Cruise Report

KNOX06RR

R/V Roger Revelle

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Summary

Hotspots have become a hot topic in geoscience. A few years ago it was widely accepted that many seamount chains, aseismic ridges, and oceanic plateaus were created by plume volcanism, yet today the idea of mantle plumes is undergoing unprecedented re-examination. In particular, questions have arisen concerning the existence and source depth of mantle plumes, the role of plumes in forming large igneous provinces, and the fixity (i.e., motion or lack thereof) of hotspots in the mantle. Hotspots form regional and global reference frames that require regional and global study. We have proposed IODP drilling expeditions to hotspot tracks in the Indian Ocean (Chagos-Laccadive and Ninetyeast Ridges) and Atlantic (Walvis Ridge) to complement paleomagnetic results from the Hawaiian-Emperor chain in the Pacific (ODP Leg 197) that show extensive motion of the Hawaiian hotspot. These proposed drilling cruises will provide data for re-examining hotspot models for these seamount chains as well as testing whether or not they are fixed relative to the spin axis or mantle reference frames. The Ninetyeast Ridge is an important Indian Ocean hotspot track because it is long (5000 km), is a major constraint for the motion of the Indian plate relative to hotspots, and its older end is contemporaneous with the northern Emperor chain. However an understanding of the Ninetyeast Ridge is hampered by lack of high quality geophysical data as well as a lack of state of the art geochronological data that can discern among various tectonic hypotheses for aseismic ridge formation. For example, simple hotspot models for the Ninetyeast Ridge have a monotonic age progression whereas recent hypotheses for its evolution include spreading ridge jumps that may have produced a discontinuous and possibly inverse age progression.

To collect site survey data for the proposed drilling program and to test the hotspot hypothesis for Ninetyeast Ridge, we proposed the collection and analysis of geophysical data (bathymetry, magnetic, and seismic) and sampling of igneous basement by dredging at several sites along the 5000-km long ridge. This project is a collaborative effort of three primary investigators William Sager (TAMU; geophysics), Frederick Frey (MIT; geochemistry), and Malcolm Pringle (MIT; geochronology). These investigators are collaborating with one Canadian geochemist (D. Weis, UBC), two geophysicists from India (D.Gopala Rao and K. S. Krishna), and one from Russia (O. Levchenko), all of whom provide significant additional expertise and access to non-US data on Ninetyeast Ridge.

The cruise was originally scheduled as a 56-day expedition from Phuket, Thailand to Malé in the Maldives; however, the ship's bow thruster developed problems shortly before the cruise, so it was necessary to change the end port to Singapore and to remove 6 days from the cruise. The *Revelle* departed Phuket at 1600 (local) on 18 June 2007 and landed at Singapore at 0800 (local) on 6 August 2007 after 48.6 days at sea.

During the cruise, 3631 km of seismic data were collected with the Scripps 48-channel streamer at six sites and multibeam echosounder bathymetry, 3.5 kHz echosounder profiles, magnetic, and gravity data were collected continuously while underway. These geophysical data will be used to determine the morphology, structure, and tectonics of ridge volcanoes and to determine whether the volcanoes reflect centralized (plume) or distributed (crack) eruptions. Seismic data documented the shift in sedimentation regime from north to south, from thick sediments covering most edifices nearly completely to thin sediments on the younger part of the ridge. The multibeam and seismic data show dramatic differences in the edifice structures, from individual large volcanoes in the north, to small seamounts and ridges in the middle, and the large high ridge in the south. Both datasets also show that the edifices in the central and southern part of the Ninetyeast Ridge are highly dissected by faults with two or three different

trends, possibly indicating different sources or mechanisms of deformation. Preliminary results will be presented at the fall AGU (Eisin, A., et al., " Preliminary Geophysical Results from the Ninetyeast Ridge Expedition").

Dredging was done at 33 stations, spanning 3000 km of the Ninetyeast Ridge, recovering 3144 kg of rock, including 2238 kg of basalt. Geochemical and isotopic studies of the basaltic basement will be used to infer the magmatic evolution of the ridge, specifically, are the geochemical characteristics consistent with the plume hypothesis, and a connection to existing hotspots (e.g., Kerguelen). Recovery of basalt at 23 locations will enable determination of local geochemical variability, that is study of several dredges from a single seamount, and long-term geochemical variation, that is study of dredges from multiple seamounts spanning 3000 km of the Ninetyeast Ridge. Geochronological data for the dredged rocks will be used to examine the duration of volcanism at the various sites and to determine if the along-ridge age progression fits a simple hotspot track model. At the fall 2007 AGU we will present an abstract based on our new geochronogical data for core samples from 5 drill sites on the Ninetyeast Ridge (Pringle, M. S., et al., "New Ar/Ar ages from the Ninetyeast Ridge, Indian Ocean: Beginning of a robust Indo-Atlantic hotspot reference frame").

I. Background

Ninetyeast Ridge and the Hotspot Hypothesis

For more than 30 years, "hotspots," i.e., melting anomalies that create age-progressive, linear seamount chains or ridges, such as the Hawaii-Emperor Chain and the Ninetyeast Ridge (NER), have been attributed to mantle plumes. As applied today, the hotspot hypothesis consists of three related ideas. The first is the kinematic hotspot hypothesis, in which an age progressive volcanic chain is formed as the lithosphere moves over a melting anomaly (Wilson, 1963). The second is the fixed hotspot hypothesis, in which melting anomalies show little relative motion and can therefore be considered markers for the mantle (Morgan, 1971). The third is the mantle plume hypothesis, which explains hotspots as decompression melting from buoyancy-driven columnar upwellings of deep mantle material (Morgan, 1971). Although widely-accepted, the latter two hypotheses have recently come under increased scrutiny.

Early models of plate motion relative to the hotspots were formulated mainly from geometry because geochronologic data were sparse and often of poor quality. Model calculations were based on the observation that many prominent seamount chains appeared to follow small circles congruent with common rotation poles (Morgan, 1971; 1972). During the 1970s through 1990s there was widespread documentation and confirmation of hotspot-based plate motion models in the Pacific, Indian, and Atlantic oceans as more reliable geochronological data became available (e.g., Jarrard and Clague, 1973; Morgan, 1981; 1983; Duncan, 1981; Duncan and Clague, 1985; Duncan, 1991; Müller et al., 1993; Wessel and Kroenke, 1997; Harada and Hamano, 2000). In general, the fit of geochronlogic data to simple first-order velocity fields was considered a success story for the hotspot hypothesis and the idea gained wide acceptance. Indeed, the hotspot reference frame has been used as the foundation for thousands of tectonic and paleogeographic studies (e.g., Engebretson et al., 1984; Besse and Courtillot, 2002).

The existence and behavior of hotspots also has important implications for mantle geodynamics. Morgan (1971; 1972) argued that the upper mantle was too fluid to maintain hotspot fixity and therefore plumes must be rooted in the lower mantle. He thus concluded that mantle plumes were a primary form of upwelling, implying some degree of whole mantle convection. As more age-progressive seamount chains were documented, postulated hotspots proliferated (e.g., Wilson, 1973; Vogt, 1981) to the point where doubts arose about all of them being sourced in the lower mantle. A recent review of hotspot volcanism divides plumes into three classes, based on the depth of origin: primary plumes rooted in the deep mantle, secondary plumes starting from the transition zone or middle upper mantle, and tertiary plumes with shallow, sub-lithospheric sources (Courtillot et al., 2003). If such interpretations are correct, the number of "primary" or deep-rooted plumes may be small.

During the past few years, the fixed hotspot and mantle plume hypotheses have received unprecedented criticism. While many scientists still think these ideas are valid (e.g., Besse and Courtillot, 2002; Sleep, 2003), a growing minority dismisses them entirely, alternatively attributing melting anomalies to upper mantle and plate processes (e.g., Smith and Lewis, 1999; Anderson, 1995; 2000; 2001; 2005; Foulger, 2002; Foulger, in press). Furthermore, computer modeling of the evolution of mantle density anomalies (e.g., Steinberger and O'Connell, 1997; 2000) implies that upper mantle plumes should not be fixed, but instead are distorted by mantle flow. Moreover, the mismatch between Pacific and Indo-Atlantic hotspot reference frames (Cande et al., 1995; Raymond et al., 2000) and troubles with reconciling the bend in the

Hawaiian-Emperor seamount chain with regional tectonics and mantle dynamics (Norton, 1995; 2000) have led others to dismiss the idea of fixed hotspots (e.g., Tarduno et al., 2003). As a consequence, the hotspot hypothesis is being re-examined and results of new tests will have a huge impact on geodynamics theories and research.

The Deep Sea Drilling Project (DSDP) and Ocean Drilling Program (ODP) have played a pivotal role in the debate about hotspots. Several early legs cored hotspot-related features, resulting in many important geochemical and age constraints, but few holes penetrated deeply into igneous basement. Deeper (>100m) penetrations of igneous basement were achieved during Legs 183 and 192, which focused on understanding the origin of the two very large submarine igneous provinces, the Ontong Java and Kerguelen Plateaus, and testing the plume head model for the origin of ocean plateaus. The only recent ODP leg that directly sampled a hot spot lineament was Leg 197, which cored three seamounts in the Emperor Chain to test the fixity of the Hawaiian hotspot via paleomagnetism (Tarduno et al, 2002; 2003). Leg 197 paleomagnetic data confirmed prior results (Kono, 1980; Gordon and Cape, 1981; Sager and Bleil, 1987; Petronotis et al., 1994; Tarduno and Cottrell, 1997; Petronotis and Gordon, 1999) indicating ~14^{o} southward drift of the Hawaiian hotspot from 81-45 Ma (Tarduno et al., 2003). Although these data confirm the southward hotspot drift, the results do not answer unequivocally the question of whether hotspots constitute a mantle reference frame. Do hotspots move in concert or independently in different ocean basins? This question can only be answered by examining hotspot seamount chains in other oceans. Without data elsewhere, we cannot determine whether the Hawaiian hotspot drift resulted from a coherent motion of all hotspots (i.e., true polar wander (TPW), e.g., Duncan and Storey, 1992) or whether the shift is regional.

We have proposed a drilling cruise (IODP Proposal #620) to core basalt samples from the NER and Chagos-Laccadive Ridge in the Indian Ocean (Fig. 1) with the goal of determining hotspot motions and evolution in the Indian Ocean using paleomagnetic, age, and geochemical data from deep basaltic basement penetrations (200-300 m). We targeted these ridges because they are the main hotspot tracks that have been used to define Indian Ocean plate motion relative to the mantle (e.g., Morgan, 1981; 1983; Duncan, 1981; Royer et al., 1991; Müller et al., 1993). Even though the plate motions derived from hotspot models of these ridges are widely used, the existing geochronological data base is not sufficient for detailed plate motion calculations (c.f., Baksi, 1999).

A significant hurdle for IODP-620 is the paucity of site survey data. The NER and Chagos-Laccadive Ridge have received scant attention from scientific cruises in recent years. As a result, we were forced to propose drilling at existing DSDP and ODP drill sites because there are few recent-vintage seismic data from either ridge. Moreover, seismic data used for previous DSDP and ODP drilling cruises were mostly collected >25 years ago. Therefore, both data density and quality are low. Because a critical objective of the IODP-620 program is to determine reliable paleolatitudes for the drill sites, high quality data are needed to understand the geological and tectonic development of possible drill sites.

Although our IODP proposal addresses both hotspot tracks, we focused this cruise exclusively on the NER. By itself, the NER is a very large feature, ~5000 km in length, and proposing a survey of both ridges is too much for one cruise. Furthermore, there are significant uncertainties about the evolution of the NER that must be solved to understand results from drilling. The NER also records a longer span of plate motion relative to the mantle and it is the location of more of the proposed drill sites. A major objective of this proposal is to obtain state-of-the-art seismic and bathymetric data required for selection of drill sites. Equally important are radiometric ages and geochemical data from basement dredges at several sites to provide tighter constraints on hypotheses for origin of the NER. Expanded areal data coverage will complement basement sampling at drill sites, which are necessarily limited in number. In comparison, we sampled igneous basement at 23 sites, whereas igneous basement recovery by drilling has occurred at only 7 sites.

Tectonic Overview

NER, an aseismic, volcanic ridge, is one of the longest linear features on earth, stretching N-S from 31°S at its intersection with Broken Ridge to 10°N, where it disappears beneath sediments of the Bengal Fan (Fig. 2). At its tallest, the ridge rises ~3.5 km from the surrounding abyssal plain to summits shallower than 2000 m. Magnetic lineation breaks and satellite altimetry data show that the NER is nearly, but not exactly, parallel to fracture zones formed at a paleospreading ridge that once separated the Indian and Australian plates (Royer and Sandwell, 1989; Krishna et al., 1995; 1999). Despite its apparent continuity, the morphology of the ridge varies with latitude. Its northern end, from 10°N to the equator, consists of individual, irregular edifices separated by areas of abyssal seafloor (Fig. 2). At ~10°S, the morphology changes to a narrow, high, linear ridge. In the interval between 10°S and the equator the ridge consists of low edifices, that are smaller than those to the north and south. Krishna et al. (2001) postulated that this section was down-dropped by ongoing faulting related to the breakup of the Indo-Australian plate; however, the continuation of Central Indian Basin faulting into NER is unproven. Most authors attribute these differences in morphology to the changing geometry of the plate boundaries near the hotspot eruption site (e.g., Royer et al., 1991).

