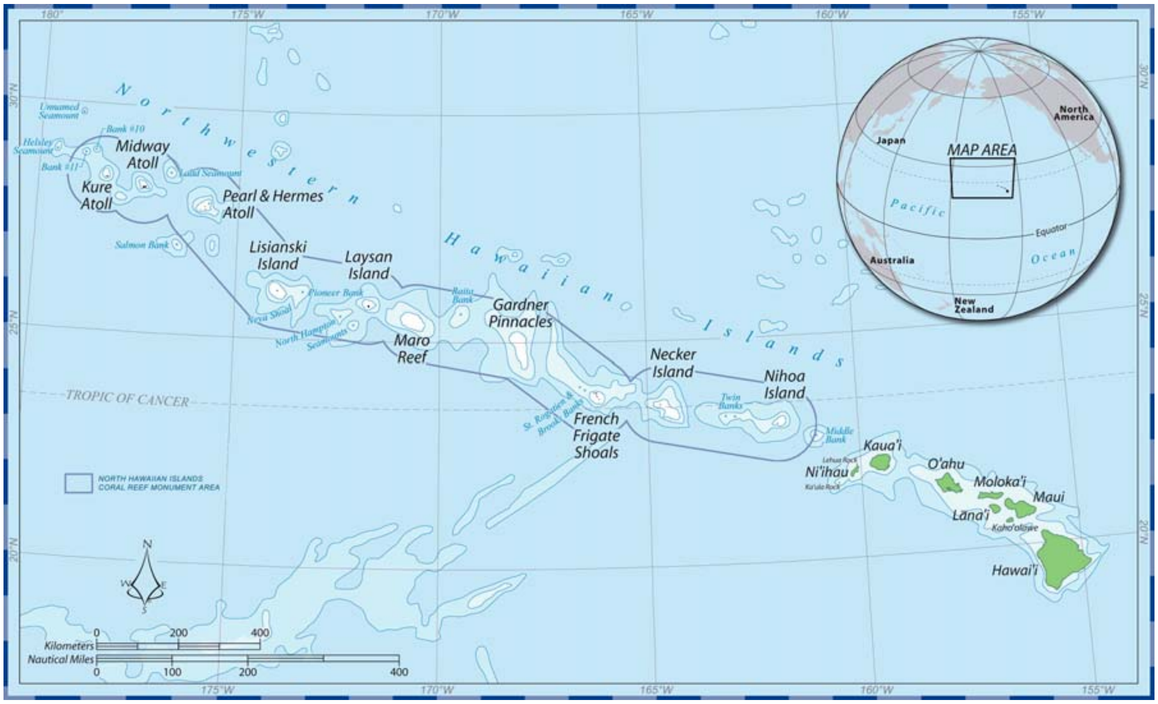

Fig. 1: Map of the Papahānaumokuākea Marine National Monument (PMNM). Credit: NOAA via Wikimedia Commons.

These volcanoes, which are now dormant seamounts and eroded banks, have yet another unique geologic feature: manganese (Mn) crusts found at 800-2,500 m depths on their exposed rocky slopes that have precipitated from the overlying water at an average rate of 2.5 mm/Myr (Moore & Clague, 2004). The Mn crusts found in the Central Pacific have the richest content of cobalt (Co) and other commercially valuable minerals of the world, including copper, rare earth metals, and other elements crucial in the manufacturing of high tech products such as cell phones, solar panels, and wind turbines (Hein et al, 2014). As a result, this area has been designated as the Prime Crust Zone (PCZ) and is already being targeted by various countries interested in developing the technology to mine these crusts. The total area of Mn crust habitat inside the monument is unknown, and is believed to be substantial, a fact that will likely increase in importance as deep sea mining progresses. This is because whatever process is developed to extract the crusts will be extremely destructive to deep sea communities at depths below 800 m. A handful of surveys in the monument below this depth have discovered the presence extraordinary high density coral and sponge beds that appear to be associated with seamounts and rift zone ridges where topographically induced upwelling is occurring (Kelley, unpub data). Identifying where these beds occur and what type of topography they are associated with is one of the major goals of this project. This information could potentially lead to international legislation aimed at directing mining activities away from these types of biologically sensitive sites in the PCZ.

The acquisition of high resolution seafloor mapping data is an essential precursor to making significant geological and biological discoveries in the monument as well as in any other part of the world. However, these data can be both expensive and difficult to acquire in remote regions. Prior to the cruises described in this report, only four dedicated mapping cruises had taken place in the monument (*Kilo Moana* 0206, *Hi'ialakai* 0501, 0508, and 0610). The first, which took place in 2002 was the only major one (Evans et al., 2004), a fact that has clearly restricted the pace by which discoveries are being made. Supplemental mapping during transits and in areas of specific interest have taken place since then on fishery and submersible cruises. Even so, the total proportion of the monument that had been previously mapped amount to only 48%, with much of it as simple transit lines by a multitude of ships, and with the different mapping systems yielding data of varying quality (Fig. 2). Approximately 190,000 km^2 of monument waters were as yet unmapped by the time the project began, mostly in the northern half and in depths below 1,000 m where mn crusts are found.

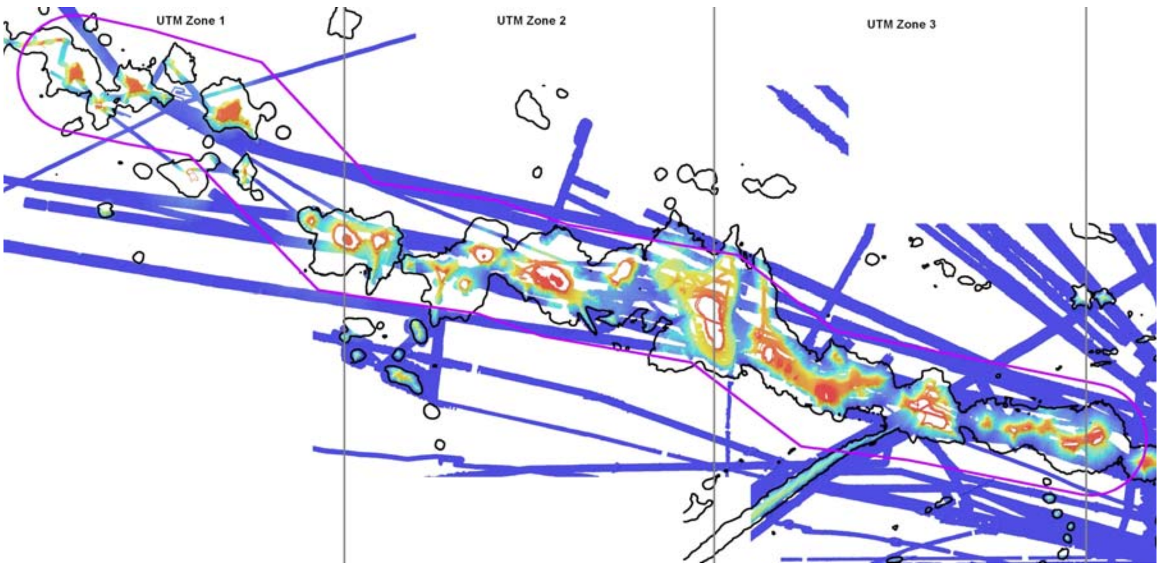

Fig. 2: Map showing the multibeam coverage in the monument (purple lines) before the cruises. Four thousand meter contours (black) and UTM zones (grey) are also shown.

Project Objectives

This project was designed to significantly increase the multibeam coverage of the PMNM's seafloor and in so doing, provide new information that addresses the following specific objectives stated in the original proposal.

Objective 1: Map seamounts and rift zone ridges located in the northern half of the monument. This survey focuses on Mn-crust habitats and the discovery of new high density coral and sponge beds that are associated with seamount and ridge topography.

Objective 2: Map drowned reef terraces on Gardner Pinnacles that reach depths of at least 2,000 m. The focus will be to complete mapping that has already been started, thereby improving our understanding of the geologic history of this important volcano.

Objective 3: Map the 50-150 m depth range around Laysan Island, Gardner Pinnacles, Pioneer Bank and if time permits, Raita Bank. The focus will be on the monument's important mesophotic zone habitats however drowned reefs are also found in this depth range. This objective will therefore be synergistic with objective 2.

Objective 4: Complete mapping the ridge southeast of French Frigate Shoals, with a focus on providing full coverage of an important internal tide generation site. As part of this last objective, we are also requesting approval to deploy an oceanographic instrument mooring owned by the University of Hawaii's Department of Oceanography to record data on the velocity and density structure of the water at this site for two fortnights or approximately 28 days.

The proposal was originally for a project involving a single 36 day cruise on the *Falkor* awarded from the SOI proposal review process. However, a number of unexpected events took place prior to the start of the project that prompted changes and additions to these objectives. First, the PI was informed that the oceanographic mooring would not be available for the cruise, thereby reducing objective 4 to simply completing the mapping of the French Frigate Shoals ridge. Secondly, the PI was awarded 36 additional ship days to continue mapping in the monument on a second cruise due to a scheduling issue with the ship. Two long cruises separated by only 3 weeks presented a staffing issue since most of the participants on the first cruise were unavailable for the second. Therefore a decision was made to conduct both cruises, but primarily the second, as the field component of a graduate level Spring semester course for the University of Hawaii (UH) Geology and Geophysics Department (i.e., G&G 614 Field Study) under the instruction of Michael Garcia (land-based instruction) and this project's PI and chief scientist, Christopher Kelley (at sea instruction). A third event was that one of the graduate students taking the course (Jonathan Tree) along with his faculty advisors Michael Garcia and Garrett Ito were able to secure both a magnetometer from UH and a gravimeter leased from the Woods Hole Oceanographic Institute (WHOI) with funding assistance provided by the National Science Foundation (NSF). These instruments, both of which are passive data recorders, were to be operated simultaneously with the multibeam systems during the mapping surveys on both cruises.

Finally the fourth event took place during the monument permit application process. A considerable amount of discussion arose regarding the possible effects of multibeam sonar on the marine mammal populations in the monument. While researching this issue, it became apparent that no documented observation data existed on the reaction of marine mammals to multibeam sonar. Concerns about negative effects led to the incorporation of a number of operational requirements in our permit, one of which was the posting of a marine mammal observer on *Falkor*'s upper deck during all daylight hours. Instead of just trying to meet this requirement, we chose to create a sixth objective for the project that involved inviting trained observers from the NOAA Observer Program to participate on the cruise who would oversee efforts to carefully document each and every encounter with any species of marine mammals. Below is the modified objective list that was used to guide the activities on both cruises.

Objective 1: Map seamounts and rift zone ridges located in the northern half of the monument. This survey focuses on Mn-crust habitats and the discovery of new high density coral and sponge beds that are associated with seamount and ridge topography.

Objective 2: Map drowned reef terraces on Gardner Pinnacles that reach depths of at least 2,000 m. The focus will be to complete mapping that has already been started, thereby improving our understanding of the geologic history of this important volcano.

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Objective 4: Complete mapping the ridge southeast of French Frigate Shoals, an important internal tide generation site.

Objective 5: Acquire gravity and magnetics data for the purpose of identifying the precise origin and locations of the volcanoes under the various banks and seamounts in UTM Zones 1 and 2 of the monument.

Objective 6: Document encounters with cetaceans and monk seals inside the monument for the purpose of improving our understanding of the effects of multibeam sonar on marine mammals.

Final changes to the original proposal objectives were the extension of our maximum targeted mapping depth from 3,000 to 4,000 m and the "spreading out" of the objectives over two instead of just one cruise. As a result, the first cruise focused primarily on objectives 1, 5, 6, and to a lesser extent, objective 3 while the second cruise focused primarily on objectives 2, 3, 4, and 6.

Materials and Methods

The two cruises were carried out March 7 to April 11 (FK140307) and May 2 to June 6, 2014. With occasional excursions outside the boundaries to dump grey water, all ship operations took place in the PMNM. Fk140307 targeted the seamounts, banks, and atoll flanks located in UTM zone 1 (-180 to -174), with a small amount of additional mapping being carried out around the more southern Maro Reef and West Northampton Seamount while the ship awaited the passage of a storm further north on the up leg. FK140502 targeted the seamounts, banks, and atoll flanks located in UTM zone 2 (-174 to -168). This cruise also mapped the northern rift zone ridge off St Rogatien bank and a small part south of French Frigate Shoals in UTM zone 3 (-168 to -162).