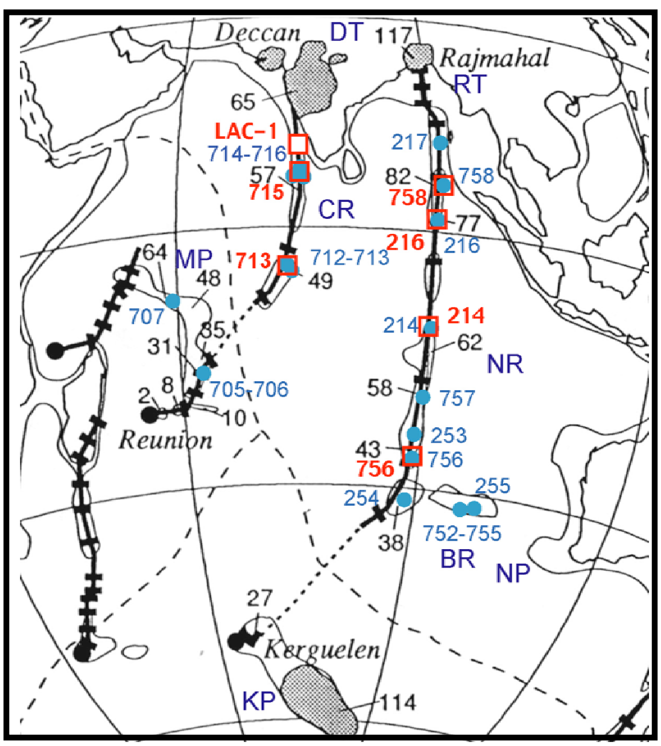


Figure 1. Locations of Ninetyeast and Chagos-Laccadive ridges and proposed primary and alternate drill sites (red boxes) from IODP proposal #620. LAC-1 and 756 are alternate sites; the other five are primary. Blue filled circles and numbers are DSDP and ODP drill sites that cored these hotspot tracks. Lines with ticks represent hotspot tracks and predicted ages (Duncan and Storey, 1992). Black numbers give ages along hotspot chains.
NR=Ninetyeast Ridge
KP=Kerguelen Plateau
BR=Broken Ridge
CR=Chagos-Laccadive Ridge
MP=Mascarene Plateau, Saya de Malha, and Nazareth banks
NP=Naturaliste Plateau
DT=Deccan Traps
RT=Rajmahal Traps.

Sediments atop the summit of the NER are typically ~150-500-m thick pelagic oozes that grade to volcaniclastics near basement (von der Borsch et al., 1974; Luyendyk, 1977; Peirce et al., 1989). Nevertheless, seismic sections show that the ridge flanks have many bare spots. In particular, along the east side of the southern NER (from Site 253 to 214), the ridge is bounded by a steep scarp that may have resulted from fracture zone tectonics (Royer and Sandwell, 1989; Krishna et al., 2001). Elsewhere, steep seamount flanks and local zones of erosion provide exposures of basement (e.g., Davies et al., 1974; Krishna et al., 2001).

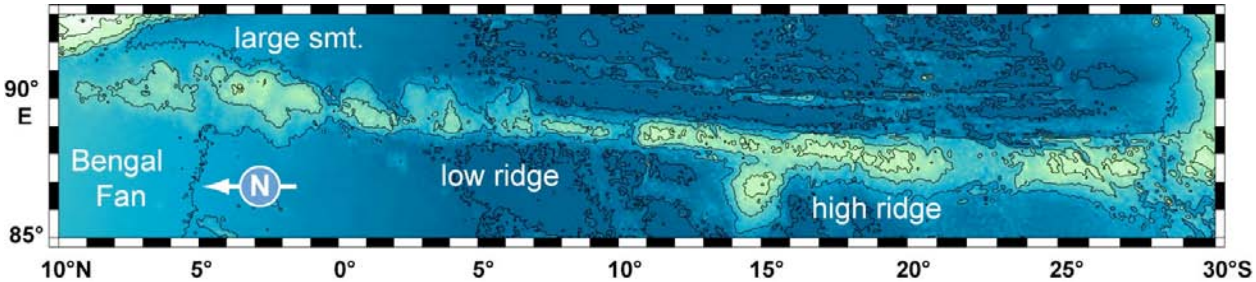


Figure 2. Morphology of the Ninetyeast Ridge. North is at left. Predicted bathymetry contours at 1000-m intervals (Smith and Sandwell, 1997).

Origin of the Ninetyeast Ridge

Many different tectonic explanations have been given for the origin of the NER. It has been suggested that the ridge formed by an uplifted fragment of thick ocean crust (Francis and Raitt, 1967; Laughton et al., 1970), a ridge uplifted by overthrusting between two converging parts of the Indian plate (LePichon and Heirztler, 1968), a relict ridge resulting from a reorganization of the Southeast Indian Ridge (McKenzie and Sclater, 1971), an abandoned, paleospreading ridge (Veevers et al., 1971), and volcanism along a leaky transform fault (Sclater and Fisher, 1974; Sclater et al., 1974). Following fossil dating, radiometric dating, and geochemical studies on cores from DSDP Legs 22 and 26 and ODP Leg 121, the consensus is that the NER formed from age progressive, hotspot volcanism from a mantle plume source (e.g., Royer et al., 1991; Weis et al., 1992). The most widely accepted hypothesis is volcanism from a single hotspot, now located beneath Kerguelen Plateau (Royer et al., 1991). This model predicts ridge edifice ages that increase monotonically northward (Fig. 3). A two-hotspot model has also been proposed (Luyendyk and Rennick, 1977), with both the Kerguelen and Amsterdam-St. Paul hotspots contributing to ridge formation. In this scenario, volcanism may have occurred twice at locations along the ridge, with a gap of 10-15 m.y., as sites drifted over both hotspots. Existing radiometric dates and geochemical data from NER are too few, however, to test such a model. A significant issue for the single hotspot model is that fact that surrounding spreading ridges imply that the amount of Indo-Australian plate created at the Wharton spreading center was much less than the length of NER and that there were southward jumps of that ridge (Krishna et al., 1999). If that is so, then we might expect to find some elements of the ridge with reverse age progressions. Some authors reject the hotspot hypothesis altogether, for example, postulating the NER formed from volcanism along tensional cracks in the Indian plate (e.g., Sheth, 1999). The trouble with this hypothesis is a lack of detail and predictive power, making testing difficult.

According to the single hotspot hypothesis, which is widely accepted, NER formed from Kerguelen hotspot volcanism on the Indian plate as the plate drifted northward during the Late Cretaceous and Cenozoic (Royer and Sandwell, 1989; Royer et al., 1991). The hotspot built much of Kerguelen Plateau during the Mid-Cretaceous near the intersection of India, Antarctica, and Australia when these continental blocks were still close to their Gondwana assemblage (Royer and Sandwell, 1989; Coffin et al., 2002). At about Chron 34 time (84 Ma), the Southeast Indian Ridge (SEIR; a.k.a., Wharton ridge) began slowly separating Australia from Antarctica and connected to existing spreading ridges south of India and in the Wharton Basin, forming a triple junction near the western edge of Kerguelen Plateau. The SEIR also began rifting Broken ridge from Kerguelen Plateau at this time, even though the rifting would not be completed for another ~45 m.y. (Royer and Sandwell, 1989). At about the same time, the northern end of the extant NER began to form over the hotspot, which was located near the triple junction. The hotspot simultaneously emplaced basalts on both the Indian and Antarctic plates, forming a ridge on the rapidly northward-moving Indian plate while augmenting the plateau on the Antarctic plate (Royer and Sandwell, 1989; Royer et al., 1991).

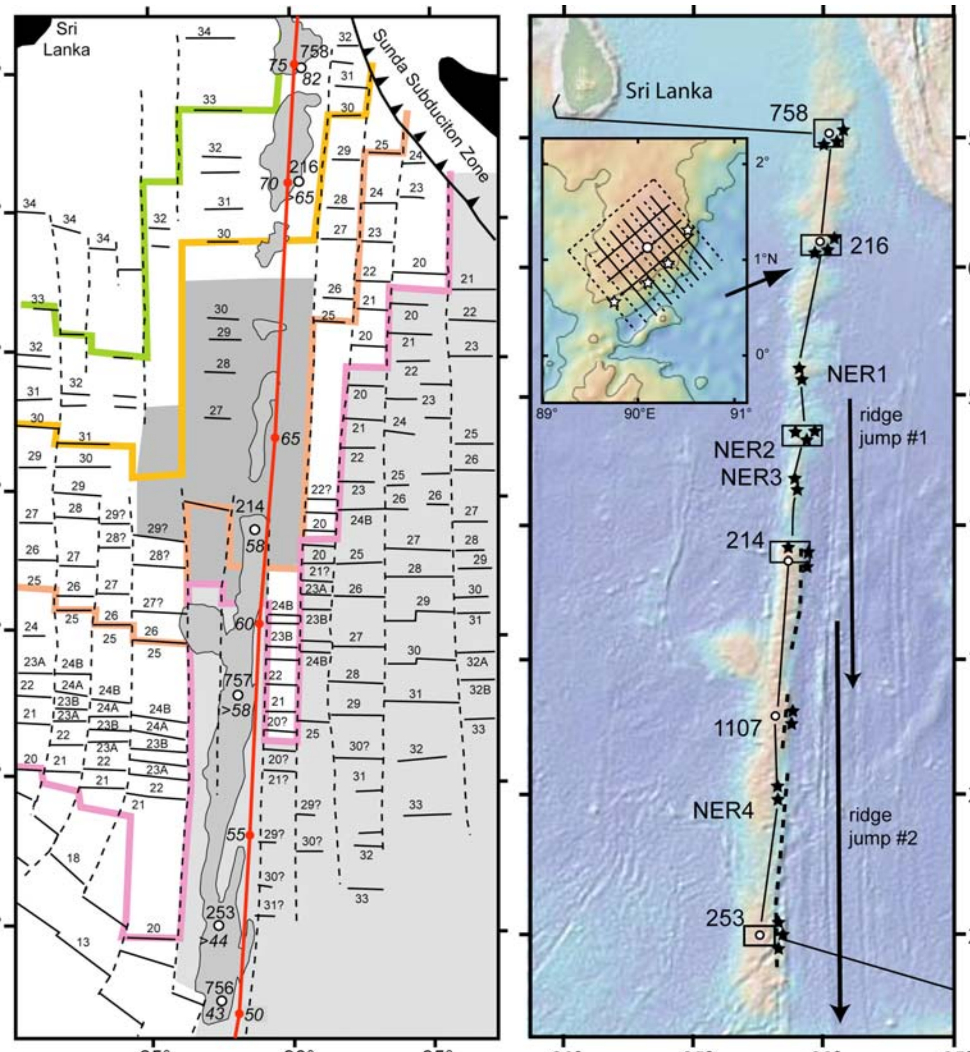


Figure 3. NER tectonic map (left) and proposed cruise work sites (right). Magnetic lineations (Krisha et al., 1995) shown at left as light lines with anomaly numbers. Dashed lines show inferred fracture zones. Outline of NER shown in gray with DSDP and ODP sites numbered. Numbers in italics next to sites are basement ages. Heavy colored lines show ridge crest at selected times: anomaly 33 (76 Ma), 30 (68 Ma), 25 (56 Ma), and 20 (43 Ma). Gray areas show Australian plate crust amalgamated into the Indian plate by proposed ridge jumps at anomaly 30 (Royer and Sandwell, 1989) and 20 (Krishna et al., 1995). Continuous, red, N-S, line near NER shows a hotspot drift model (Royer et al., 1991) with ages (in italics) every 5 m.y. (dots). Sites for survey (boxes) and dredging (stars) are shown in cruise plan at right. Inset shows example survey for Site 216 environs. Lines in survey pattern denote data types: all data

(bathymetry, seismics, gravity, magnetics) on solid lines; no seismics on dashed lines. Stars show dredge locations and open circle is Site 216. Cruise tracks are plotted on satellite-derived bathymetry (Smith and Sandwell, 1997).

Because the Kerguelen hotspot was near a triple junction, the junction geometry and the hotspot location relative to the three plate boundaries is an important factor controlling the evolution of NER. For example, if the hotspot was centered on the India-Australia ridge (Royer et al., 1991), hotspot volcanism was emplaced on both plates and the NER should display a uniform age progression. Alternatively, if the ridge were north of the hotspot, the ridge might have jumped southward to stay near the hotspot. Unfortunately, the precise location of the hotspot relative to ridge is uncertain because magnetic anomalies are difficult to recognize in the neighborhood of the NER (Royer and Sandwell, 1989; Krishna et al., 1995; 2001). The most recent tectonic models predict one or more major ridge jumps that may have moved reversed-age trend sections of the NER onto the Indian plate. Royer and Sandwell (1989) posit that a southward ridge jump at chron 26 time (60 Ma), transferred the section between ~7°-16° S (~60-70 Ma) from the Australian to the Indian plate, possibly resulting in a reversed age progression. This model also calls for several additional unspecified jumps farther south. Furthermore, the apparent abandonment of the India-Australia ridge at chron 19-20 time (43 Ma) resulted in a reversed age trend in the section of Australian plate amalgamated into the Indian plate (Krisha et al., 1995; 1999), possibly implying that other reverse-age segments of the NER formed on this part of the plate. Surprisingly, such age reversals are not addressed in accepted hotspot models of the ridge (Fig. 3), perhaps because of sparse age data along NER. Whatever the evolution of the southern ridge, it appears that volcanism continued to build the southern NER until the early Cenozoic (~40 Ma) when the Kerguelen hotspot moved south of the SEIR and subsequent volcanism was emplaced solely on the Antarctic plate.

Geochemical Evolution

The NER was sampled by DSDP and ODP drilling at 7 sites (Fig. 1) with basalt recoveries ranging from 35 cm at Site 253 to 119 m at Site 758. All sites recovered tholeiitic basalt that is unlike MORB in abundances of incompatible elements and radiogenic isotope ratios of Sr, Nd, Pb (Figs. 4, 5). NER basalt geochemical characteristics are similar to ocean island basalt; therefore, to first order a plume origin is favored (Frey et al., 1991; Weis and Frey, 1991; Weis et al., 1992; Frey and Weis, 1995). Unlike Hawaiian volcanoes, no alkalic basalt has been recovered from the NER. Frey and Weis (1995) inferred that the absence of alkalic basalt is expected in a near-ridge centered hotspot, such as Iceland.