Multibeam Sonar Surveys

Multibeam mapping involved the use of the *Falkor*'s Kongsberg EM 302 and EM 710 multibeam sonars. Links to downloadable documents providing complete specifications to these instruments are:

http://www.km.kongsberg.com/ks/web/nokbg0397.nsf/AllWeb/A915A71E90B6CFAEC12571B1003FE84D/$file/306106_em_302_product_specification.pdf

http://www.tdi-bi.com/vessels/em710_.pdf

Multibeam data files were transferred to data processing computers brought on the ship by the science teams. Raw data files (.all files) were ping-edited in Leidos SABER software then converted to GSF files. SABER was also used to create PFMs where GSF files were merged with other *Falkor* data files as well as pre-existing multibeam files from other sources. These files then underwent a secondary editing in the context of the overall data coverage. PFM edits were then back saved to each of the GSF files, which were then imported into MB- System software to create grids in GRD (i.e., netCDF) format. In addition, a minimal filter was applied to create a slight smoothed copy of each bathymetry grid. These grids, which included both bathymetry and backscatter files, were then imported into ArcGIS and/or Fledermaus to create the final map files.

CTD and XBT Deployments

Daily sound velocity profiles (SVPs) were obtained with the *Falkor*'s CTD or deployment of Deep Blue expendable bathythermographs (XBTs) provided by SOI. Synthetic SVPs were obtained from the World Ocean Atlas of 2009's database which is built into the SVP Editor's server. The server profiles were primarily used during extended transits when it didn't make sense to deploy either the CTD or XBTs. Links to descriptions of these instruments and the SVP Editor manual describing the server are:

http://www.schmidtocean.org/story/show/47
http://www.sippican.com/stuff/contentmgr/files/0dad831400ede7b5f71cf7885fdeb110/sheet/xbtxsv.pdf
http://mac.unols.org/sites/mac.unols.org/files/SVP_Editor_Manual_v1.0.2.pdf

All sound velocity profiles obtained in the monument during FK140307 were through the use of the CTD or were downloaded from the server. XBTs were only deployed outside of the boundaries because we did not have a permit to use this method during that cruise. In April after the first cruise, an application for a permit amendment to use XBTs in the monument during the second cruise was submitted and approved. The amendment only allowed for 30 deployments, with subsequent profiles being obtained by CTD or the server.

Gravity Surveys

The gravimeter used during both cruises is a geophysical device that measures accurately and precisely the acceleration of gravity due to the Earth's gravity field. This device, a Bell Aerospace BGM-3 marine gravimeter, was rented from the Woods Hole Oceanographic Institute's (WHOI) program: the Multidisciplinary Instrumentation in Support of Oceanography (MISO) and is part of their Potential Fields Pool Equipment (PFPE). The instrument was shipped to Hawaii after WHOI obtained the necessary ITAR permit and was installed by WHOI engineers on March 5-6. The device was located in the dry lab, slightly above water level and slightly portside of the ship's centerline. The gravimeter was land tied prior to departure on March 6. Data from the BGM-3 was continuously logged along the ship track and was paired with the *R/V*

Falkor's navigation data from the *Falkor*. Output measurements of observed gravity were expressed in units of mGal.

Fig. 3: Installation of the BGM-3 gravimeter leased from WHOI prior to the first cruise.

Magnetometer Surveys

The magnetometer used during both cruises was a Geometrics G-882 marine magnetometer provided by the University of Hawaii. The device works by detecting variations in the resonance of a self-oscillating split-beam cesium vapor. It has an accuracy of <3 nT over an operating range of 20,000 nT to 100,000 nT. The G-882 was attached to a multiconductor tow cable that was paid out to a maximum of 169 meters from the stern of the ship using an electrical winch on the *Falkor's* aft deck and supported by the ship's A-frame. The offset between the A-frame and the ship's GPS antenna is 22 meters, giving a total offset of 191 meters between magnetometer and the ship's logged geographic coordinates. The raw data was digitized by the Geometrics DC/Data junction box in the *Falkor's* dry lab and then logged via an automatic rsync process to the ship's SCS system on channel COM28. *Falkor* marine technicians also chose to log the data independently via the ship's Hypack system. Data was logged continuously at 10 samples per second (10 Hz) and included a timestamp, gamma value in nT, Larmor frequency level, and scaled instrument depth.

Fig. 4: SOI's multibeam technician Colleen Peters preparing to deploy the G-882 magnetometer leased from the University of Hawaii.

Cetacean observations

A trained NOAA observer was present on each cruise to oversee the cetacean observation data and ensure compliance with our permit requirements. The observers were each assigned to a daytime watch stand and were assisted by science team members before, during, and after their shifts in order to meet the sunrise to sunset observation requirement in the permit. All observations were made from the *Falkor*'s "monkey deck" located directly above the bridge (Fig. 2). This deck has a large compass mounted on a pedestal that was used to estimate bearings to the animals and the animal headings during encounters (Fig. 3). Observers were equipped with binoculars, cameras, data sheets mounted on a clipboard and a watch set to GMT time. When an encounter occurred, the observers recorded the time, distance to animal(s), best identification, the animal behavior, bearings and headings, and other data required on the data sheets. At night after observations had ceased, the encounter times were entered into a script created by one of us (J. Taylor) that accessed the ship underway data stream and provided the ship heading, speed, and GPS coordinates for the observations. These data were added to the data sheets. The data were then entered into a Microsoft Access database, and exported as a Microsoft Excel file after the cruises that was imported into ArcGIS. Polyline vectors were created with a COGO tool in ArcGIS to plot the ship headings, animal positions and animal headings for each encounter. These plots enabled visualize of the ship and animals movements and determine whether the animals passed through multibeam sonar ensonification plane.

Fig. 5: NOAA Observer Daniel Luers with science team member Belinda Dechnik observing for cetaceans on the Falkor monkey deck.

Fig. 6: NOAA observer Joshua Tucker determining the bearing to a cetacean using the Falkor's pedestal mounted compass.

Outcomes

<u>Multibeam Sonar Surveys</u>

FK140307

This cruise was completed on schedule with no days lost to mechanical problems, instrument problems, or weather. During the transit up to UTM zone 1, two days were spent mapping further south off Maro Reef and West Northampton seamount due to the captain's prediction of poor weather when we were scheduled to arrive at the northern end of the monument. The transit was resumed after the weather system had passed. Mapping was conducted 24 hrs a day during all 36 days of this cruise, with the exception of the periods between Honolulu and the monument boundary on March 7 and April 11, when the systems were purposely turned off.

Within the monument, 61,000 km^2 of seafloor were mapped that included a total of 18 seamounts (Fig. 7). Only nine of these seamounts currently have names and include Academician Berg, Turnif, Woollard, Wentworth, Nero, Ladd, Gambia Shoals, East of Salmon, and Bank 9. The other 9 seamounts are un-named however the paperwork required for this process will be completed and submitted later this year. Additionally, we added extensive mapping data for the deeper areas off Kure, Midway and Pearl and Hermes Atolls, which had only been partially mapped by other ships. As a result of this cruise, all significant features in the UTM zone 1 area of the monument are now completely mapped.

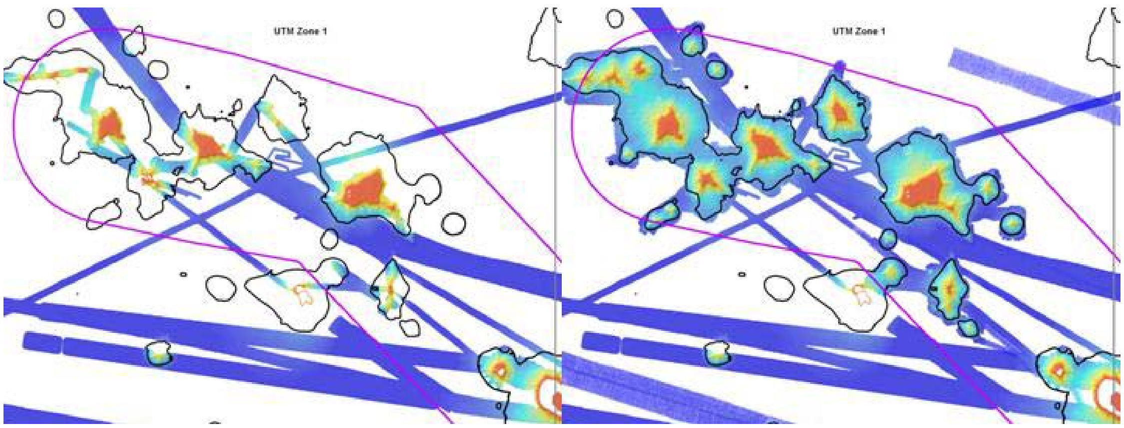

Figure 7: Images of the multibeam bathymetry coverage before (left) and after (right) the cruise in the northern section of the monument located within UTM zone 1. Previous data were collected primarily by NOAA and were also obtained from the National Geophysical Data Center (NGDC). Purple line is the monument boundaries, black lines are the 4000 meter contours and the vertical grey line is the boundary between UTM zones 1 and 2.

Four different types of volcanic features were identified in this area of the Monument including 1) atolls (3) that are presently at the surface, 2) shallow guyot (i.e., flat-topped) seamounts (6) having summit depths between 68 and 158 m, 3) deep guyot seamounts (3) having summit depths between 1380 and 1700 m, and peaked or cone-shaped seamounts (11) with summit depths between 1188 and 2769 m (Fig. 8). Guyot seamounts were atolls at some point in their histories and have subsequent sunk below the surface whereas peaked seamounts have never been at the surface and therefore have not been subjected to the erosional and/or reef building processes that create flat-topped guyot summits. The presence of deep guyots in the monument had not been known prior to the cruises.

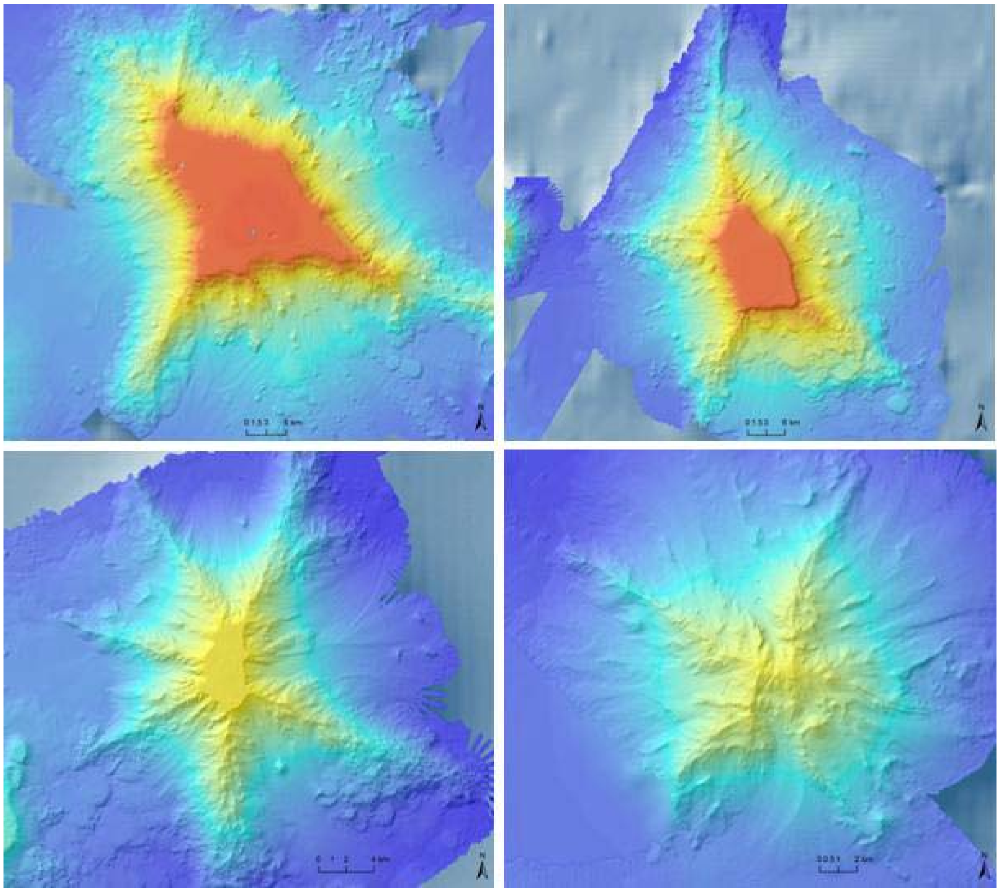

Fig. 8: The four types of features found in the northern end of the monument, which include emergent atolls such as Midway (upper left),shallow guyot seamounts such as Ladd (upper right), deep guyot seamounts (lower left), and deep peaked seamounts (lower right). The latter two are currently un-named.

Analysis of dredged lava samples obtained in the 1970s through 1990s prior to the creation of the monument discovered that in addition to younger "Hawaiian" seamounts (i.e., 20-30 Myrs), this area has 3 older Cretaceous seamounts dating back 82-92 Myrs (in O'Connor el al 2013). Two of these were deep guyots and one was a peaked seamount but at the time of the dredges, their morphology was unknown. These were believed to have originated further to the southeast and were subsequently rafted to the vicinity of the Hawaiian archipelago on the Pacific plate when the younger Hawaiian volcanoes were erupting over the Hawaiian hot spot. Assuming all deep guyots and peaked seamounts are Cretaceous (a hypothesis considered reasonable by several geologists), then the new *Falkor* multibeam data from this cruise indicate there are upwards of 14 Cretaceous seamounts in this area of the monument, exceeding the number of atolls and shallow guyots of Hawaiian origin (9). This area of the monument is therefore a fascinating but confusing mosaic of seamounts having vastly different ages and origins.

Of particular interest is a seamount presently called Bank 9, which a dredge sample indicated was Cretaceous (Fig. 9). This seamount has been an anomaly because its summit reaches a depth of 117 m indicating that it should be Hawaiian. The new *Falkor* data however revealed that Bank 9 appears to be a composite of a younger Hawaiian guyot that erupted through the northern rift zone ridge of an older Cretaceous guyot already existing on the seafloor. A second less obvious example of this type of phenomenon was revealed by the data obtained from an un-named seamount located right on the northern boundary of the monument (Fig. 9). In this second case, a much greater portion of the deeper guyot is covered by the shallower guyot. Clearly, these conclusions can only be confirmed by submersible or ROV surveys that obtain additional rock samples, which is something that the *Falkor* data will likely provoke. It's also worth noting the presence of a completely smooth volcanic cone just west of this last seamount (see Fig. 9b) that may be composed of fragmental pyroclastic material (Clague, pers comm). If this is true, then it would imply that the cone was formed as a result of an explosive eruption, which is unusual in deep water.

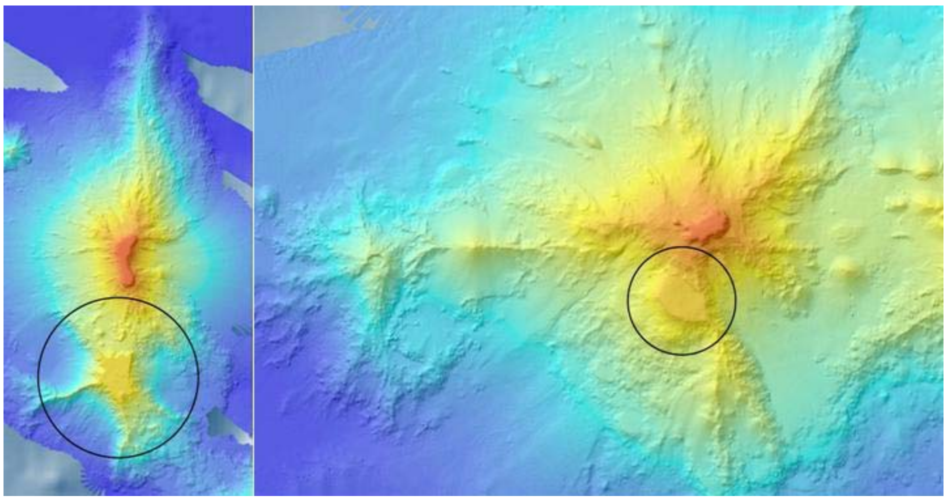

Fig. 9: Bathymetry of a) Bank 9 (left) and b) an un-named seamount north of Kure (right). Circled areas are the confirmed (a) or inferred (b) Cretaceous guyots to the south of the inferred Hawaiian guyots.

Other interesting findings in the UTM zone 1 area of the monument include well preserved drowned reef terraces on the summit of Academician Berg, disproportionately large landslides on the summit and flanks of an un-named seamount southwest of Nero, and unusually long erosional features that appear to be extending out and downslope from Kure's lagoon revealed by the *Falkor*'s EM302 backscatter data (Fig.10).

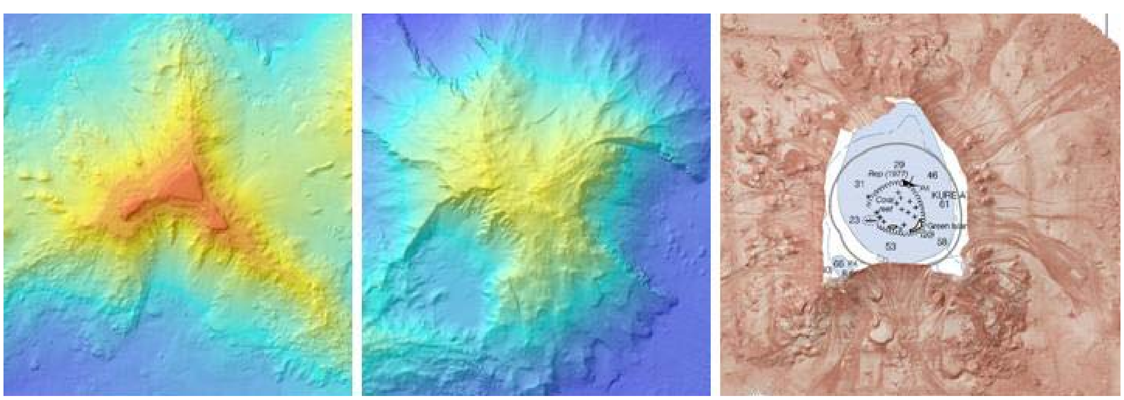

Fig. 10: Drowned reef terraces on Academician Berg (left), major landslides on an un-named seamount southwest of Nero (center), and Falkor backscatter data revealing erosional features extending more than 33 km out from the east side of Kure Atoll (right).

Furthermore, the EM710 backscatter data revealed subtle, low relief structure on the summits of Nero and Ladd resembling the lagoons of Midway and Pearl & Hermes atolls (Fig. 11). However it's unknown at this point whether these structures represent drowned remnants of shallow reefs and lagoons when these seamounts were atolls or whether they are live mesophotic reefs.

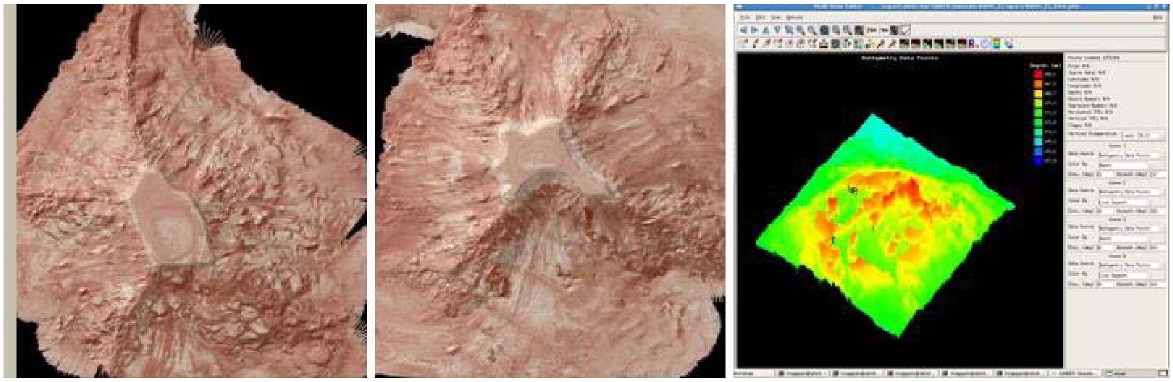

Fig. 11: Summits of Ladd (left) and Nero (center) seamounts. Faint rings resembling lagoons are visible on the otherwise flat guyot tops that when exaggerated in SABER reveal structures that appear to be either live or dead reefs (right).

Rift zone ridges that are likely sites of dense coral and sponge beds were found on most of the seamounts (see Figs 9 and 10 for examples). Submersible or ROV dives are required to confirm their presence however the new maps will provide the necessary data and imagery to plan those dives. PMNM is a known site for unusually large rift zone ridges that in several cases extend over 50 km. One of these, the south rift zone ridge of West Northampton seamount in UTM zone 2, was re-mapped during the transit up to UTM zone 1 while waiting for a storm to pass. The ridge had been previously mapped however the data were poor due to the manner the survey was conducted. The new *Falkor* bathymetry and backscatter data bring out beautiful details of the ridge's volcanic structures and drowned reef terraces (Fig. 13).

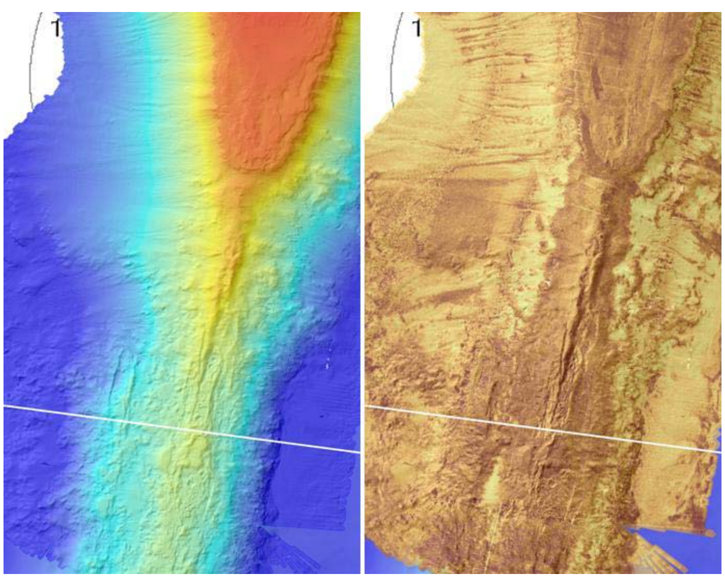

Fig. 13: Bathymetry (left) and backscatter (right) of the south rift zone ridge of West Northampton seamount.

Similar to the first cruise, this second cruise was completed on schedule with no days lost to mechanical problems, instrument problems, or weather. Mapping was conducted 24 hrs a day during all 36 days of this cruise, with the exception of the periods between Honolulu and the monument boundary on May 2 and June 6, when the systems were purposely turned off. Within the monument, 66,000 km^2 of seafloor were mapped, 5,000 km^2 more than the first cruise, which is attributed to our obtaining a permit to use XBTs in the monument. XBTs can be deployed while the ship is actively mapping whereas CTDs require the ship to stop mapping for 60-90 min each day.

Unlike the distinct seamounts found in UTM zone 1 during the first cruise, the volcanic platforms in UTM zones 2 and 3 were much larger and overlapping down to a depth of 4,000 m. The smallest isolated structure seen in this area was the Pioneer-Lisianski platform, which was still a sizeable feature. More data from other ships existed for this area before this cruise, however, the seamounts and banks were much larger than in UTM zone 1 and therefore it was not possible to complete the mapping of their entire extents between 50-4000 m. Instead a decision was made to focus on mapping in the optimal depth range for the EM302 multibeam system, between 1,000 to 4,000 m. While the shallower bank and seamount tops still remain to be mapped after the cruise was completed, the data obtained still made a significant contribution to the goal of mapping the entire seafloor in the monument (Fig. 14).