Is there compelling geochemical evidence for NER lavas being related to the Kerguelen plume? In recent years much has been learned about the Kerguelen plume from basalt recovered from the Cretaceous Kerguelen Plateau during ODP Leg 183 and studies of the Cenozoic flood basalt forming the Kerguelen Archipelago (see papers in "Origin and Evolution of the Kerguelen Plateau, Broken Ridge and Kerguelen Archipelago" in *Jour*. *Petrol*. 43 (7), 2002). Pertinent observations for understanding the NER are: (1) the continental signature that occurs in some (but not all) Kerguelen Plateau basalts is absent in NER lavas (Fig. 6); therefore, the continental fragments that contributed to the Cretaceous basaltic volcanism of the plateau (e.g., Mahoney et al., 1995; Nicolaysen et al., 2001, Ingle et al., 2002; Frey et al., 2002) did not affect basalts forming the NER. Perhaps the continental influence was confined to the early stage of Gondwana breakup. (2) The isotopic characteristics of NER basalts range from plume-like, e.g., overlap of Site 216 basalt with Kerguelen Archipelago basalt having the lowest $^{143}Nd/^{144}Nd$ and highest $^{87}Sr/^{86}Sr$ (Fig. 4) to possible mixtures of such plume-derived lavas with MORB, e.g., Site 214 and 758 (Fig. 5). Lavas from the northern Kerguelen Plateau at ODP Site 1140 are the best example of such mixtures (Figs. 4-5; Weis and Frey, 2002).

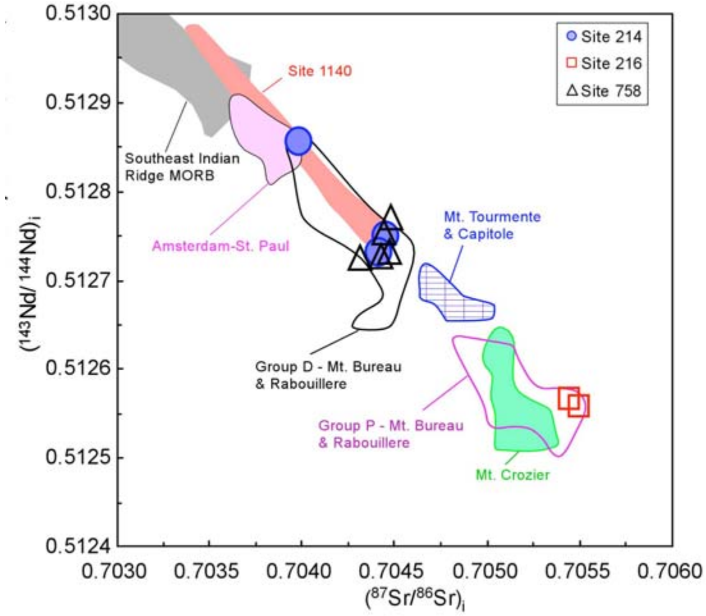


Figure 4. Plot of $^{143}Nd/^{144}Nd$ vs. $^{87}Sr/^{86}Sr$ showing that NER lavas (Sites 214, 216, and 758) encompass the range found in the Kerguelen Archipelago (fields for Mt. Crozier, Bureau, Rabouillère, Tourmente, and Capitole). This range is commonly inferred to reflect mixing between components derived from the northern Kerguelen plume (Mt. Crozier field) and a MORB source. Site 1140 lavas from northern Kerguelen Plateau are a good example of this mixing (Weis and Frey, 2002). Note that NER lavas are much more diverse than lavas from Amersterdam and St. Paul islands. See Figure 12 of Weis and Frey (2002) for data sources.

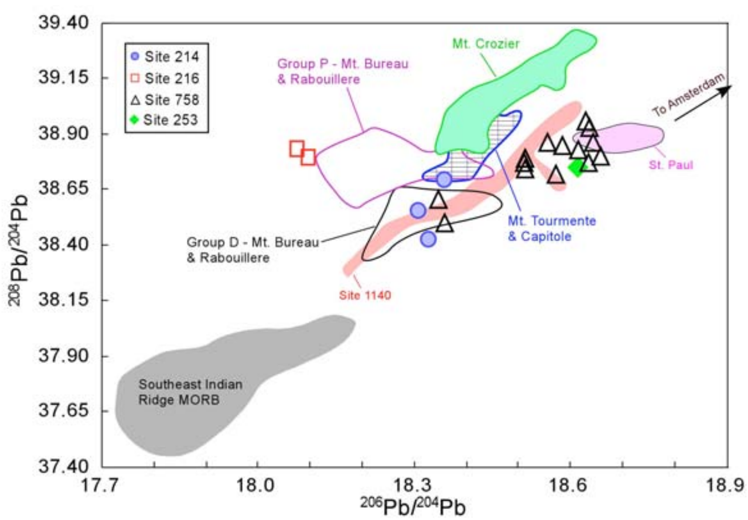


Figure 5. Plot of $^{208}Pb/^{204}Pb$ vs. $^{206}Pb/^{204}Pb$ for basalt shown in Figure 3. The anomalously low $^{206}Pb/^{204}Pb$ ratios of Site 216 lavas likely reflect the high and probably non-magmatic U/Pb ratios used for age correction (Frey and Weis, 1995). The other NER lavas are intermediate between field for SEIR MORB

and the fields for flood basalt sections from the Kerguelen Archipelago and St. Paul Island. Note that Pb isotopic ratios for some NER sites (i.e., 253, 758, and 756 (not shown) are similar to the field for St. Paul Island. Data sources as in Figure 4.

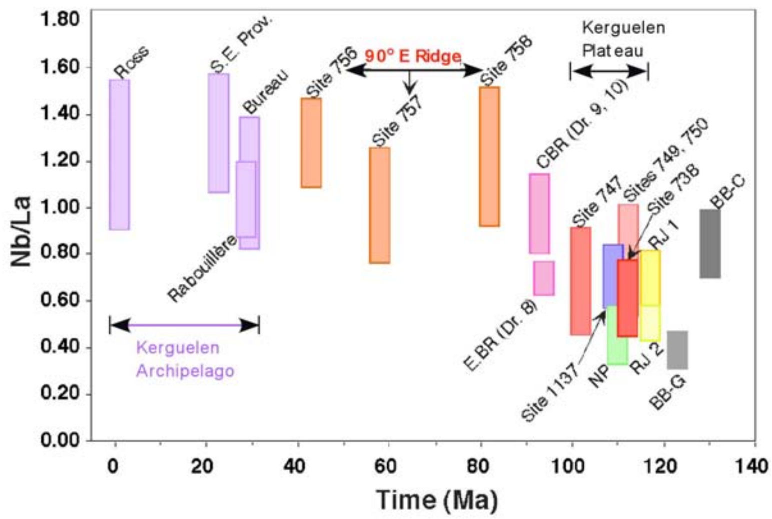


Figure 6. Nb/La versus age for basalt related to the Kerguelen plume. As discussed by Arndt and Christensen (1992), Nb/La <1 is an indicator of a continental crust component. Cretaceous basalt ranging from the continental Bunbury (BB) and Rajamahal (RJ) to Kerguelen Plateau and Broken Ridge (738, 747, 749, 750, 1137, EBR and CBR) all have Nb/La <1. In contrast Nb/La =1 in basalt from the NER and Kerguelen Archipelago. (Data sources given in Frey et al., 1991; Mahoney et al., 1995 and Frey et al., 2002).

Radiometric Dates

Tests of the kinematic and fixed hot spot hypotheses require accurate and precise age data, but acquiring realiable age data from volcanic rocks that have been altered in the submarine environment can be difficult. Ar/Ar geochronogy, and in particular the Ar/Ar step-heating technique, has proven to be the most reliable radiometric technique able to provide such data. However, it is only over the last 10 years that sample preparation and analytical procedures have been improved to the point that they are able to provide the precision and accuracy necessary for new tests of hotspot age progression. Essentially, what is required is (1) careful sample selection based on petrographic criteria, (2) careful groundmass and mineral separation including several acid-leaching techniques, and (3) use of of the latest generation of noble gas mass spectrometers for Ar/Ar analyses. Many of these techniques have been developed in response to samples collected from various ODP legs, or dredging programs in support of those legs (i.e., Pringle, 1992, 1993; Mahoney et al, 1993; Koppers et al, 1998, 2003).

A major goal of this program is to apply these new Ar/Ar techniques to Indian Ocean hotspot volcanism. The earliest products of Indian Ocean hot spot volcanism, and especially early products of the the proposed NER hotspot source, i.e., the Kerguelen Plateau and its on-land equivalents, are now well-studied (i.e., Coffin et al 2002; Duncan, 2002; Kent et al 2002). However, it is remarkable that no modern Ar/Ar analyses exist for the NER itself. R. A. Duncan provided nearly all of the existing Ar/Ar age data for the NER system in several seminal papers (Duncan, 1978; Duncan 1981; Duncan, 1991). These data are consistent with a general age progressive nature of volcanism, from ~82 Ma at ODP Site 758 to ~43 Ma at Site 756 and ~38 Ma at DSDP Site 254 (Figs 1, 3). However, all of these analyses were done on previous generation, lower resolution and sensitivity mass spectrometers. For example, Duncan was able to do no more than 6 to 8 step-heating experiments on samples 1-2 grams in size, whereas we can now do 12 to 20 step experiments on samples less than 100 mg in size, even for relatively low potassium phases such as plagioclase. A greater number of more precise analyses for each incremental heating experiment enables more rigorous statistical analysis necessary for the detailed hypothesis testing required in the proposed project.

IODP-620 and the need for site survey data

In IODP-620, drilling is proposed for three sites on the NER (Sites 214, 216, 758) and two on Chagos-Laccadive Ridge (713, 715) with the goal of collecting 200-300 m of lava flows at each site. Because of the lack of modern site survey data, we proposed reoccupying sites already drilled. At some sites it may be advantageous to build upon existing paleomagnetic data, but this strategy also restricts the project from addressing new sites that might provide insight about the evolution of the NER. Additionally, some sites have produced a paleolatitude that does not fit expectations (Vandamme and Courtillot, 1990; Klootwijk et al., 1991). Such results are often dismissed as "tectonically disturbed" without any geologic evidence to support the interpretation. Modern site survey data are badly needed to map the basement surface and faulting, to understand edifice tectonics, to avoid late stage volcanism (identified by volcanic cones on basement surface (e.g., Kopf et al., 2001), and to determine whether the single hotspot model is the best explanation for the NER formation.

Cruise Plan Overview

We proposed a 50-day geological-geophysical cruise to collect bathymetry, magnetic, seismic data and dredge samples. The long duration of the cruise was dictated by the length and remote location of NER as well as the ambitious science program. At five sites (boxes in Fig. 3), we planned to map a segment of the ridge with a multibeam echosounder, shoot a grid of seismic data, and take several dredges. At approximately 4 other locations, we planned only dredging. During all underway transit operations, we planned to collect multibeam bathymetry, magnetic, and gravity data. Although we would have liked more extensive geophysical surveying of the NER, we recognized that the immense size of the ridge would not permit a broader investigation. We were confident that suitable dredge samples could be obtained because of prior dredges collected from the NER. Furthermore, numerous published seismic profiles show scarps and outcrops (e.g., Krishna et al., 1995; Pilipenko, 1996). The planned work distribution for the cruise was as follows: 10 days of dredging (30 dredges at 3/day); 12 days of seismic profiling; 12 days of multibeam mapping; and 16 days of transit both between sites as well as to and from port (assuming ports in Columbo and Freemantle).

Sites were chosen with the following rationale. We proposed visiting each of the three sites currently proposed for NER drilling (214, 216, 758) as well as two additional potential drill sites (NER2 and Site 253). The IODP drilling proposal seeks to investigate the paleolatitude drift of the hotspot as well as the geochronologic evolution of the ridge as a whole and of individual sites. The chosen sites are distributed approximately evenly along the NER and they allow us to build upon existing data to better understand the existing sites and their context. At Sites 214, 216, 253, and 758, drilling has already occurred at the ridge summit, so ridge flank dredging some tens of km away will investigate temporal and geochemical variation near these sites. This will help answer the question whether the drill sites are representative of the whole edifice or whether there are significant age and geochemical differences within a small part of the ridge. Site NER2 was added because it is on a small edifice in the low portion of the ridge at a spot where volcanism appears to stretch from the center of the ridge eastward to a fracture zone. Site 253 was added to constrain ages and geochemistry on the far south part of the ridge. Sites NER4, 1107, NER3, and NER1 are dredge locations only, with the purpose of obtaining basalts suitable for radiometric dating and geochemical study. Although some multibeam bathymetry mapping will be done at dredge sites, it was envisioned that the coverage would be less than at survey sites where seismic profiles are also collected. Geochronology from sites NER1, 216, and 758 will provide an age progression north of any proposed ridge jump (Fig. 2); sites NER2, NER3, and 214 will give the age progression in the possibly reversed zone of the first ridge jump; and sites 757, NER4, and 253 will constrain the age and geochemical progression on the southern ridge. Site 1107 (757) is also the site of a cased, re-entry hole that could be deepened by future drilling.

II. Equipment and Methods

Geophysical Equipment

EM120 Multibeam Echosounder

A Kongsberg Simrad EM120 multibeam echo sounder was used for seafloor mapping for the duration of the cruise. This 12 kHz echosounder uses wideband, linear receiver-transmitter arrays that are arranged in a Mills cross configuration on the ship's hull. The sonar electronics form 191 beams per ping in a line perpendicular to the ship's axis. The EM120 is capable of creating a swath up to 150 degrees wide, equivalent to 7.5 times the seafloor depth. The transmit waveform is a FM sweep chirp, which uses pulse correlation in the receiving process to increase resolution and penetrating depth. The echo sounder achieves high accuracy independent of beam pointing angle by using a combination of phase and amplitude detection. Raw multibeam data were plotted on the ship's Calcomp pen plotter for use in real time survey and dredge planning. Multibeam data were later edited and processed onboard using Mbsystem software.