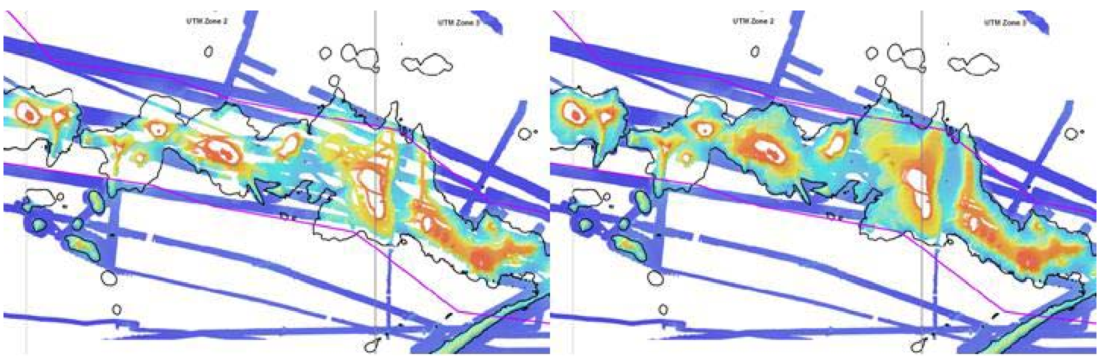

Fig. 14: Images of the multibeam bathymetry coverage before (left) and after (right) the cruise in the middle section of the monument located within UTM zone 2. Previous data were collected primarily by NOAA and the University of Hawaii. Purple line is the monument boundaries, black lines are the 4000 meter contours and the vertical grey lines are the boundary between UTM zones.

While seamounts were the highlight features of the first cruise, drowned reef terraces, landslides and rift zone ridges were the highlight features of this cruise. Of particular interest was Gardner Pinnacles, where the ship spent over 2 weeks of time in an effort to complete the coverage of this feature, the largest in the monument. All but the shallow bank top has now been mapped, revealing a curious secondary cone, landslides, and large numbers of drowned reef terraces, the most prominent of which shows an uncharacteristically high and dramatic upturned edge reaching 200 m in height (Fig 15). Furthermore, off its northern side spanning the monument boundary is an unusual field of small to medium sized structures that are either volcanic or have resulted from a major landslide event.

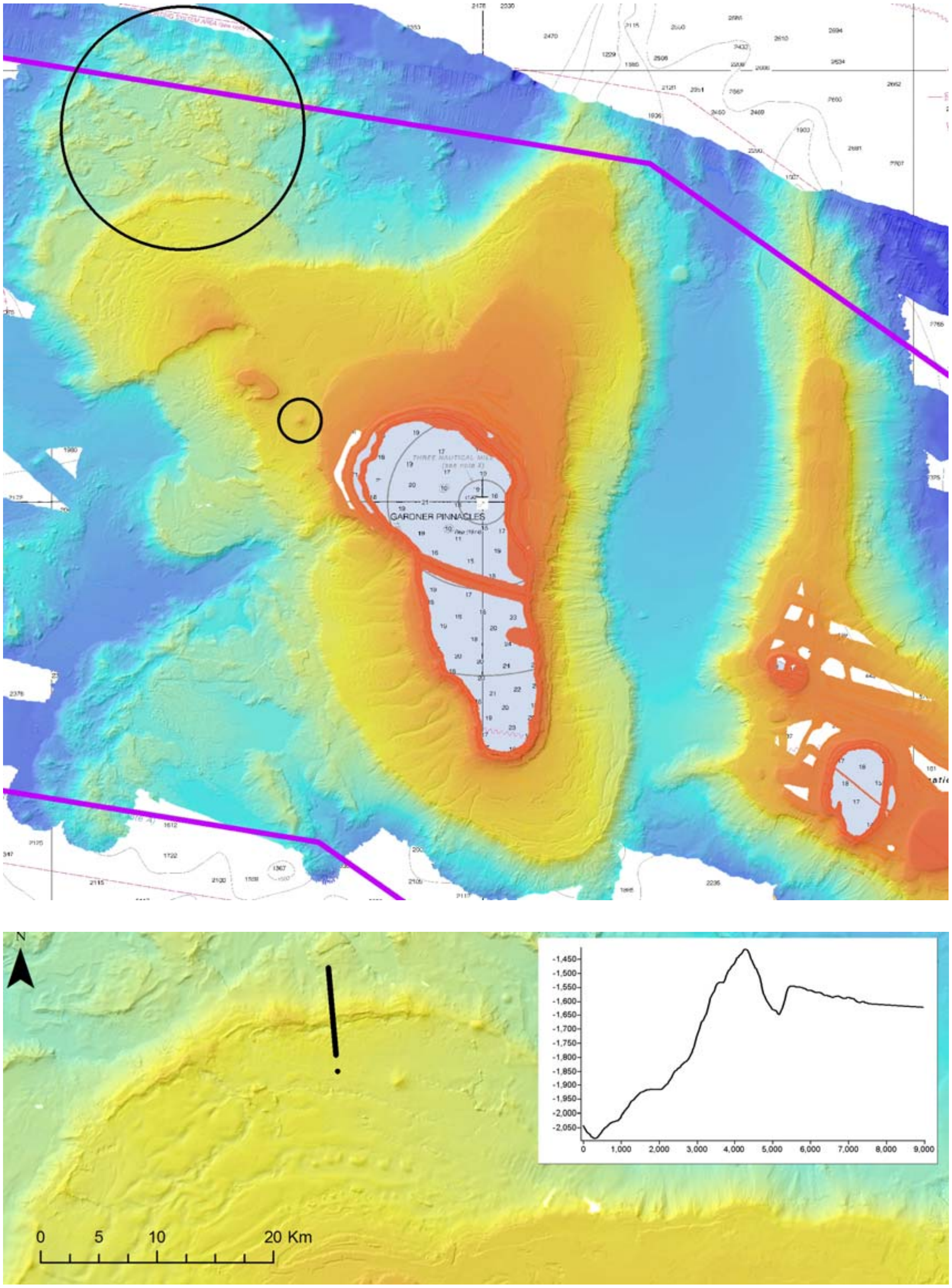

Fig. 15: Gardner pinnacles (top) showing the small volcanic cone (small circle), 200 m high drowned barrier reef, and northern field (large circle). Monument boundaries are purple lines and are 185 km wide. Northern rift zone ridge of St Rogatien is shown to the east of Gardner. Bottom image shows a closeup and profile of the unusually high drowned barrier reef.

The entire extent of the rift zone ridge extending north from St Rogatien bank was another major feature mapped during this cruise (Fig. 15). This is the largest such ridge in the monument and is covered by multiple layers of drowned reef terraces that have not been investigated by either ROV or submersible to date.

Northwest of Gardner is Maro Reef that the new *Falkor* data revealed has been subjected to significant landslides in the past (Fig. 16). The odd shape of this feature, which resembles a pig (pua'a in Hawaiian) running away toward the west, is a result of these flank failures that have occurred on its northern, eastern, and southern sides. Further contributing to the illusion are the rift zone ridges on the eastern side, the northern-most one having an unusually large crater forming the pig's tail. Although the crater had been previously mapped, it was remapped on this and the first cruise to obtain gravity data that might provide clues to its origin (Fig. 17).

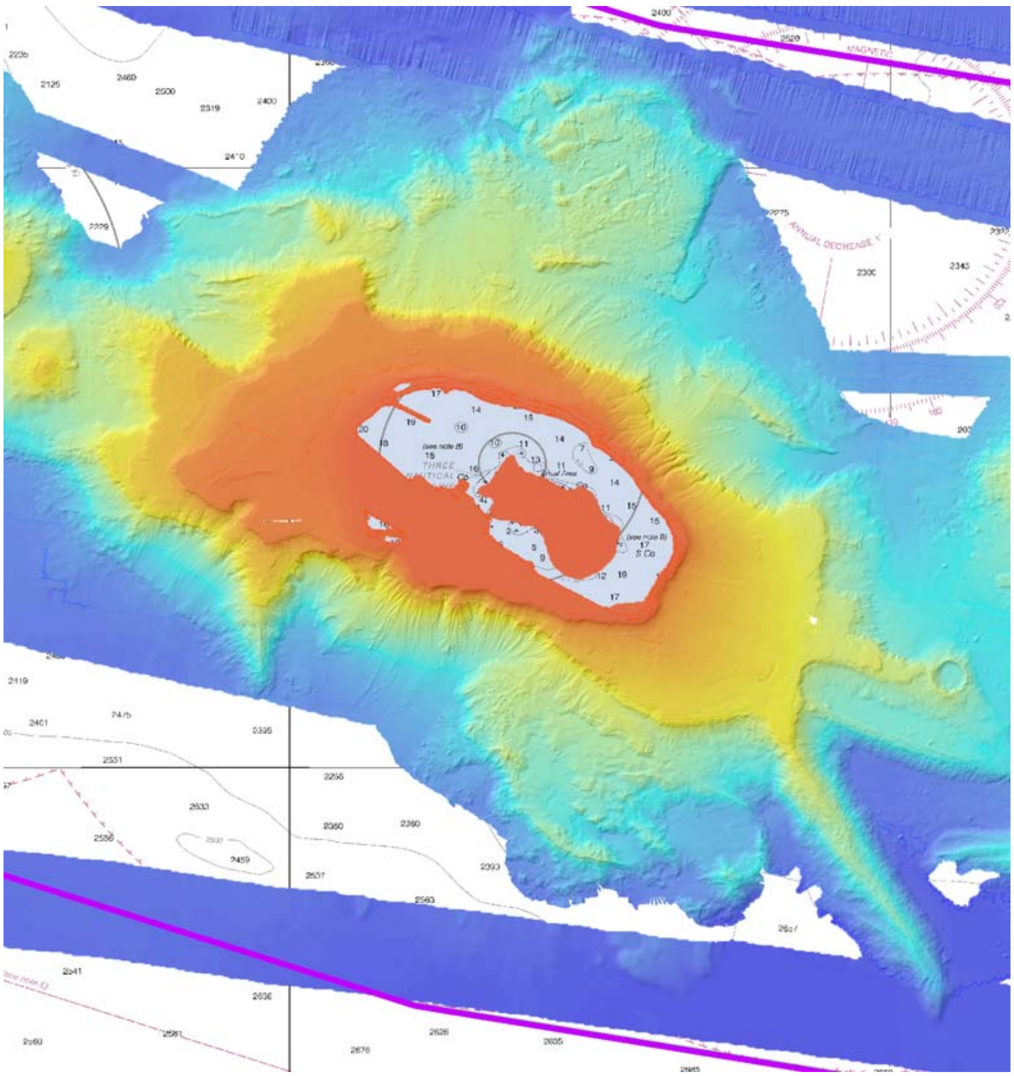

Fig. 16: Maro reef showing significant landslides and rift zones, one of which has a large crater on top.

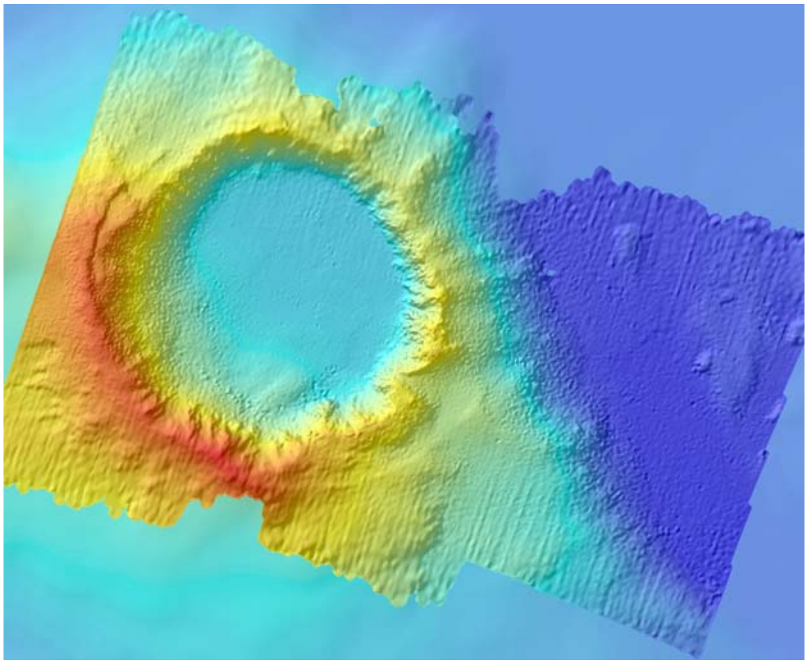

Fig. 17: Maro's 6 km wide enigmatic crater. The crater floor is at 3000 m depth and the tallest side rises 800 m to a depth of 2200 m.

The presence of giant landslides in the monument was previously known, which seem to be relatively common on many of the larger banks. However, the new *Falkor* data revealed something that is quite uncommon: a large landslide that had taken place on eastern side of the rift zone ridge extending south from Pioneer bank (Fig. 18). This ridge flank failure took off a significant portion of the eastern side, resulting in a razor sharp summit edge that extends for almost 23 kilometers. Unlike most other features revealed in the data, this razor edge was surveyed at 1800 m by submersible in 2003 that discovered one of the most amazing and dense deep sea coral and sponge habitats found so far in the Central Pacific (Baco et al, unpublished). The landslide that created it produced an even steeper barrier to longitudinal bottom flow than unaltered ridges and increased acceleration over the top that likely attracted the large number of filter feeding animals. Without the additional mapping from this cruise, the mechanism by which this summit was created would have remained hidden.

Some of the cruise time was dedicated to completing the coverage along the south side of the French Frigate Shoals platform and attempting to map selected mesophotic reef locations on Gardner, Pioneer, Raita, and Laysan Banks. The *Falkor*'s EM710 multibeam system, while providing good detail of the seafloor, does not have the multibeam swath width of higher frequency systems designed to map in shallow water. Narrow swath widths couple with a slow survey speed of 4 nm in shallow water for safety reasons made mapping in mesophotic depths an inefficient use of ship time. Therefore, much less time was spent on objective 3 than anticipated. With that said, the limited amount of mesophotic mapping carried out did reveal dramatic reef structures on both the southern tip of Raita and the southwestern side of Gardner Pinnacles at a depth between 40-60 m (Fig. 19).

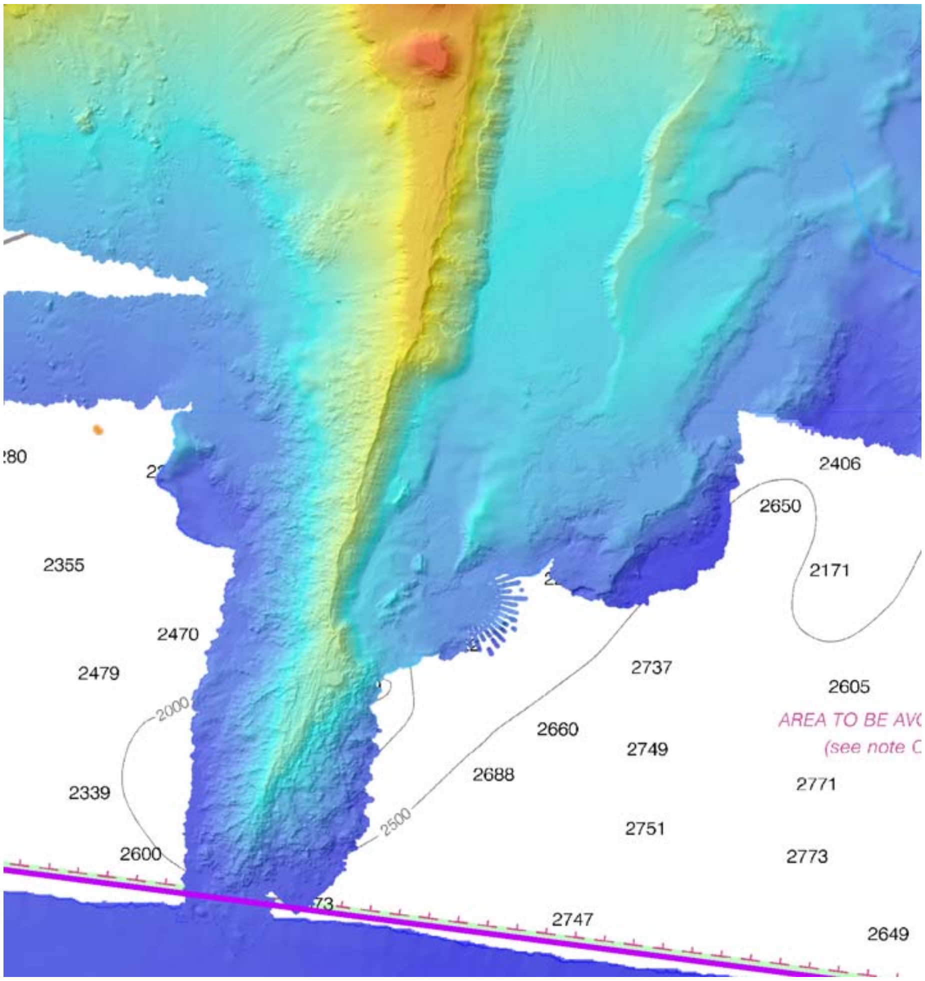

Fig. 18: The south rift zone ridge off Pioneer Bank, showing the mid-ridge failure that created a razor sharp edge 23 km long.

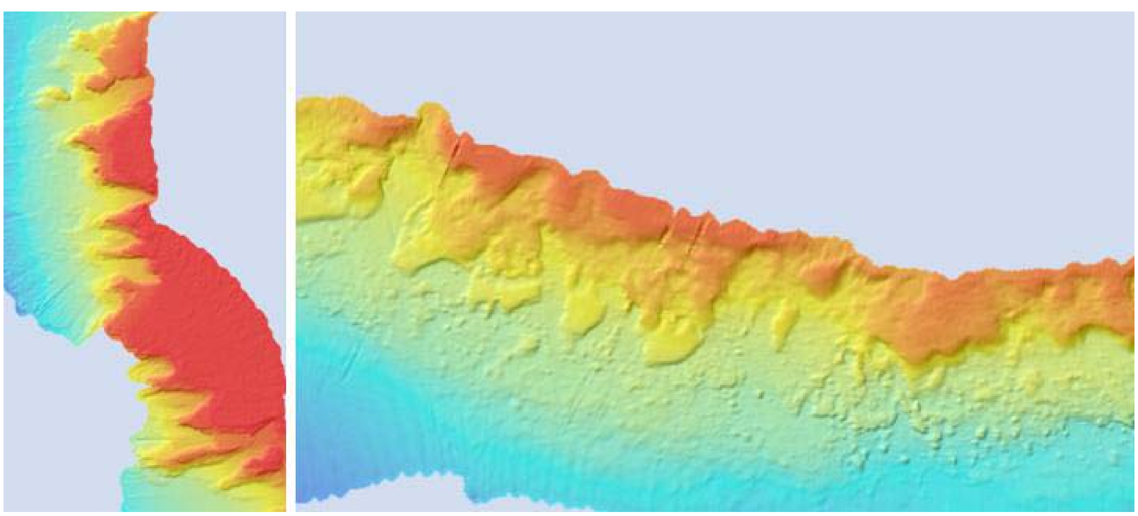
Fig. 19: Mesophotic reefs at 40-60 m revealed by the Falkor's EM710 multibeam system off Gardner (left) and Raita (right).

Multibeam summary for both cruises

With only a few areas as exceptions, most of the monument's seafloor from approximately 50 to 4,000 m has now been mapped (Fig. 20). This depth range encompasses the more significant features including all of the seamounts, banks, and atolls and their platforms. Based on SMRT30 satellite data, unmapped areas deeper than 4,000 m appear to be primarily flat abyssal sediment. The new data should therefore allow much more accurate area estimations of PMNM's deepwater geologic and biologic resources such as Mn crusts and dense animal communities. While less attention was focused on objective 3 as planned, the project did meet the other three objectives, and on that basis should be considered a success.

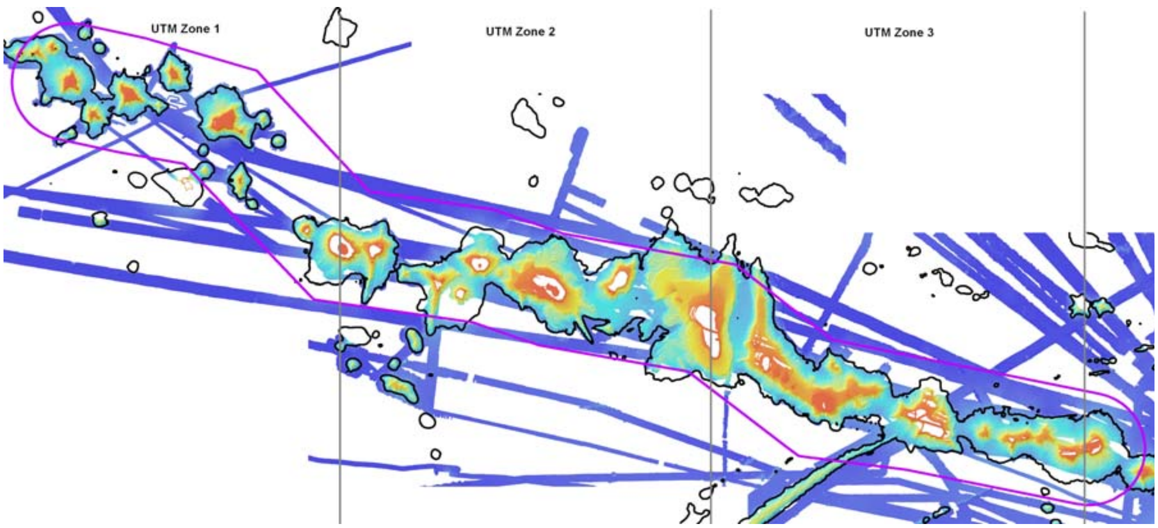

Fig. 20: Map showing the multibeam coverage in the monument (purple lines) after the cruises. Four thousand meter contours (black) and UTM zones (grey) are also shown.

CTD and XBT Deployments

Figures 21 and 22 provide two Google Earth images showing the ship track and positions of CTD (red) and XBT (green) casts conducted on each of the cruises. Data were collected for a total of 21 CTDs and 45 XBTs during both cruises.

Gravity Surveys

The Bell BGM-3 marine gravimeter outputs hourly logs and one daily log of gravity data that can be used for processing and data analysis (data files with suffix of *.GEF and *.RGS respectively). Daily processing was completed after the GMT day was finished and one full day of data along our track was available. Traditional gravity data processing was completed by filtering the gravity data string using filter tools from Linux and Generic Mapping Tools Version 4.5.12. The data reduction steps taken include resampling on 15 second increments, applying a spatial and vector correction to account for our location on the Earth and our velocity in a given heading (termed the Eötvös correction), and lastly the removal of the Earth's gravitational field by the IGRF 1984 approximation for gravity.

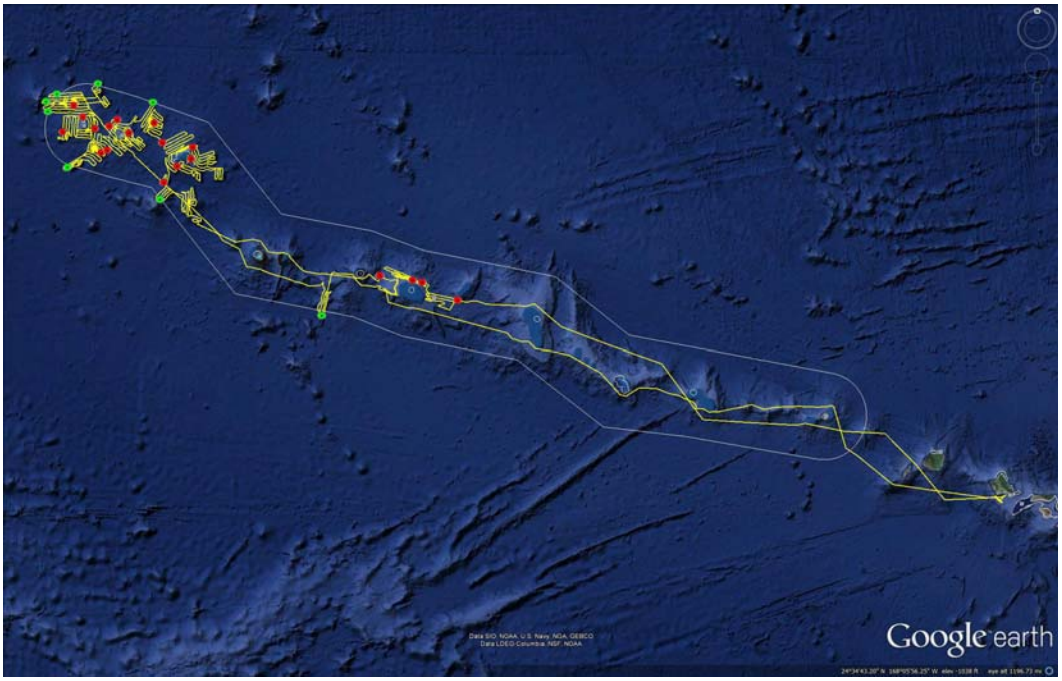

Fig. 21: Google Earth image of the Falkor ship track (yellow line) during cruise FK140307. The white line shows the boundary of the Papahānaumokuākea Marine National Monument in the Northwestern Hawaiian Islands. Red dots are the CTD station locations and green dots are the XBT station locations. The ship departed from, and arrived back into the port of Honolulu shown near the right edge of the image.