Corrections for variations in the sound velocity of the water column were made in the EM120 software. At each site, a Lockheed Martin Sippican Fast Deep Expendable Bathythermograph (XBT) was used to measure the temperature structure of the water column to a depth of 1000 m at each site and these data were entered into the EM120 software. Because the temperature is the main cause of changes in sound velocity with depth, typically only the temperature is measured with depth. The instrument also uses the salinity of the surface water, which was measured by a device in the ship's instrument well.

Knudsen 3.5 kHz Chirp Echosounder

A Knudsen 320B Series Black Box digital echo sounder was used to collect 3.5 kHz echosounder profiles of the seafloor and shallow subsurface during the cruise. This echosounder sends and receives acoustic pulses through a hull-mounted transducer. It processes the received signal using a bandpass filter with a passband centered at the transducer frequency, allowing the received echo to pass through while rejecting the ambient noise at all other frequencies. This echo sounder automatically compensates for the effect of draft (depth of the transducer below the sea surface) in the geographic record as well as in the digital depth display. Echo sounder data were recorded digitally as SEG-Y files. Profiles were processed and compiled onboard using ProMAX software.

Multichannel Seismic System

High-resolution 2D seismic reflection data were collected at six sites along the NER using the same configuration of source and receiver at all sites. The sound source was two GI air guns and the receiver was a 48-channel hydrophone array (streamer). System geometry is shown in Figure 6.

Airguns. An array of two identical generator/injector (GI) air guns was used as a seismic sound source. These devices have generator volumes of 45 in^3 and injector volumes of 105 in^3. The air guns were towed 24 m behind the stern at a depth of ~4 m. Shots were fired every 10 seconds at a ship speed of 6 knots, yielding a shotpoint interval of 30.9 m and ~10 fold data. One air gun was towed off the starboard side of the stern and the other off the port side. If the magnetometer was not in use, both towing points were moved as far from the centerline of the ship as possible. When the magnetometer was in use, it was towed from the crane off the starboard side and the GI gun on that side was moved to a tow point at the base of the starboard pillar of the a-frame.

Hydrophone Array (Streamer). A Geometrics GeoEel Digital Seismic Streamer System was used to receive the seismic signals. The streamer consisted of a 25 m stretch section (nearest the stern), a 65-m inactive leader, followed by six active sections, each 100 m long, followed by a 65 m leader. Each active section of streamer contains 8 hydrophone groups or channels, with 12 hydrophones per group, and a group interval of 12.5 m. This configuration produces 48 channel data. Four DigiCOURSE birds were spaced evenly along the streamer to assist in maintaining a streamer depth of 3-5 m.

Recording. A Geometrics GeoEel digital recorder using CNT-1 controller marine software was used to record the data in SEG-D format (8058 Rev 1). Seismic data were written continuously to disk and digital data tapes at a 0.5 ms sample interval. For quality control and viewing purposes, raw data were displayed in the form of raw shots and receiver gathers of channels 10 and 24**.**

Marine Mammal Shutdown Policy. In compliance with the Department of Commerce-National Oceanic and Atmospheric Administration-National Fisheries Service-Incidental Harassment Authorization (IHA), a marine mammal shutdown policy was strictly enforced. Two NMFS-approved marine mammal observers (MMOs) were employed to monitor marine mammals within a 40 m radius of the air gun array 30 minutes prior to and for the duration of the seismic profiling. Air gun shooting was curtailed whenever marine mammals were within the exclusion zone or the MMOs could not monitor the exclusion radius because of inclement weather. Only about 2.5 hours total of time was lost to shutdown related to IHA monitoring and that occurred on several occasions when rain showers lowered visibility around the air guns.

Scripps Institution of Oceanography
Seismic System Geometry

Ship: R/V Roger Revelle

Cruise: KNOX06RR

Chief Scientist: Sager

	Meters	Feet
Length of tow leader	65	213.25
Length of tow stretch	25	82.02
Antenna to stern	40	131.23
Antenna Height	25	82.02
Center of near trace	136.25	447.01
Center of far trace	723.75	2374.48
Gun Setback from Antenna	64	209.97
Near inline offset	72.25	237.04
Active cable	600	1968.48
Far inline offset	659.75	2164.51

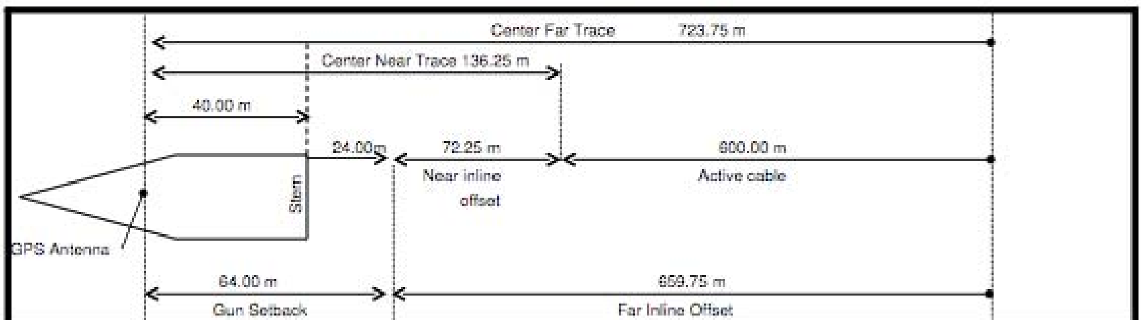
Number of traces 48

Setback of Single Trace 1

136.25 meters

447.01 feet

Bird Locations	
Bird 1	Start of Head Stretch
Bird 2	Start of Ch 17 (Active 3)
Bird 3	Start of Ch 33 (Active 5)
Bird 4	Start of Tail Stretch



SOURCE TYPE	Source	Pre Amp Gain	No. of Guns	Source Depth	**Notes**
G.I. Guns	G/I 45/105	24 dB	2	4m	
PRIMARY	Sample Interval	Record Length	No. of Channels	Cable Depth	
	.500 ms	varies	48	3-5 meters	
FILTERS	Low Cut	High Cut	60 Hz Notch	Monitor Filter	
	out	out	out	60Hz Notch	
DIGITAL RECORDER	Model	SEG Format	Tape Density	Auxiliary Channel Number	
	GeoEel	D 8058 Rev 1	N/A	TB : Aux 1	
CABLE LAYOUT	Far Trace No.	Far Offset	Near Trace No.	Near Offset	
	48	723.75 m	1	136.25 m	
FOLD = No. Traces * Grp. Int / 2*(Shot Interval)	Grouping Int.	Shooting Int.		Navigation Fix Interval	
	12.5 meters	10 sec @ 6kts		N/A	

Figure 7. Scripps Institution of Oceanography seismic system geometry.

Magnetic Gradiometer

The magnetometer used on KNOX06RR is a Marine Magnetics Sea Spy marine gradiometer. This instrument has two sensors, towed 100 m apart, with the leading sensor 350 m behind the ship. The Sea Spy uses the Overhauser effect, so it is more sensitive by two orders of magnitude than normal proton precession magnetometers. The output of both sensors was recorded to disk approximately once per second along with a GPS navigation position in each record.

Gravimeter

The gravimeter used for KNOX06RR is a Bell Aerospace/Textron BGM-3 Dual Gravity Measuring System, consisting of a gravity sensor subsystem, auxiliary battery drawer, and a stabilized platform subsystem that provides a vertical reference for the gravity sensor. The sensor subsystem has a minimum measurement range of 880 gals to 1080 gals, sufficient to account for normal gravity anomalies and vertical accelerations due to ship motions. Gravity data were automatically correlated with P-code GPS navigation to ensure vessel position accuracy, filtered, and recorded continuously onto primary and backup disks for the duration of the cruise. The gravimeter was mounted in the main lab, next the outer bulkhead near the ship's centerline and approximately amidships in the fore-aft direction.

The gravimeter was set up in San Diego before the *Revelle* departed for the Indian Ocean. It ran continuously on its own without any human intervention during the cruise. We could not make a gravity tie at the dock in Phuket because there is no local gravity reference station. A gravity tie was made to the ship meter at the dock in Singapore. The tie station is located just outside the main gate to the Royal Navy base at Sambawang, where *Revelle* ended the cruise.

Navigation

A Furuno GP-90 GPS Navigator satellite receiver was used for navigation and in recording of vessel position, course, and speed for all scientific instrument logs. The GP-90 is an integrated GPS receiver and video plotter, which consists of a 1575.42 MHz antenna unit and a display unit. Tracking up to 12 satellites simultaneously, it uses an 8-state Kalman filter to ensure an optimum accuracy of 10 m 95% of the time, and with a position update interval of 1 second.

Dredge

Standard Scripps dredges (Fig. 8) were used on KNOX06RR. These dredges consist of a toothed bail approximately 50 cm x 1 m in dimension with five teeth on each side. This bail is attached to a four-chain yoke and a chain-link basket is hung from the back of the bail. Two of the yoke attachment points have shear-bolts to give way at 8,000 lbs pull. In addition, the yoke attachment to the dredge wire also has a shear bolt, rated at 17,000-20,000 lbs, depending on depth. A nylon inner net is used within the dredge bag to keep small samples from dropping out through the larger chain mesh. Usually a 10-15 kg weight was placed inside the bag to help it stretch out on the sea bottom. To help track the position of the dredge, a Benthos 12 kHz pinger was attached to the trawl wire, 150 m from the dredge. This pinger was tracked on a depth recorder in the electronics lab.

Figure 8. Photograph of one of the dredges used on KNOX06RR.

III. Cruise Operations

Pre-cruise Schedule Adjustments

Cruise KNOX06RR was scheduled in 2006 as the sixth in a group of cruises taking place in the Indian Ocean. There was uncertainty about the final schedule because of uncertainty about whether KNOX05RR, the cruise immediately before, would take place because of delays in receiving permission to work in Indonesian waters. There was also uncertainty about the beginning and ending ports. Initially Freemantle and Columbo were proposed, but Phuket took the place of Freemantle in order to dovetail with the preceding cruise. Later, concerns were raised about safety in Columbo because of reports of Tamil rebel activity rising again in that nation. Male in the Maldives was selected as a replacement for Columbo. The cruise dates were set as 20 June to 14 August, departing from Phuket, Thailand and ending in Male.

Approximately two weeks before KNOX06RR was to depart, the *Revelle*'s bow thruster became inoperative. This posed a problem because the bow thruster loss negatively affects the *Revelle*'s ability to keep station. Approximately one week before KNOX06RR was due to leave port, it was decided that the cruise would end in Singapore, rather than Male. It was not until two days before *Revelle* departed from Phuket that the cruise length was established. Originally, the cruise was scheduled for 56 days at sea; however, in the end six days were lost to the need to compress the cruise schedule for repairs. The cruise dates were reset to departure from Phuket on 18 June and landing in Singapore on 6 August.

Week 1: 19-25 June 2007

R/V *Revelle* departed Phuket at 1600 (local) on 18 June 2007 and headed around the south end of the island onto a southwest course for the Ninetyeast Ridge. On board was a scientific party of 22 people including scientists from the US, India, Russia, students from all over the U.S., one from Canada, and two from South Africa, and a teacher from Colorado. The entire cruise ship track is shown in Figure 9 and detail over the Ninetyeast Ridge is shown in Figure 10.

Revelle steamed southwest for 1.8 days toward the first study site, where a survey over ODP Site 758 was planned. Neptune decreed sloppy weather to initiate the crew as the ship plunged ahead at 10-11 kt into winds reaching >45 kt and swells of 7-10 ft. The ship arrived on site at 0700 UTC on 20 June (note: henceforth all times given in UTC unless stated otherwise). Because of the early departure from Phuket, the ship reached the first site before permission arrived from NOAA to conduct seismic operations. As a result, seismic shooting was delayed and multibeam surveying was done first. The southeast edge of the seamount upon which Site 758 is located and two small seamounts nearby were surveyed (Fig. 11). A dredge was conducted on the summit of one of those seamounts, but the dredge returned empty except for some carbonate crusts and a fish (Table 1; Appendix 1). By that time the IHA permission form was approved and we were able to begin seismic data acquisition. Seismic operations were conducted for approximately 30 hours (Table 2), resulting in 272 km of seismic lines recorded (Fig. 12). The seismic survey revealed the reason that the first dredge was nearly empty: the seamounts are completely covered by sediment, even at their summits.

Having finished surveying the area around Site 758, *Revelle* made way south to the next survey site, running along the east flank of an intervening complex of seamounts along the way (Fig. 13). Multibeam bathymetry showed a steep-sided, u-shaped canyon at 3°15'N, so the transit was interrupted for a dredge (Table 1). Dredge 2 was successful, returning 44 kg of rock samples. Most of the dredge haul consisted of mudstone and volcaniclastic rocks, but several samples of basalt were also recovered (Appendix 1).

Transit was resumed southward and *Revelle* arrived on the seamount containing DSDP Site 216 at 2000 UTC on 23 June.