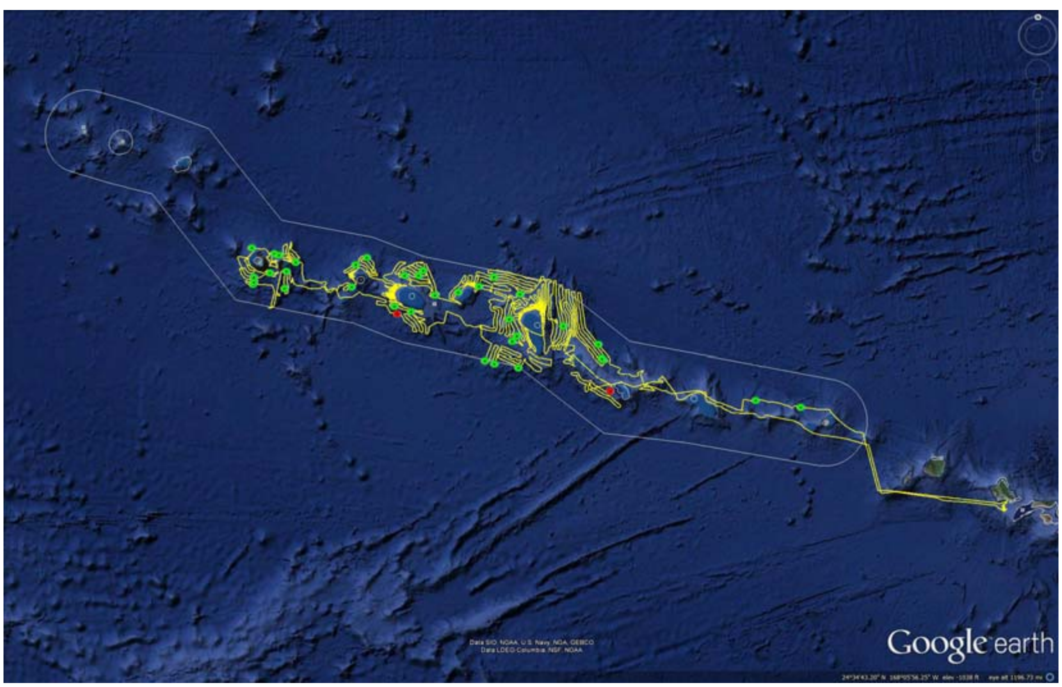

Fig. 22: Google Earth image of the Falkor ship track (yellow line) during cruise FK140502. The white line shows the boundary of the Papahānaumokuākea Marine National Monument in the Northwestern Hawaiian Islands. Red dots are the CTD station locations and green dots are the XBT station locations. The ship departed from, and arrived back into the port of Honolulu shown near the right edge of the image.

Qualitative observation of this data was conducted using MATLAB and quality individual “lines” were extracted from the continuous dataset of the day’s duration. The quality of the line was defined as containing no anomalous data spikes that correlate with sharp turns of the ship or other unknown data interference. The product of this reduction is called the Free-air Anomaly and shown plotted in Fig. 23. This is the baseline product that will be analyzed further and submitted to the NGDC for archiving once full analysis has been completed.

The Bell BGM-3 is a power and motion sensitive instrument, and consequently, any disruption to these elements will yield “non-valid data”. Providentially, only minor amount of data were lost due to these conditions, which did not significantly inhibit the dataset. On the first cruise (FK140307), rough sea state was the only source for these mechanical malfunctions which occurred twice briefly (one hour of stationary data disruption) during two CTD casts and once on transit through rough waters over featureless seafloor. On the second cruise, rough seas and CTD stations were not problematic in stabilization problems with the gravimeter. This time however, planned/unplanned power outages resulted in the gravimeter’s power source interruption and reliance on its external battery source. These power disruptions did not last long enough to harm any components of the device itself, but some data were lost during these instances.

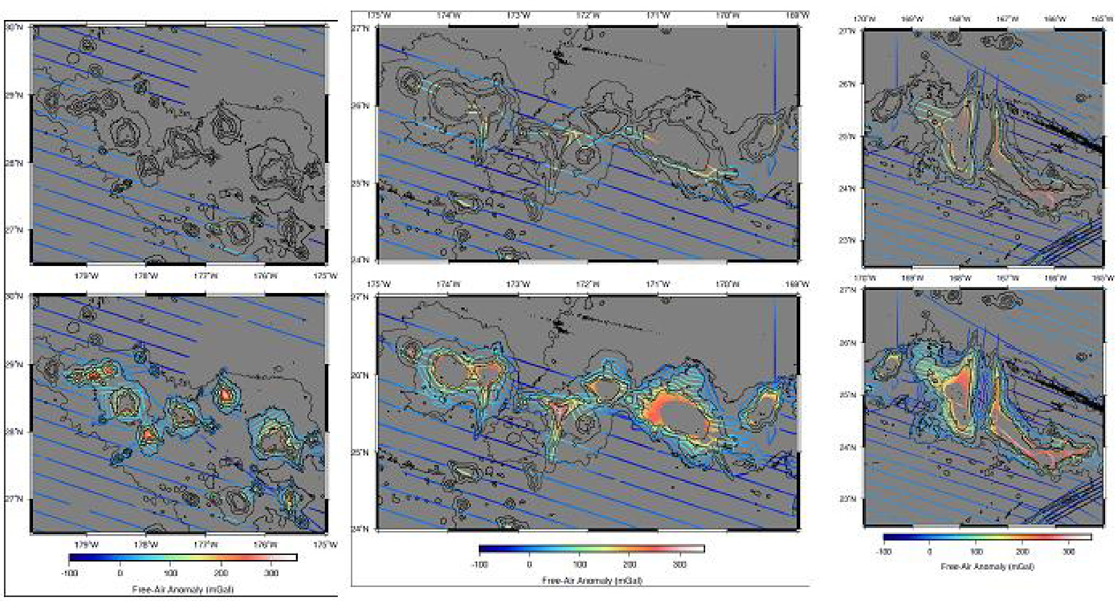

Fig. 23: Free-air Anomaly maps before (top) and after (bottom) of the monument survey areas in UTM zone 1 (left), UTM zone 2 (center) and UTM zone 3 (right). Contours are 1000m intervals and were generated from a synthesis of SRTM30_PLUS satellite altimetry and multibeam data from the Falkor. This figure was produced using computer program: Generic Mapping Tools v 4.5.12 by J. Tree.

Data that were collected in this region fill a large hole in the existing geophysical dataset for this region, making these data invaluable to the marine geophysical community (Fig 24). Previous gravity surveys were primarily in the main Hawaiian Islands with only a few sporadic areas in PMNM, and were focused on larger features neglecting seamount flanks and other smaller features of interest. In contrast, the new data collected on the *Falkor* was primarily from seamount summits and flanks. Due to the nature of the bathymetric survey plan, these data will enable the location and imaging of most of these seamount volcanic centers and quantification of the dimensions and physical properties of once active magma chambers that fed these volcanoes. In so doing, they will yield valuable insight in to one of the most interesting sections along the Northwest Hawaiian Ridge. Questions that these data should help answer are:

1. By locating extraordinarily dense subsurface structures relict from volcanic magma chambers, how many individual volcanoes were formed in this region of the Hawaiian Chain?
2. How much of the volcanic materials were extrusive (i.e., lava flows on the surface) vs. intrusive (i.e., magma filled chambers, dikes, and sills)?
3. How strong is the lithosphere that holds up these volcanoes? Does this strength change when a larger or smaller volcanic load is emplaced atop of it? Does it vary with the size/volume of the seamount?
4. Not all of these seamounts were formed from the Hawaiian hotspot, which ones are Hawaiian volcanoes and which ones are older Cretaceous seamounts that were present long before the Hawaiian volcanoes erupted on to the seafloor?
5. This area seems to be the onset of major volcanic production by the Hawaiian hotspot, which of these seamounts are the first that are constructed of multiple volcanoes making one edifice?

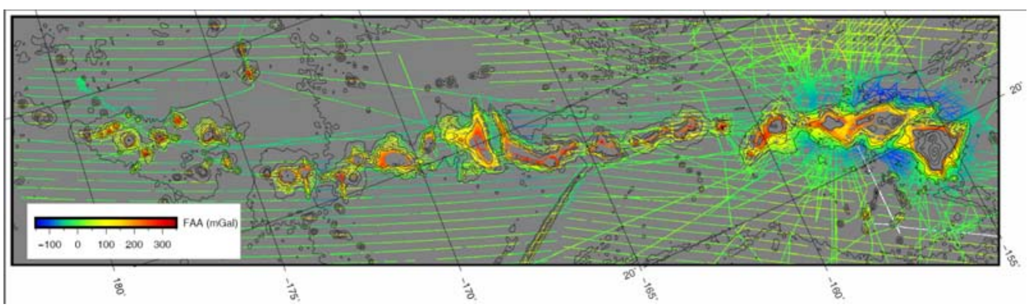

Fig. 24: New Free-air Anomaly map of the entire Hawaiian Archipelago combining the Falkor data with those collected previously by other ships. Contours are 1000m intervals and were generated from a synthesis of SRTM30_PLUS satellite altimetry and multibeam data from the Falkor. This figure was produced using computer program: Generic Mapping Tools v 4.5.12 by J. Tree.

Magnetics data

The Geometrics G-882 marine magnetometer collected 28,010,619 measurements of the total magnetic field throughout the FK140307 cruise between March 7 and April 11, and 28,611,216 measurements throughout the FK140502 cruise between May 2 and June 6 2014. The instrument was towed 169 meters behind the *Falkor's* aft deck A-frame at an average depth of approximately 9 meters below sea level depending on the ship's speed. Raw data was collected at 0.1 second intervals and stored redundantly via both the SCS and Hypack systems. Science watchstanders monitored the magnetometer's data stream in the Science Control Room and logged its activity every hour for the duration of the cruise. The marine technicians and scientists temporarily retrieved and then redeployed the instrument whenever the ship dropped its speed below

5 knots or executed unusual maneuvers. These intervals introduced short data gaps of less than two hours duration.

Figure 25 shows the extent of the magnetics data acquired during the two cruises relative to data already in existence. Since the magnetometer data did not include geographic position, it was necessary merge the 10 Hz magnetometer data with the ship's 1 Hz navigation data by decimating them to a common time sampling using a one-second median filter. The gridded total field data shown in Fig. 26 illustrate how the new *Falkor* data improved magnetic data coverage compared with pre-existing data from other sources. Going forward, we will further reduce the data by subtracting the International Geomagnetic Reference Field (IGRF), applying the Reduction to Pole (RTP) correction, and performing a crossover analysis. This will draw out small-scale magnetic variations that can provide relative age constraints on features identified in the sonar and gravity data. Thus, the magnetic information could prove to be an age discriminator to distinguish Hawaiian age from Cretaceous age seamounts within the Papahānaumokuākea Marine National Monument.

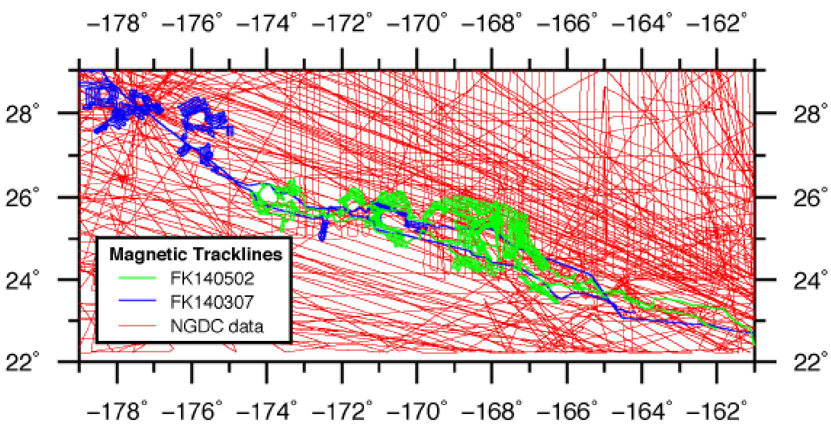

Figure 25: Ship tracks showing the extent of the magnetometer data collected during both cruises (FK140307 in blue and FK140502 in green). Tracks showing data collected on previous cruises are shown in red.

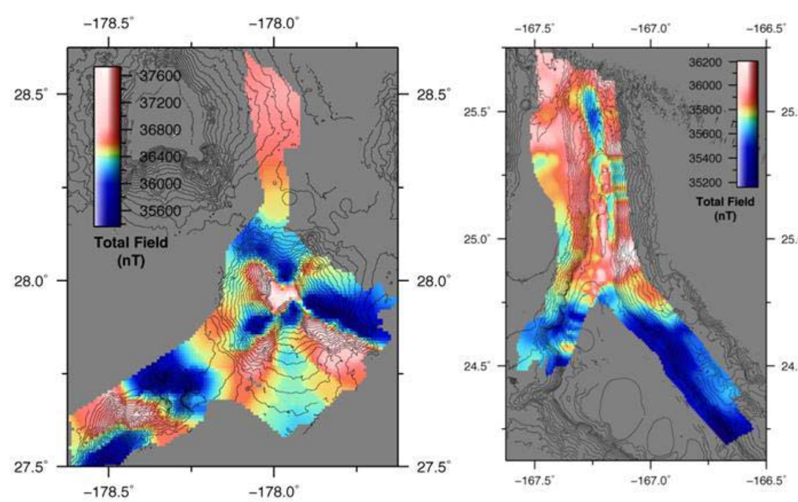

Figure 26: Examples of the total field magnetometer data obtained during the cruises on Nero seamount (left) and the large rift zone extending north from St Rogatien (right).

Cetacean observation data

A total of 29 encounters with marine mammals occurred and were documented on FK140307. The species included sperm whales, humpback whales, pilot whales, dolphins, a monk seal, and several unidentified species due to distance and the brevity of the encounter (Fig 27). Given that this cruise was conducted during the time of year when humpback whales typically migrate back north to Alaska from Hawaii, the relatively low number of encounters with this species in the monument was unexpected. The locations of the encounters on this cruise are shown in Figure 28. Of particular interest is the higher density of sperm whale encounters off the west side of Maro reef, the reasons for which are unknown.

A total of 34 encounters with marine mammals occurred and were documented on FK140502. The species included sperm whales, killer whales, pilot whales, minkie whales, and dolphins. The species seen during several encounters could not be identified due to distance and brevity of the encounter. Similar to the first cruise, the relatively low number of encounters with humpback whales in the monument was surprising. The locations of the encounters on this cruise are shown in Figure 29. As with the first cruise, sperm whales were encountered off the west side of Maro reef and their presence here on both cruises suggests that this area may be of potential interest to cetacean researchers.

Fig. 27: Photographs taken during the cruises of pilot whales (upper left), sperm whales (lower left), and dolphins (right). Credit: Daniel Luers.

Table 1 provides the total number of encounters during both cruises with each of the different species. A total of 63 encounters took place or less than 1 per day. Data from three additional encounters that took place on a 3 day student cruise around the island of Kahoolawe is included with these data since the overall aim is to better understand the effects of multibeam sonar on cetaceans. Of those identified at least to cetacean type, the largest number of encounters occurred with dolphins (19) followed by sperm whales (13), humpback whales (6) and minkie whales (6). The largest group encountered was a pod of pilot whales estimated to number at least 100 individuals. This encounter required the ship to come to a complete stop for approximately 1 hour. Of particular interest is the recording of interference from sperm whale calls on the SIS EM302 display monitor that appeared as concentric "pearls on a string" rings that showed

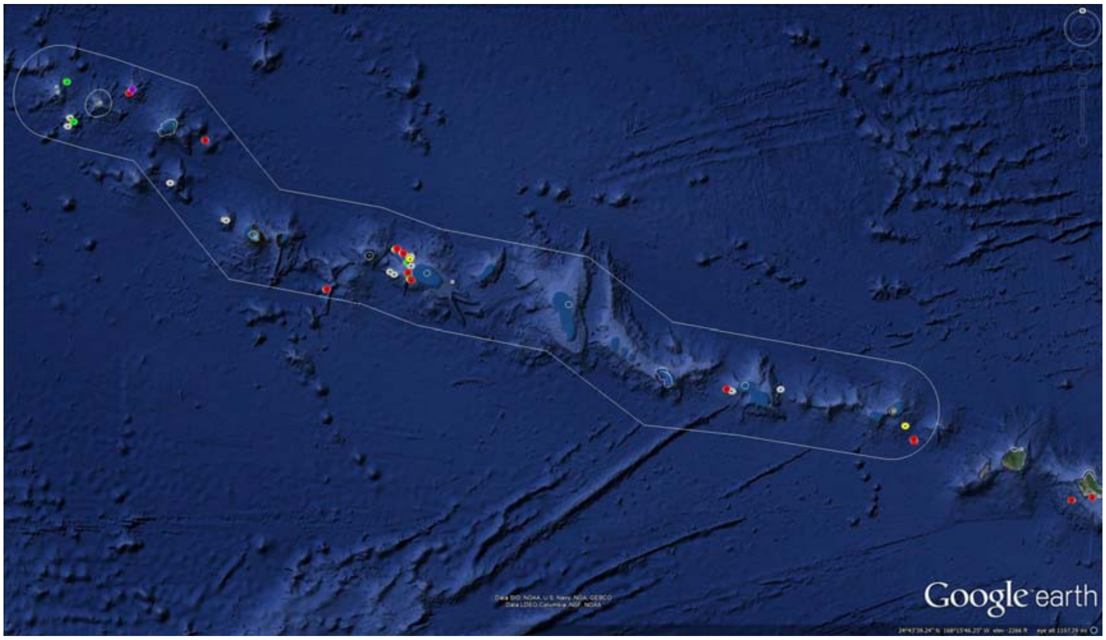

Figure 28: Google Earth image of the marine mammal observations made during cruise FK140307. The white line shows the boundary of the Papahānaumokuākea Marine National Monument in the Northwestern Hawaiian Islands. Different colored dots represent different types of mammals (red: sperm and humpback whales, yellow: pilot whales, green: dolphins, purple: monk seals, and gray: unidentified cetaceans).

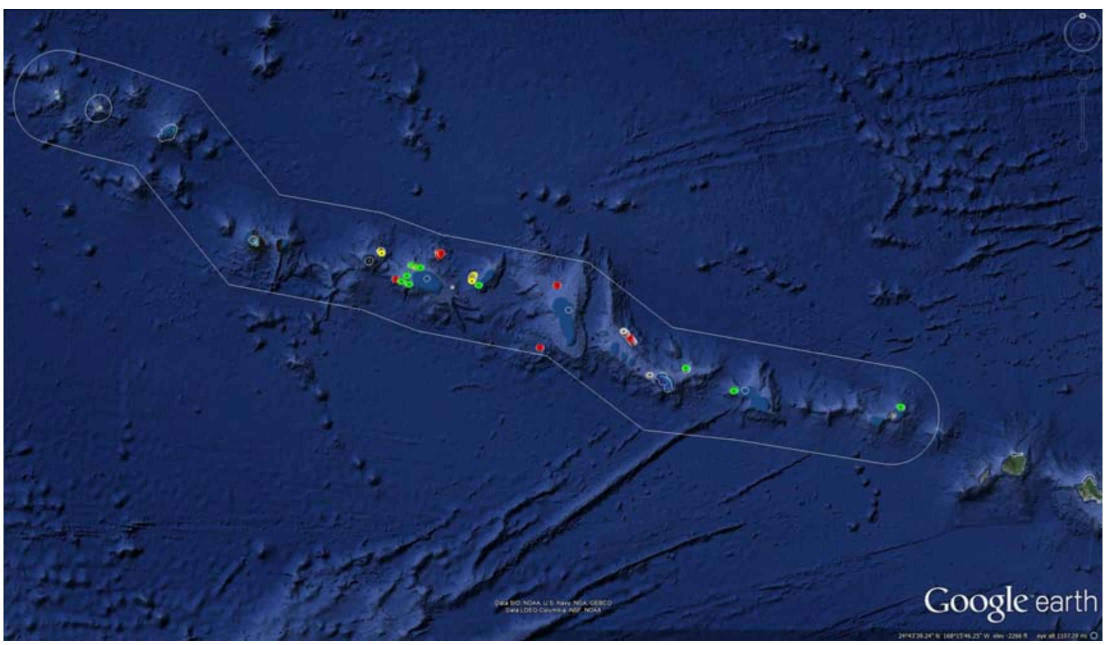

Figure 29: Google Earth image of the marine mammal observations made during cruise FK140502. The white line shows the boundary of the Papahānaumokuākea Marine National Monument in the Northwestern Hawaiian Islands. Different colored dots represent different types of mammals (red: sperm and killer whales, yellow: pilot and minkie whales, green: dolphins, and gray: unidentified cetaceans).

up on the water column window at the bottom of the display (Fig 30). This is likely the first time this phenomenon has been documented and provides a potential means of detecting that these animals are in the vicinity of the ship at night when visual observations are not possible.

Table 1: Summary of cetacean encounter data from both cruises

Category	Species	Sightings	Group min	Group max
dolphin	bottlenose dolphin	8	1	7
	dolphin sp	10	1	15
	spotted dolphin	1	3	6
whale	humpback whale	6	1	8
	minkie whale	6	2	5
	false killer whale	3	2	2
	orca	1	5	5
	pilot whale	1	100	100
	short-finned pilot whale	2	3	14
	sperm whale	13	1	6
	humpback or sperm whale	1	1	1
	unidentified whale	3	1	4
cetacean	unidentified cetacean	10	1	30
seal	Hawaiian monk seal	1	1	1
Grand Total		**66**		

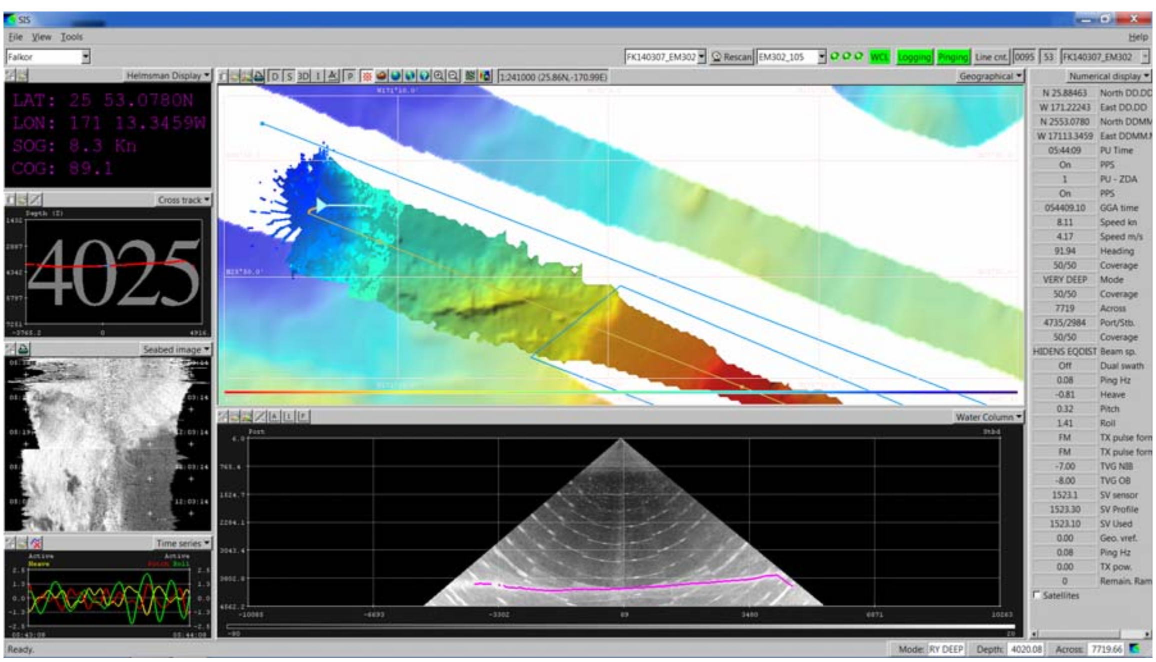

Fig 30: Screen grab of the SIS EM302 display showing apparent interference from sperm whale calls that appear as concentric "pearl on a string" rings in the water column window at the bottom of the display.