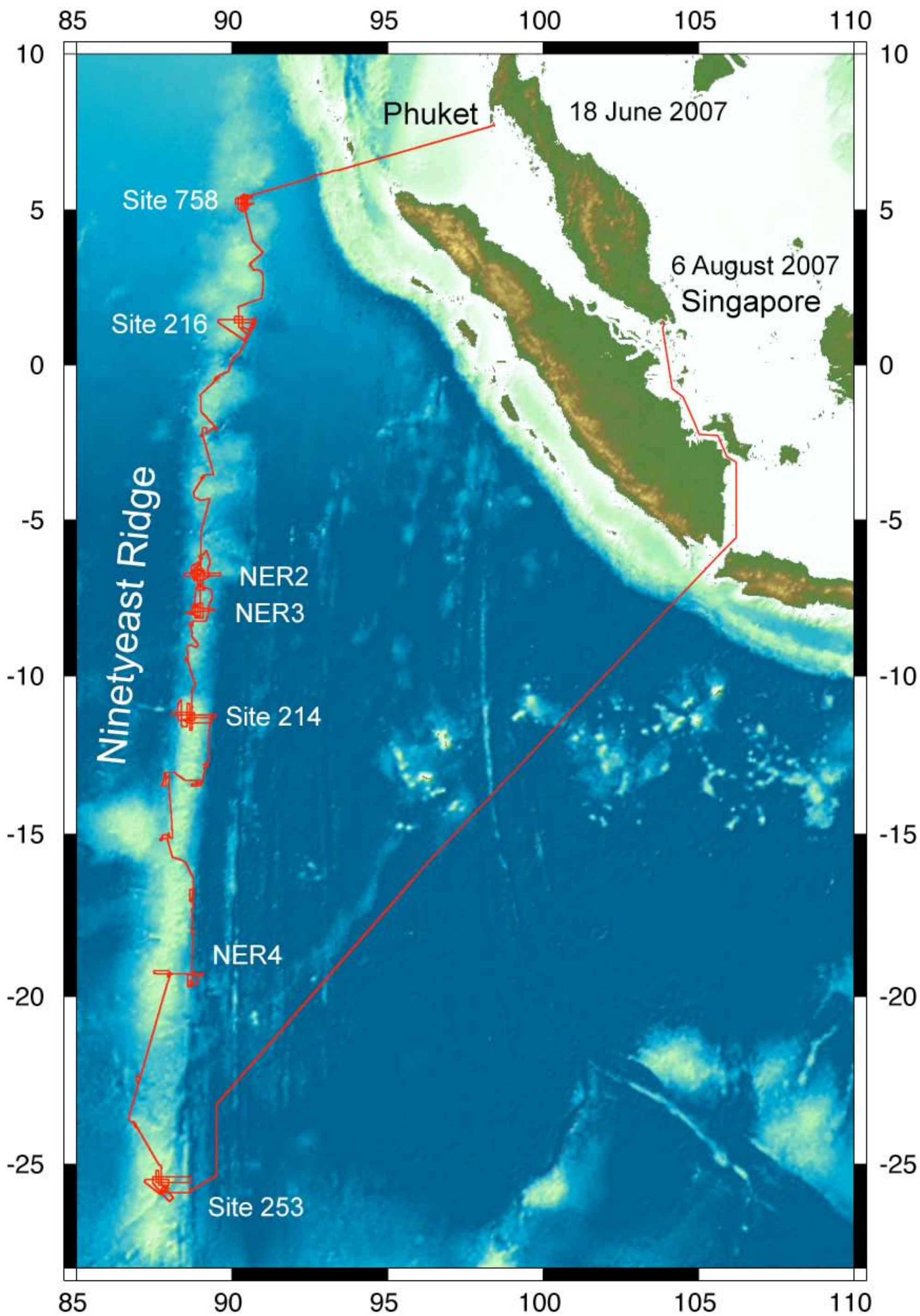


Figure 9. Ship track for cruise KNOX06RR.

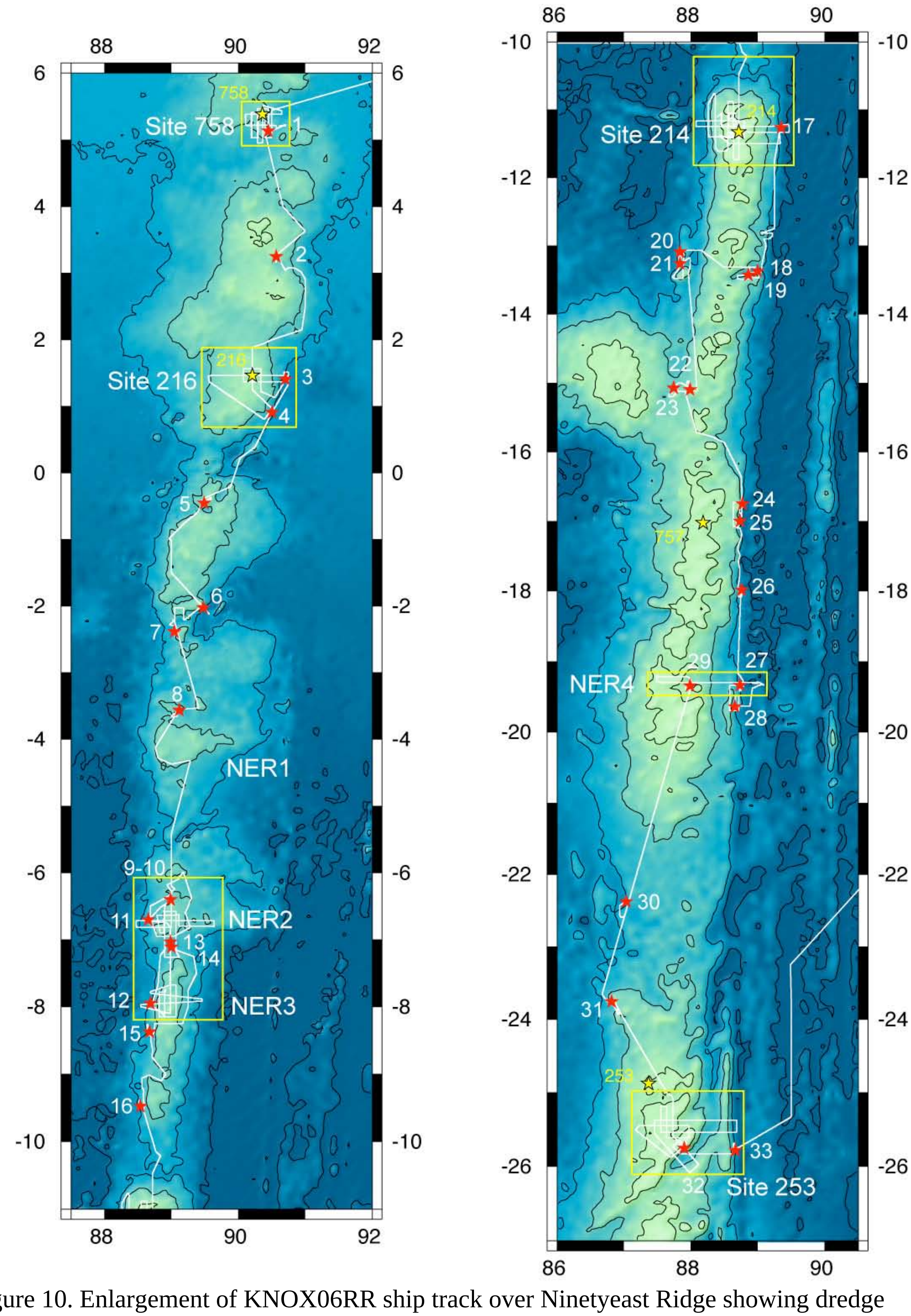


Figure 10. Enlargement of KNOX06RR ship track over Ninetyeast Ridge showing dredge locations (red stars), numbers, site designations, and areas where seismic profiling data were collected (yellow boxes). Yellow stars show DSDP and ODP sites.

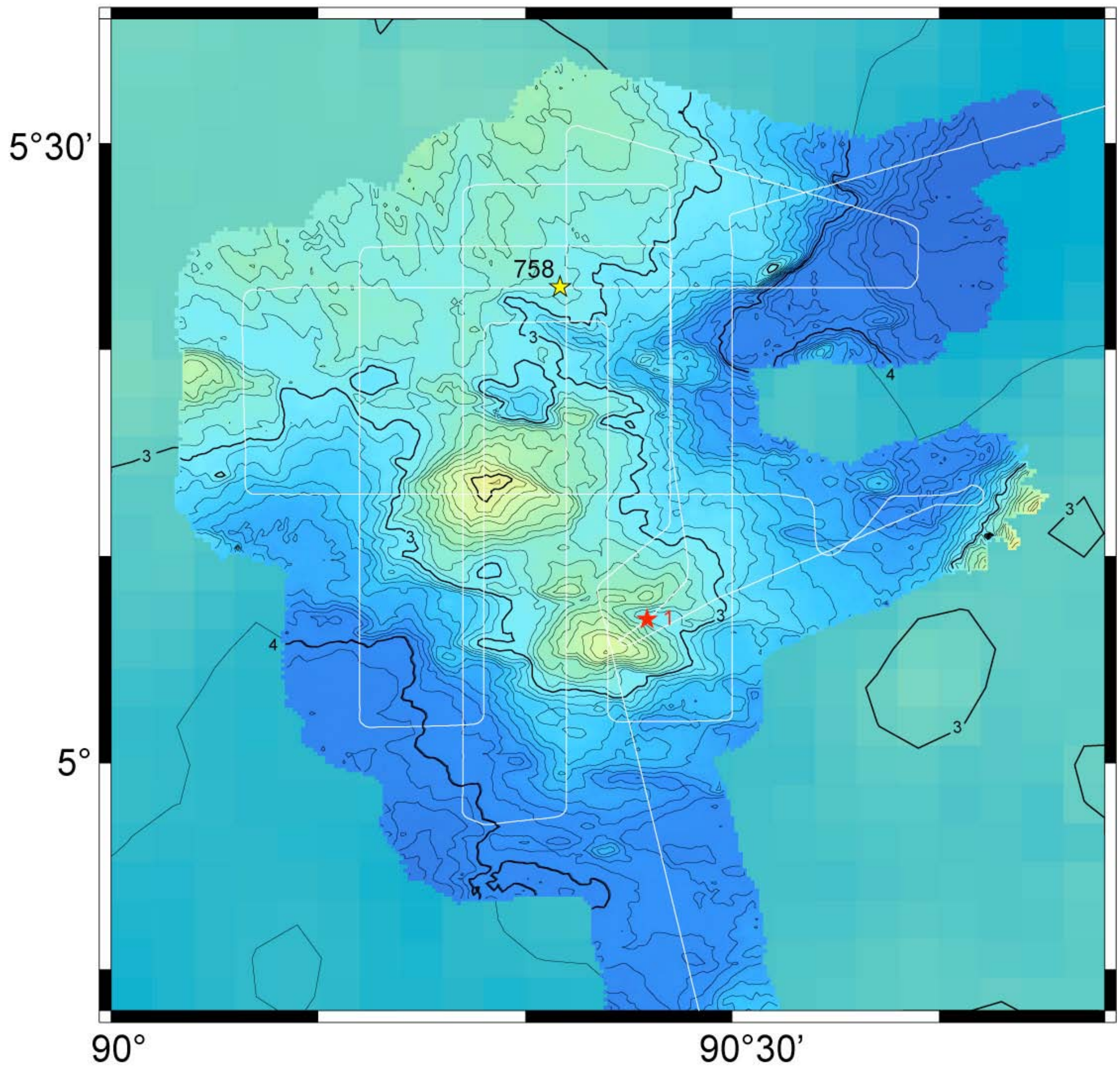


Figure 11. Site 758 survey bathymetry, ship tracks, and dredge. Brightly colored swaths show EM120 multibeam bathymetry data collected during KNOX06RR, color-coded for depth. The white line shows the ship track. The yellow star shows the site of ODP Site 758 and the red star shows the location of dredge #1. Background shading is the satellite-predicted bathymetry of Smith and Sandwell (1997). Contours shown at 50-m intervals for the multibeam data and 500-m intervals for the predicted bathymetry. Heavy lines show contours at 1000-m intervals.

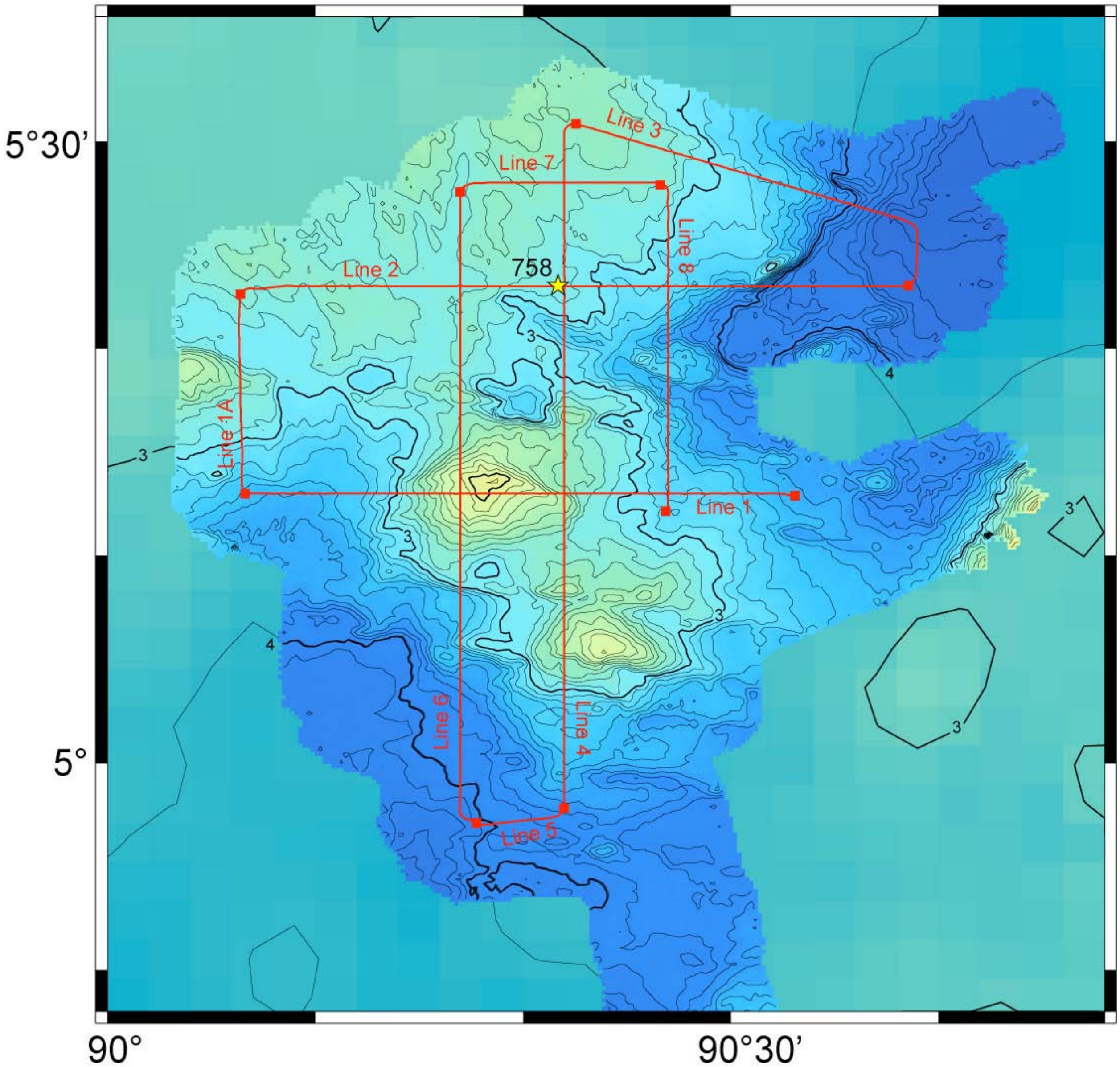


Figure 12. Site 758 seismic lines. Background bathymetry map is the same as in Figure 11. Red squares show line beginning and end points.

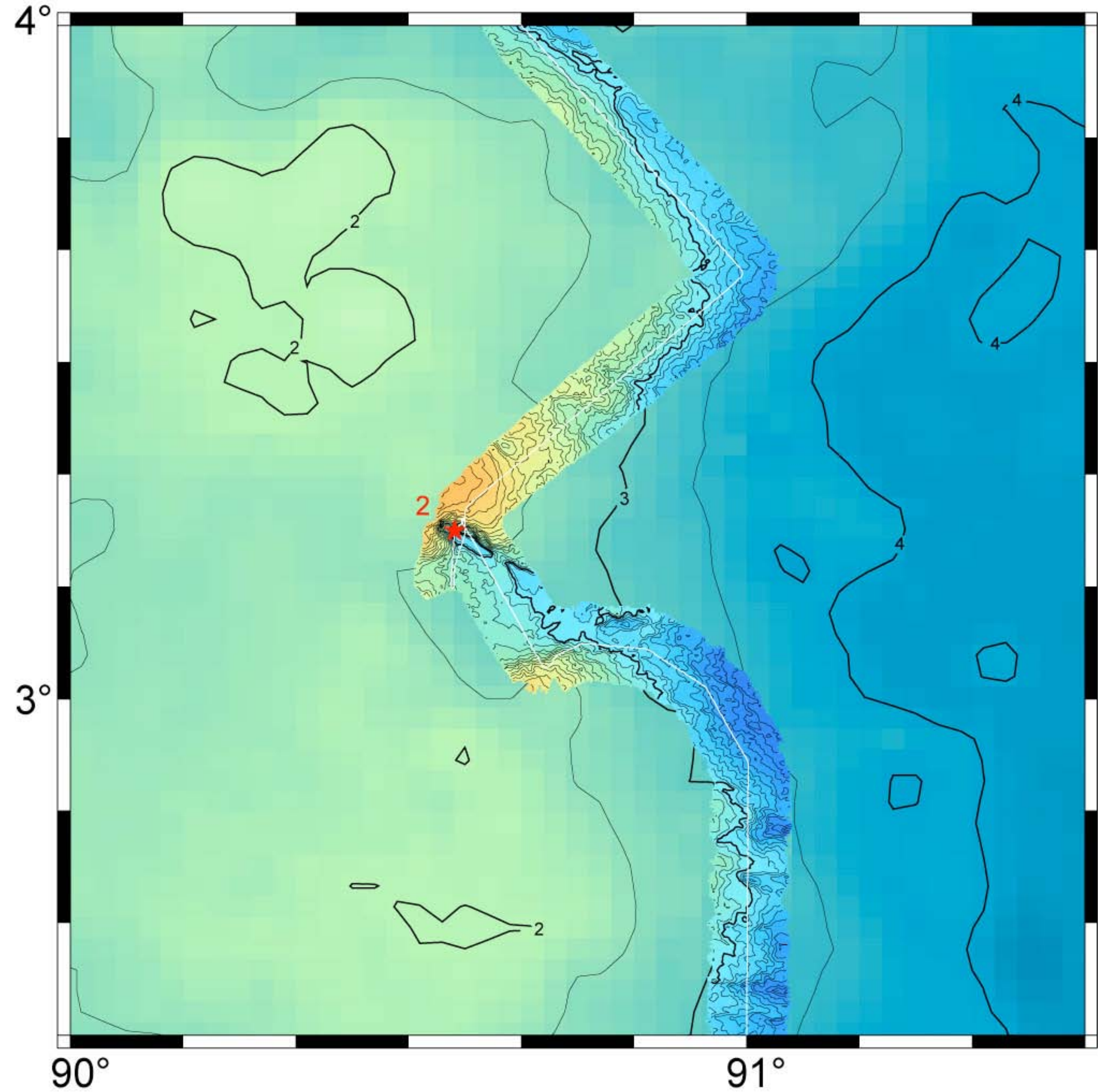


Figure 13. Location of dredge #2 (red star). EM120 multibeam bathymetry shown in color-shaded swath with 50-m contours. Background is satellite-predicted bathymetry with contours at 500-m intervals. Contours at 1000-m intervals are shown by heavy lines.

Week 2: 26 June - 2 July

On 25 June, *Revelle* began a seismic survey over the seamount upon which DSDP Site 216 was drilled (Figs. 14, 15). The seismic survey continued on 26 June with the ship towing the 48-channel streamer and the magnetic gradiometer, firing both air guns, and acquiring EM120 multibeam bathymetry and backscatter data. Seismic operations proceeded as planned and the seismic survey was finished at 23:52 UTC on 26 June. A total of 10 seismic lines were shot during 49.6 hours of seismic acquisition over 550 km of trackline (Fig. 15; Table 2).

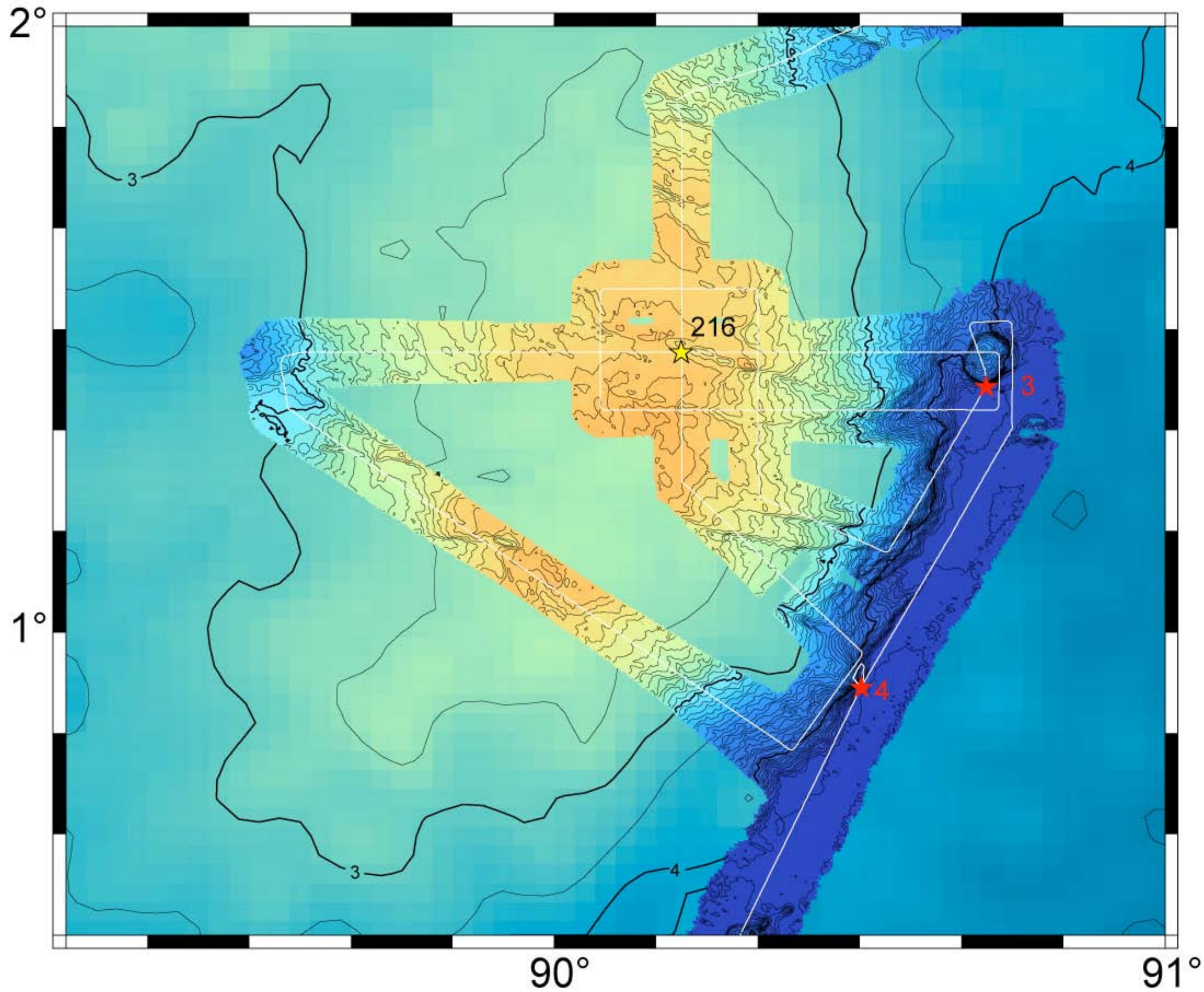


Figure 14. Site 216 survey bathymetry, ship tracks, and dredges. Brightly colored swaths show EM120 multibeam bathymetry data collected during KNOX06RR, color-coded for depth. The white line shows the ship track. The yellow star shows DSDP Site 216 and the red stars show the location of dredges. Background shading is the satellite-predicted bathymetry. Contours shown at 50-m intervals for the multibeam data and 500-m intervals for the predicted bathymetry. Heavy lines show contours at 1000-m intervals.

After finishing seismic operations, *Revelle* occupied two dredge stations on volcanic cones at the base of the Site 216 volcano. Both dredges (#3 and #4, see Table 1) were successful, returning a diverse suite of basaltic samples including several that appear suitable candidates for geochemical and geochronology study.

Revelle departed the Site 216 area at 19:30 UTC on 26 June and headed south to explore for dredge locations on several seamounts. On an unnamed seamount between Site 216 and a volcano dubbed site NER1, three additional dredges were accomplished (Fig. 16). The first dredge (#5) was taken from a scarp on the upper flanks of a volcanic cone on the northwest side of the volcano on 27 June (Table 1). That dredge returned several large pieces of manganese encrusted basalt. On 28 June the two other dredge stations on this volcano (#6 and #7) were completed on a tall, south-facing scarp on the southern edge of the volcano (Fig. 16). Both dredges were successful returning large quantities of igneous rock along with some volcaniclastics and several sedimentary rocks (Table 1).

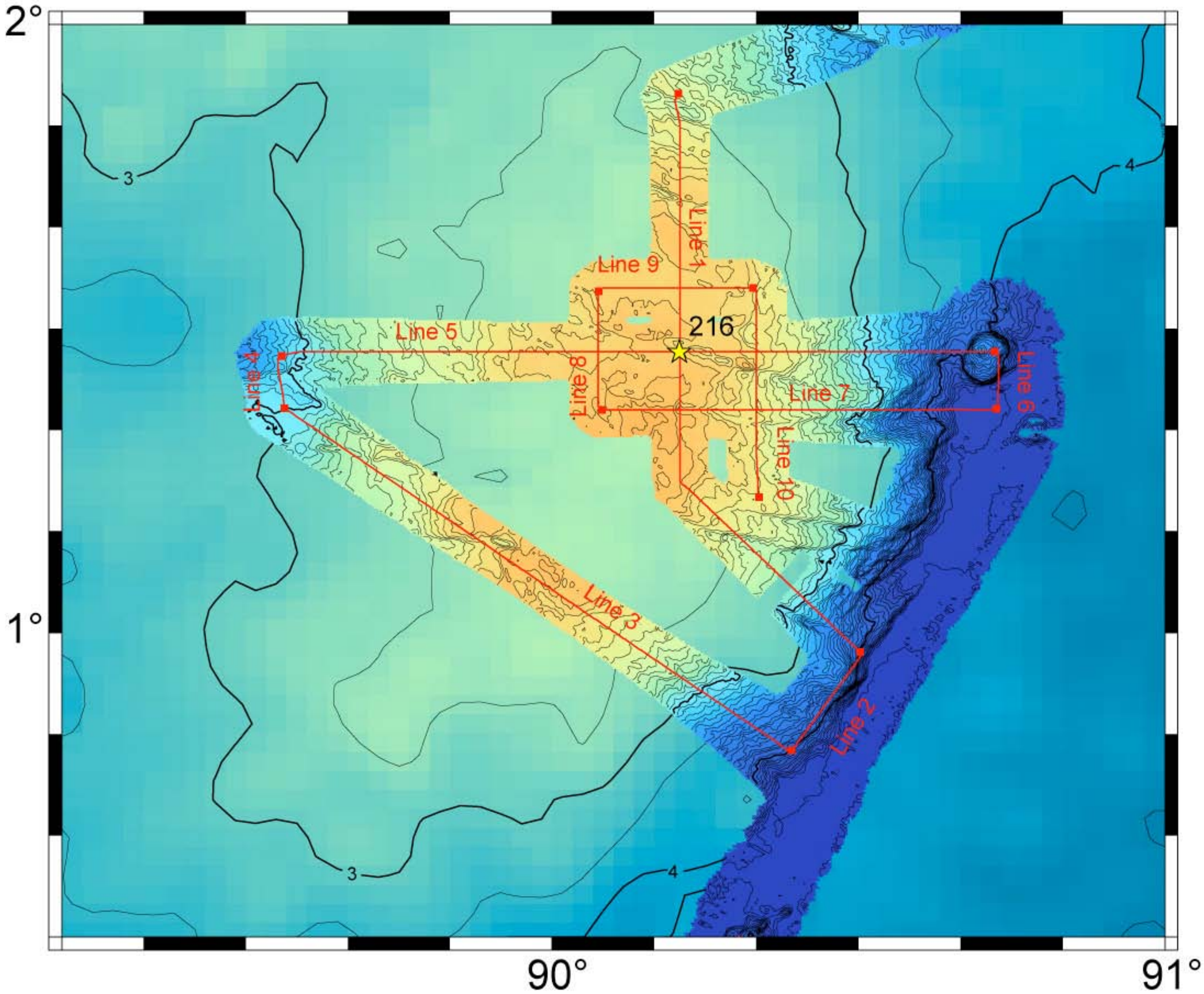


Figure 15. Site 216 seismic lines. Background as in Figure 13. Red squares show line beginning and end points.