Figure 31 provides an example of the ship and cetacean plots in ArcGIS made to illustrate how the encounter took place. Of particular interest was whether the animals potentially passed through the multibeam ensonification planes and if so, were there any discernable changes in behavior.

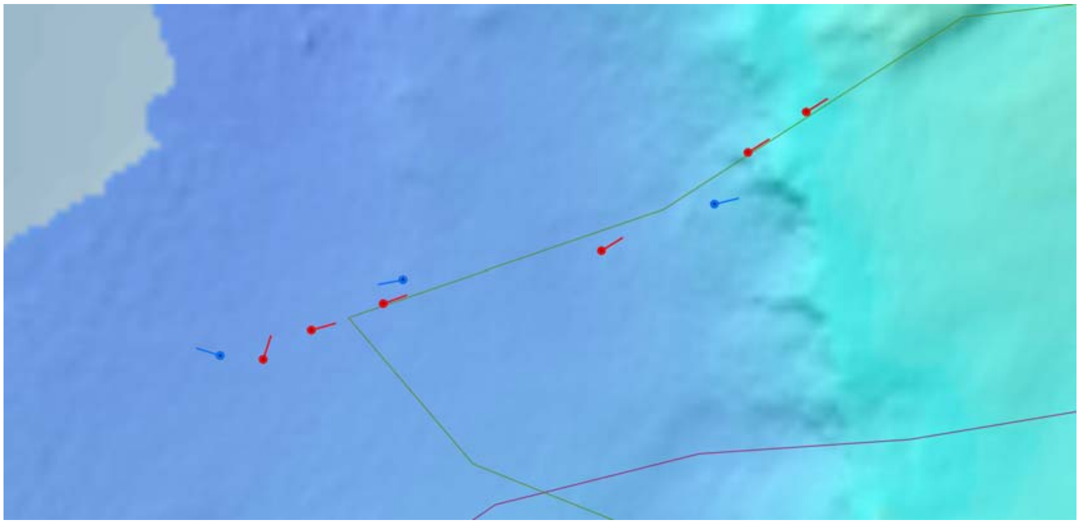

Fig 31: Example of plots showing the ship location and direction (red dots and vectors) relative to the cetacean location and direction (blue dots and vectors) created in ArcGIS.

Distance from the ship was an important part of the interpretation of these data and Table 2 provides a summary of distance information during the encounters for each species. Nineteen encounters involved animals that came within 200 m of the *Falkor* and therefore were likely exposed to sound levels reaching 160 db re 1 µpa. Thirteen of these involved dolphins and a false killer whale that approached the ship to "ride the bow wave". Thirty-two of the encounters took place between 200 and 1000 m of the ship, a range that the animals would be exposed to at least 140 db re 1 µpa if they passed through the ensonification planes. Many of these animals during these encounters did appear to be exposed to the plane. However, the trained observer did not see any obvious negative reaction by any species for these or any other encounters. All of the behaviors such as "spy hopping" were typical of those seen by the trained observer on other boats and ships not engaged in mapping activities.

Table 2: Summary of cetacean encounters showing the number of each species relative to the minimum distance they were observed from the ship

Category	Species	Sightings	200m Zone	200-1000m Zone	>1000m Zone
dolphin	bottlenose dolphin	8	6	1	1
	dolphin sp	10	5	5	
	spotted dolphin	1	1		
whale	humpback whale	6		6	
	minkie whale	6		2	4
	false killer whale	3	1	2	
	orca	1		1	
	pilot whale	1	1		
	short-finned pilot whale	2	1	1	
	sperm whale	13	2	7	4
	humpback or sperm whale	1		1	
	unidentified whale	3			3
cetacean	unidentified cetacean	10	1	6	3
seal	Hawaiian monk seal	1	1		
Grand Total		**66**	19	32	15

Publications

Since this final report is due only 3 months after the cruises, there has not been enough time for thorough data analysis, manuscript preparation, submission, review, and publication. However, within the past 3 months, a draft of the first manuscript has been prepared and is currently circulating amongst co-authors for final edits prior to submission to *EOS*. This paper is focused on the data acquired during the first cruise, a copy of which will be provided to SOI once it comes out in publication. In addition, two abstracts have been submitted for presentations at the upcoming American Geophysical Union's December 2014 meeting in San Francisco. The first, titled *"New R/V Falkor Multibeam Data from the Papahānaumokuākea Marine National Monument in the Northwestern Hawaiian Islands"* and the second, titled *"Spatial Distribution, Density Structure, and Relationship of Intrusive and Extrusive Volcanics of Seamounts Along the Northwest Hawaiian Ridge"*, provide introductions and initial interpretations of the multibeam, gravity, and magnetics data, respectively.

More publications from these cruises are a certainty because a second publication for EOS or equivalent venue is planned to present data from the second cruise and most if not all of the data will be used in J. Tree's dissertation. A complete copy of the dataset has also been sent to David Clague at MBARI who is working on the terraces around Gardner. These are just of few of what we expect will be a significant number of the publications resulting from the datasets.

Datasets and means of accessing them

Table 3 provides a summary of the data products yielded by these two cruises which is followed by a brief discussion of the data products per category.

Table 3: Summary of data acquired on FK140307 and FK140502

INSTRUMENT	DATA TYPE	CRUISE	DATASET	RANGE
EM 302 Multibeam	Bathymetry	FK140307 FK140502	60,880 km^2 65,908 km^2	30-5,543 m 28-5,188 m
	Backscatter	FK140307 FK140502	60,880 km^2 65,908 km^2	30-5,543 m 28-5,188 m
EM 710 Sonar	Bathymetry	FK140307 FK140502	2,869 km^2 6,300 km^2	30-2,315 m 28-2,034 m
	Backscatter	FK140307 FK140502	2,869 km^2 6,300 km^2	30-2,315 m 28-2,034 m
Gravimeter	Gravity data	FK140307 FK140502	14,585 km 15,254 km	30-5,543 m 28-5,188 m
Magnetometer	Magnetics data	FK140307 FK140502	14,585 km 15,254 km	30-5,543 m 28-5,188 m
CTD	depth, temp, sal, sound velocity	FK140307 FK140502	19 Stations 2 Stations	0-1000 m 0-1000 m
XBT	depth, temp, sal, oxygen	FK140307 FK140502	10 Stations 35 Stations	0-760 m 0-760 m
Observer	cetacean observations	FK140307 FK140502	29 Obs 34 Obs	surface surface

Multibeam data

A post-cruise data management meeting was held on June 27 to create the plan for distributing the data. The meeting was attended by participants from UH and NOAA CRED, with SOI's Allison Miller listening in via Skype. Following the meeting, a metadata file was created by the PI and sent with the raw and edited data along with grids to Vicki Ferrini at LDEO. Vicki offered to be a "one stop shop" for the data and provided the following plan of action via email:

"The processed MB data is very straightforward in terms of format and we will work to get it ingested into MGDS on Tuesday. I expect it to go quickly, so we should be able to send you a URL on Tuesday (Wednesday at the latest). Once processed MB data are integrated into MGDS, we will put the data in the queue for inclusion in our global bathymetry synthesis (GMRT) which will make it broadly accessible through a variety of interfaces (and will greatly benefit our user community). The next release of GMRT is scheduled for October. Any remaining unprocessed underway data will ultimately be cataloged via our partner program R2R (http://www.rvdata.us), also hosted here at LDEO, which will ensure that data are propagated to the appropriate long-term NOAA archives. We are currently negotiating with SOI to establish routine data services (via both MGDS & R2R), so the underway data will not be propagated through R2R until we finalize those details."

Vicki has already completed the first step of this process and recently provided the PI with the following URLs where the data can be accessed by the public:

http://www.marine-geo.org/tools/search/entry.php?id=FK140307
http://www.marine-geo.org/tools/search/entry.php?id=FK140502

She also stated that the data will be incorporated into their next release of GMRT for broad dissemination and in their next update to Google Ocean. Vicki has also agreed to pass the data onto Commander Ben Evans for review and potential incorporation into NOAA nautical charts.

A meeting was recently conducted with Michael Akridge at the University of Hawaii who is responsible for both the SOEST and NOAA PIBHMC websites. He has agreed to serve out syntheses of the *Falkor* bathymetry and backscatter on both websites, starting first with SOEST as soon as he receives the files. The syntheses have already been created and the PI and co-PI just need to prepare modified metadata files before sending them to Michael. This should be completed the week of September 15.

CTD and XBT Data

CTD and XBT data have already been provided to Pat Caldwell of NOAA's National Oceanographic Data Center (NODC) for incorporation into his database. Pat is the repository for this type of data from all over the Pacific.

Gravity and Magnetics Data

The gravity and magnetics data are considered somewhat different products from the multibeam data, which were collected as a result of a separate grant award by NSF. These data will be an important part of the dissertation of at least one graduate student (J. Tree) and as such, will be withheld until the dissertation is submitted and published. At that time, the data will be submitted separately to NGDC by the student.

Cetacean Observations

The PI has already met with one member of NOAA's Endangered Species (ESA) Group responsible for section 7 reviews for monument access permit applications. A second meeting involving NOAA cetacean specialists is planned at which time the data will be presented and offered to both groups. At that meeting, the PI will solicit feedback on whether the data are adequately robust for publication.

Media materials generated

Media materials such as blogs and Google "balloons" were prepared and submitted during the cruises as part of the science team responsibilities. The blogs are available on the SOI website and the balloons are available on GoogleEarth. The PI along with SOI's Colleen Peters and Mark Schrope were interviewed by Carlie Wiener, now with SOI, on her radio show "All Things Marine" (Fig. 32). SOI already has a copy of the audio file from that show. After the first cruise, the science team and SOI staff were also interviewed for local news broadcasts, from which two stations created and broadcast stories about the cruise.

Fig. 32: The PI, Christopher Kelley (left), along with SOI's Colleen Peters (center) and Mark Schrope (right) in the studio for the "All Things Marine" radio show.

Ship and science team members were also interviewed and videotaped by the producer and host of the Voice of the Sea television series for a 30 min story that will appear next Spring. The PI also took GoPro video during the cruises which he provided for the show. The PI has also done an interview for the Seawords online newsletter which was published in the September 2014 issue and can be accessed at:

http://issuu.com/seawords

Finally the PI gave a seminar about the cruises to faculty and staff of the Hawaii Institute of Marine Biology. This presentation was already provided to SOI's Carlie Wiener for use in two upcoming seminars she is giving on SOI.

Other: Geology and Geophysics Graduate Level Course

As mentioned earlier, a graduate level course in the Geology and Geophysics Department at the University of Hawaii (G & G614 Field Study) was created as part of the project. A total of 9 graduate students participated during the cruises, 3 on FK140307 and 7 on FK140502 (one student, J. Tree) participated on both. Of these, 5 were from the University of Hawaii, 3 were from University of Sydney's School of Geosciences, Geocoastal Research and one was from the University of British Columbia. All of the students gained considerable experience in carrying out projects at sea on large oceanographic vessels and were required to learn the basic functions of Hypack 2013 for survey line planning and magnetometer data acquisition, Seafloor Imaging Systems (SIS) for multibeam data visualization and acquisition, SABER and Caris for multibeam data editing and processing, SVP editor and Turo XBT for XBT data acquisition and processing, and Fledermaus as well as ArcGIS for multibeam bathymetry and backscatter data visualization and display.

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