The next stop was Site NER-1, a low volcano in a segment of Ninetyeast Ridge with smaller volcanoes (Fig. 10). Only one dredge was attempted on this volcano because it was difficult to find suitable sites for dredging owing to pervasive sediment cover. Dredge #8 was attempted on 29 June on a volcanic cone with steep sides. The dredge was successful in that it returned samples, but the rocks were sedimentary: large chunks of white chalk. Apparently these formed at the summit and spalled from the sediment cap as rubble to blanket the slope.

After site NER-1, *Revelle* approached site NER-2 where seismic operations were planned. On 30 June, the seismic streamer and air guns were deployed, but after sitting on deck for several days, neither air gun worked properly. Having no spare, we had no choice but to retrieve both guns and the streamer so that the air guns could be repaired. While the seismic techs did an all-night rebuild on the two air guns, the ship did a half-day survey of the seamount flanks with the multibeam sonar. Interesting scarps were found at the base of the west flank of the volcano. The seismic gear was redeployed on 1 July and continued until 3 July (see next section).

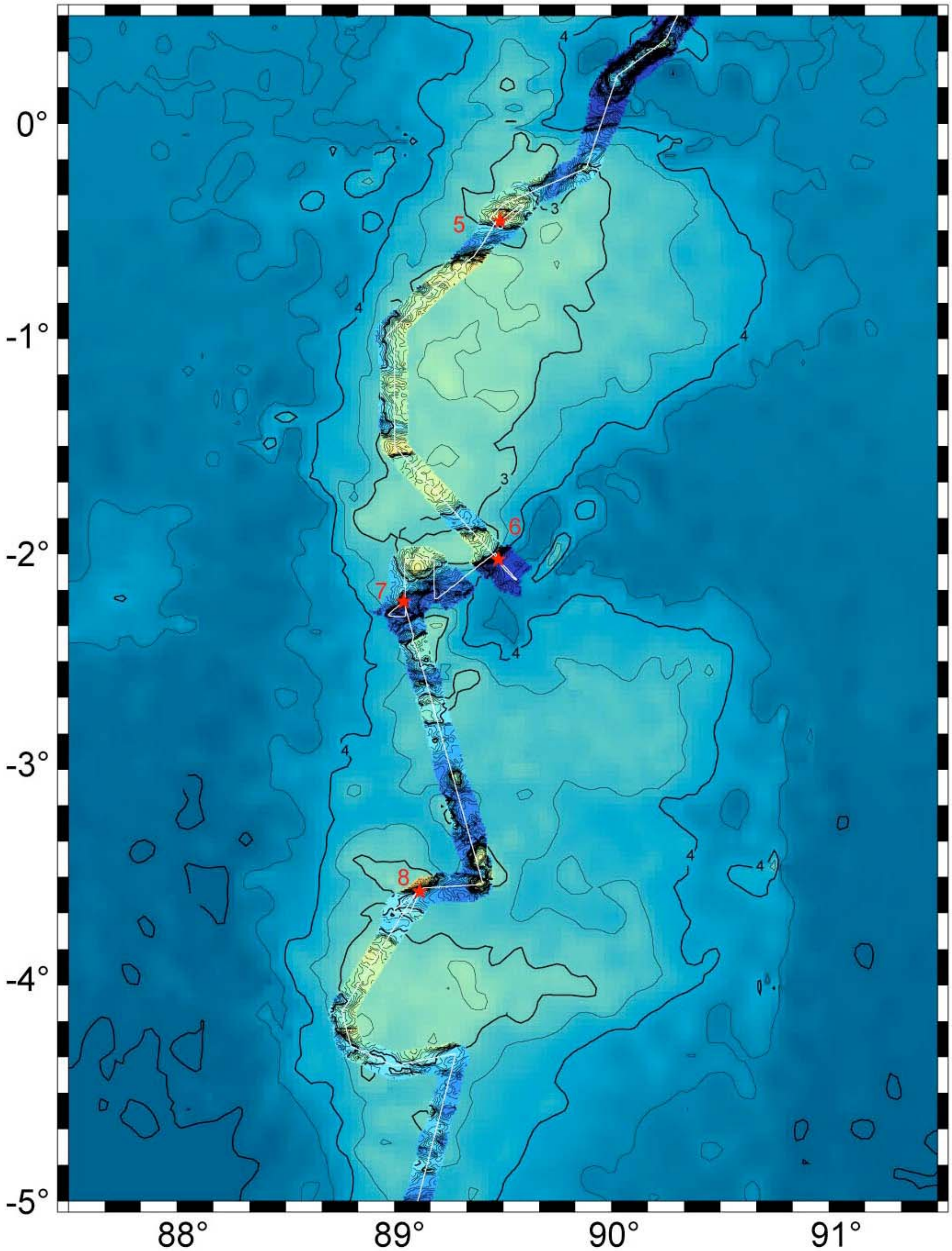


Figure 16. Multibeam bathymetry and dredges 5-8, located south of Site 216. Multibeam bathymetry is color shaded and contoured at 50-m intervals. Background is satellite-predicted bathymetry at 500-m intervals, labeled in km.

Week 3: 3-9 July 2007

During week 3, *Revelle* continued the acquisition of seismic profiles at site NER2, later to be continued at nearby site NER3. The two sites are on adjacent seamounts in the part of Ninetyeast Ridge that is made up of smaller edifices. These two sites were chosen because NER2 has a more-or-less circular planform, except for a low extension to the east, whereas NER3 is a north-south trending ridge (Fig. 17). The two edifices are adjacent, so the seismic survey for NER3 was begun with a line connecting that ridge with the NER2 seamount, crossing a graben-like structure located in between. The NER2 survey was completed on 3 July. In this survey, 13 seismic lines were run, using both air guns, collecting 528 km of seismic profiles over 47.6 hours (Fig. 18; Table 2).

At this time we were to take the first step in the evolution of dredging operations during cruise KNOX06RR. Initial dredges were at locations with fortuitous trends that allowed the ship to dredge with the stern into the wind. Without a working bow thruster, it would be difficult or impossible for *Revelle* to hold a course with the wind hitting it on one side. Captain Desjardins felt that a course to the northwest, with the ship's stern facing into the southeast tradewinds and swells, was the best course for dredging. Geology would soon dictate a change.

After the site NER2 seismic survey was completed, three dredges were attempted on the NER2 seamount (#8-10). On edifices to the north of NER2, it had been possible to dredge with the ship's stern facing into the wind because of favorable escarpment geometries. On NER2, all of the best outcrops were on north and west, meaning we either had to dredge with the bow pointed into the southeast tradewinds or not dredge at all. After consultation with Captain Desjardins, we did a position-holding test that indicated the *Revelle* could indeed hold station into the wind.

At site NER2, the first two dredges (#9-10) were attempted on a steep, bare, 1 km slope on a large, possibly late stage volcanic cone on the north flank (Fig. 17). Both dredges became stuck, one popped the shear bolts on the dredge frame, and both came back empty except for a few crusts (Table 1). The third dredge (#11) was attempted on the basal escarpment on the west side of the seamount. This dredge was successful and returned basalt samples that appear suitable for geochemical and geochronologic study (Table 1).

After the three dredges were completed, preparations were made to do the NER3 seismic survey. Because the ship was just finishing dredging the northwest flank of NER2, it was decided to start the seismic survey on top of the NER2 seamount and run line 1 of the survey across the intervening trough and up onto the NER3 ridge. The NER3 seismic survey ran for 54.6 hours from 4-6 July, covering a distance of 606 km on 9 seismic lines (Fig. 19, Table 2). Ninety minutes of seismic data were lost because the marine mammal observers shut down the air guns during a night-time rain squall.

Five additional dredges (#12-16) were attempted on the NER2 and NER3 seamounts between 7 and 9 July (Fig. 17; Table 1). Both volcanoes have basal escarpments, so we looked for those that were both steep and showing strong sonar backscatter. Such escarpments seemed best for yielding igneous rocks. Although dredge #12 on NER3 produced only samples of sedimentary rock, the four following dredges (#13-16) all returned with large quantities of igneous rock (Table 1). At the end of the third week, *Revelle* was heading south toward the high southern Ninetyeast Ridge.

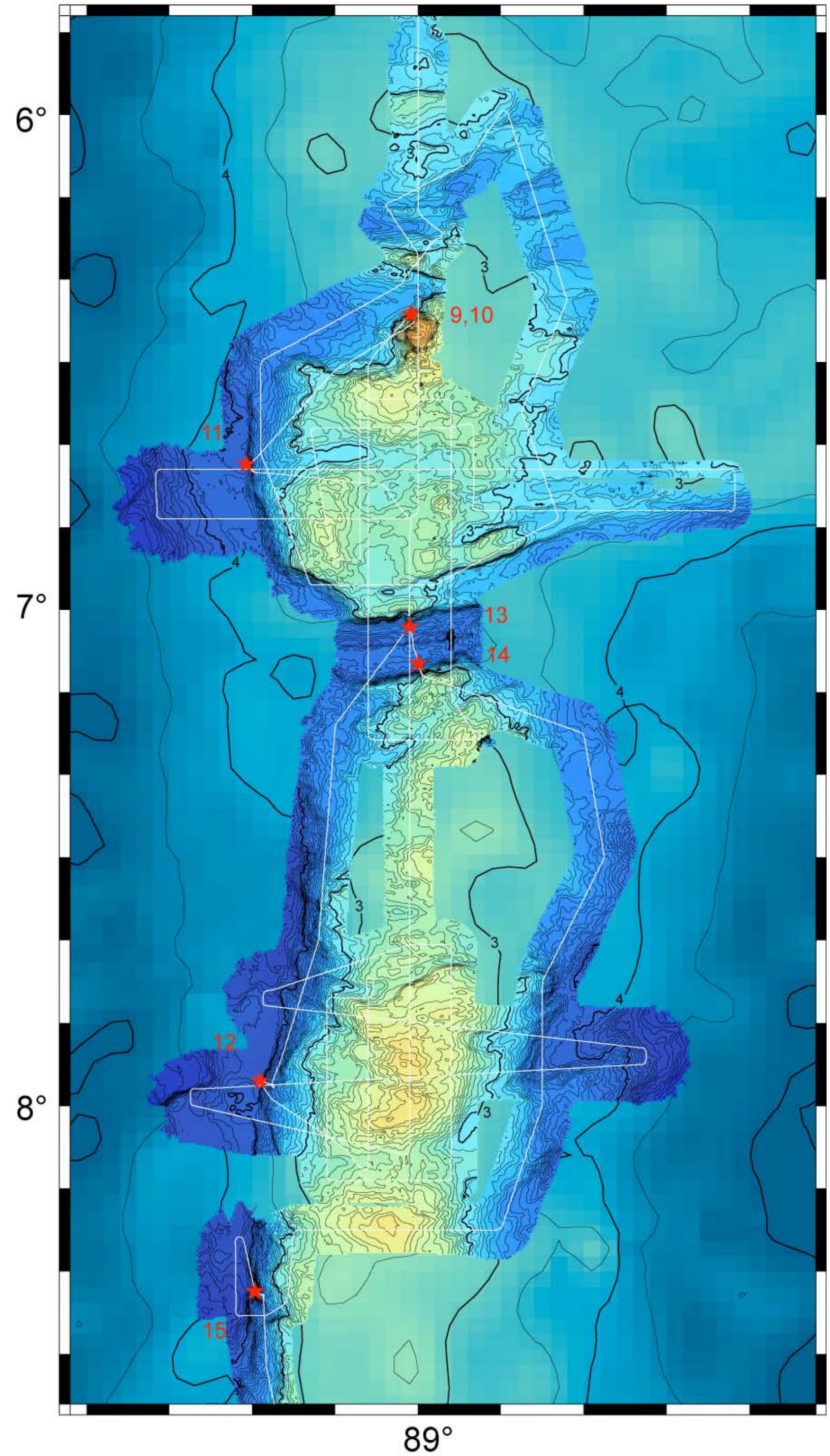


Figure 17. EM120 multibeam bathymetry, ship tracks, and dredge locations for sites NER2 (top) and NER3 (bottom). White lines show ship tracks; red stars show dredge locations. Multibeam bathymetry contoured at 50-m intervals; satellite-predicted bathymetry at 500-m intervals.

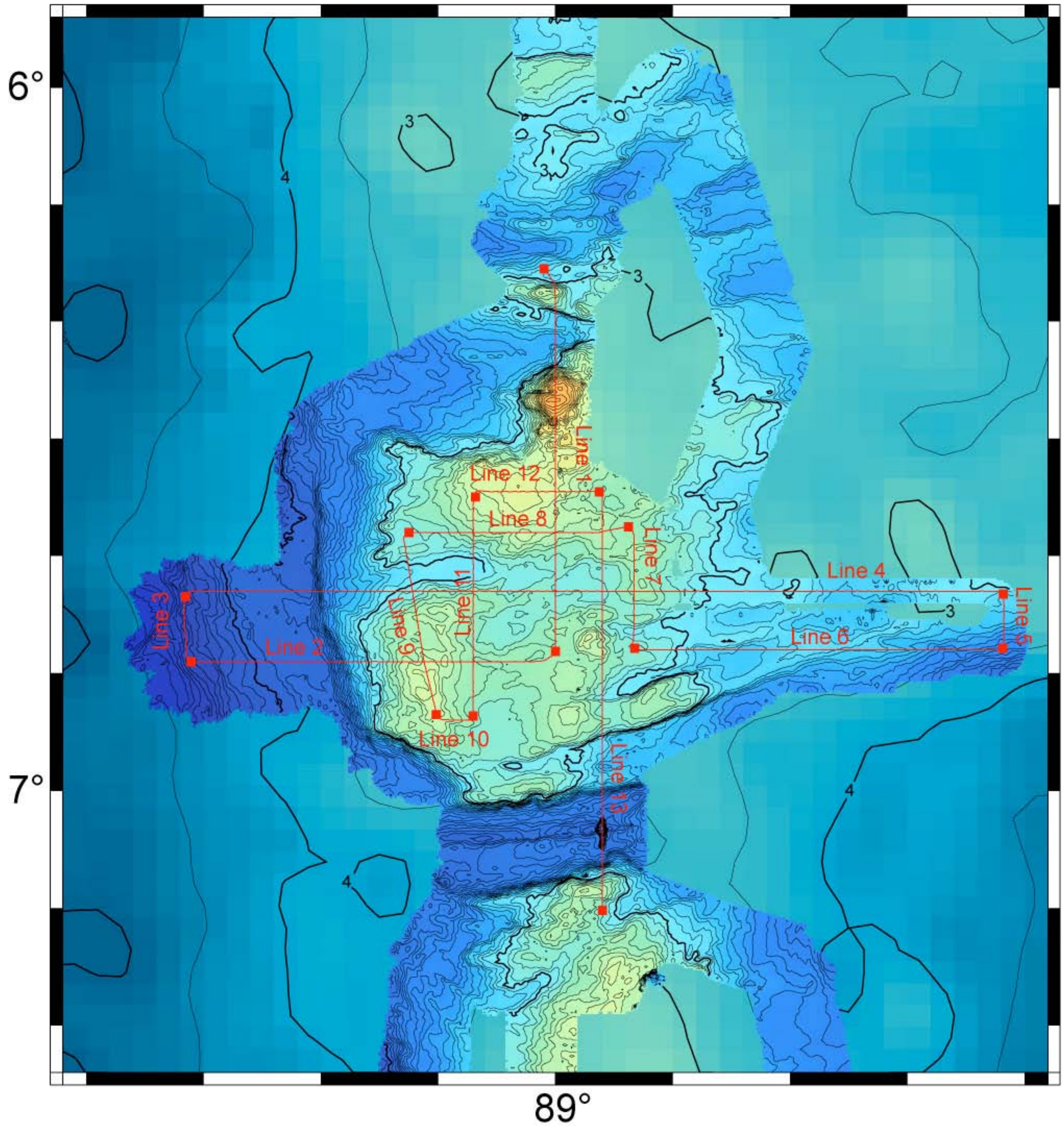


Figure 18. Seismic lines for site NER2. Bathymetry shown as in Figure 17. Red squares show line beginning and end points.

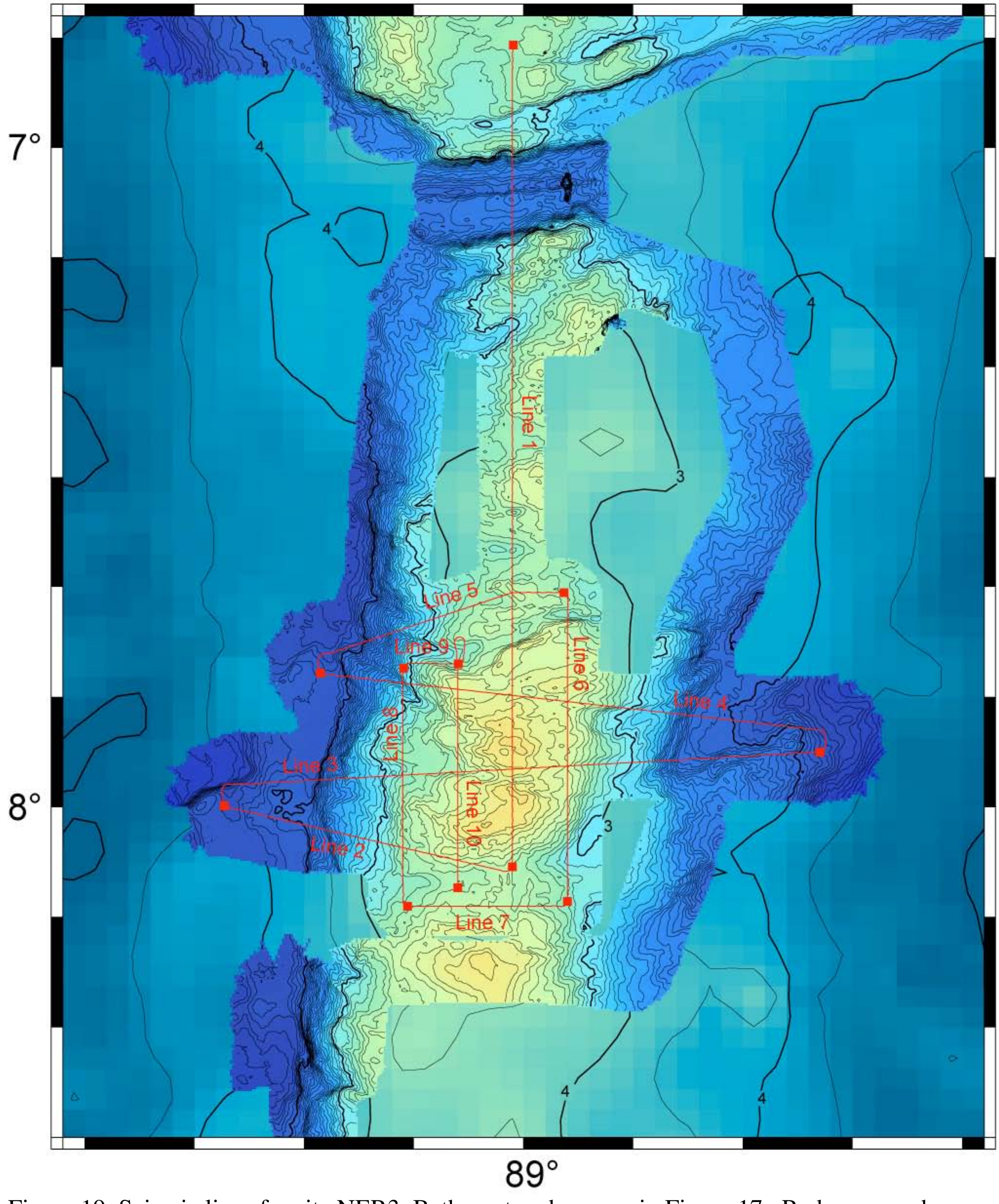


Figure 19. Seismic lines for site NER3. Bathymetry shown as in Figure 17. Red squares show beginning and end points of seismic lines.

Week 4: 10-16 July

The Site 214 seismic survey began late on 9 July with a north-south seismic line across the gap between the low south end of the NER3 ridge and the high ridge on the south. This seismic line then proceeded down the axis of the ridge ~100 km. Other seismic lines were run east-west to investigate the tectonics and morphology of the steep ridge flanks on those sides (Figs. 20, 21). The survey finished on 13 July with a grid of intersecting lines on the summit. The survey ran for a total of 72.8 hours during which approximately 808 km of seismic profiles were collected (Table 2). The survey was interrupted twice because of rough seas, with one hiatus of 17.5 hours. Another small hiatus occurred because the marine mammal observers could not see the air guns during a rain squall.

After the seismic survey, the cruise returned to dredging. Again, we looked mainly for escarpments, having had luck with these features at previous stations. Dredge #17 was taken on the basal escarpment of the east flank of the Ninetyeast Ridge. Multibeam data showed that this escarpment was >1 km in height where crossed by one of the seismic lines. Only one dredge was collected near Site 214 because rocks are already available from the DSDP cores.

Dredges #18-19 marked a change in dredging strategy brought on by rough seas. During the Site 214 survey, the tradewinds were strong (25-30 kt), causing rough seas. During dredge #17, we were still dredging with the stern into the wind (and seas); however, during the deployment of that dredge a wave broke over the stern while a scientist and the technicians were attaching the pinger, scattering some of them across the deck. The waves also pounded on the transom during the hours of the dredge and this was deemed a potential vibration problem for engine room electronics. It was decided that we could no longer dredge stern-to-the-wind.

Because of this limitation, we sailed past the escarpment south of Site 214 to a canyon cut into the NER at 13°S (Fig. 22). During the transit to this site, we passed spectacular east-facing escarpments approximately 2 km in height. At the site of dredges #18 and #19, we found a canyon with several escarpments forming terraces. Because its orientation was most favorable for dredging bow-to-the-wind, we dredged the southern escarpments (which face north). Dredge #18 sampled a deep escarpment whereas dredge #19 sampled the uppermost escarpment. Neither dredge was particularly successful for our purposes. The deep dredge (#18) yielded only highly altered basalts and sedimentary rocks and the other, from the shallower escarpment (#19), brought back only sedimentary rocks.

After completing the canyon dredges, *Revelle* steamed west to a linear seamount located approximately 25 km west of the main NER (Fig. 22). This seamount is elongated in the same direction as the NER and is parallel to fracture zones on the abyssal seafloor. Multibeam mapping showed it to consist of three conical volcanoes, one larger edifice on the south and two smaller cones on the north. We dredged the relatively steep western flanks of the two smaller cones because the orientation was favorable for bow-into-the-wind dredging courses. Dredge #20 was on the northern cone and dredge #21 was on the middle cone. The former recovered only small amount of manganese crusts and the latter came back empty.

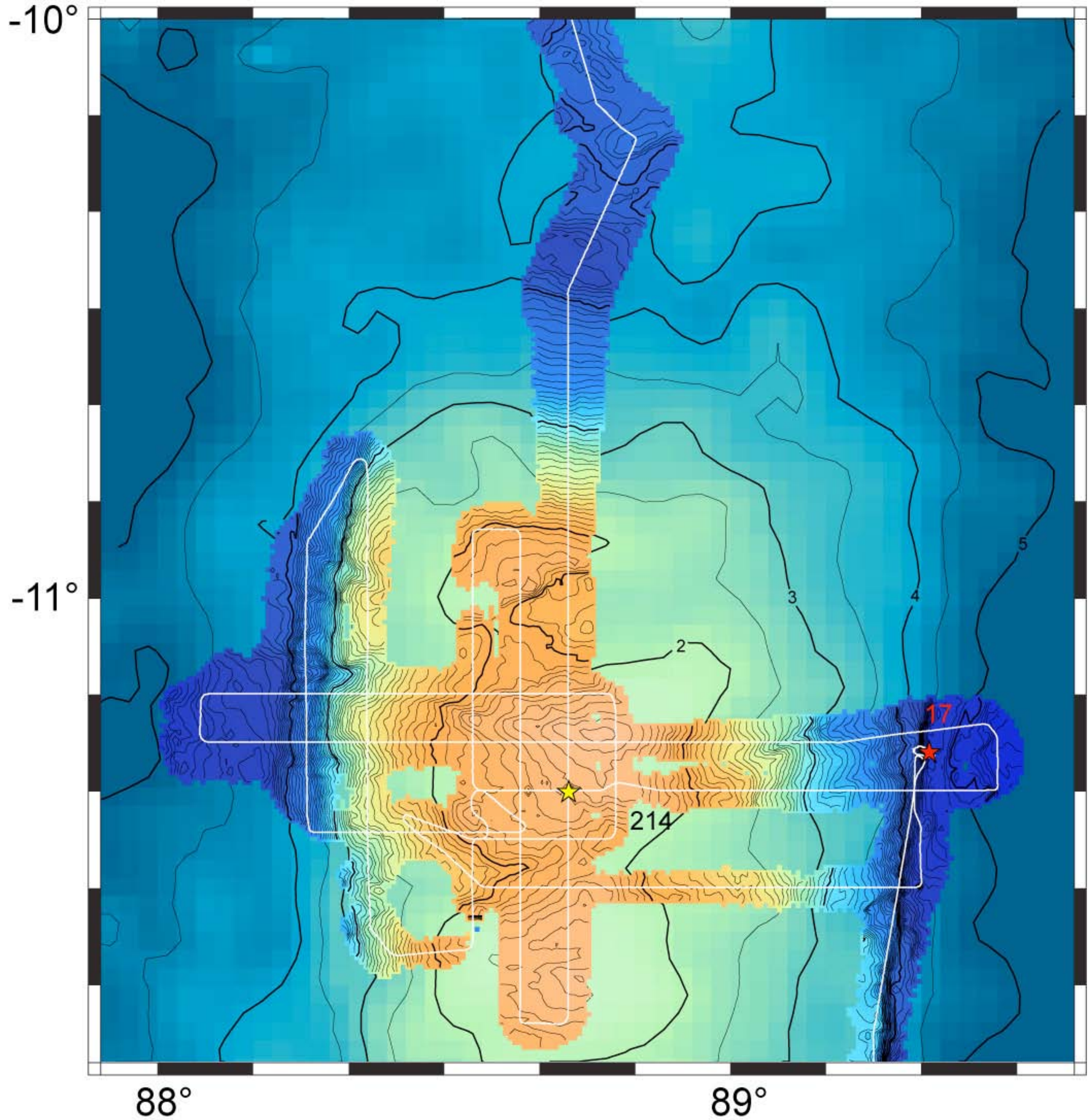


Figure 20. Site 214 survey bathymetry, ship tracks, and dredge. Brightly colored swaths show EM120 multibeam bathymetry data collected during KNOX06RR, color coded for depth. The white line shows the ship track. The yellow star shows the site of DSDP Site 214 and the red star shows the location of dredge #17. Background shading is the satellite predicted bathymetry. Contours shown at 50-m intervals for the multibeam data and 500-m intervals for the predicted bathymetry.

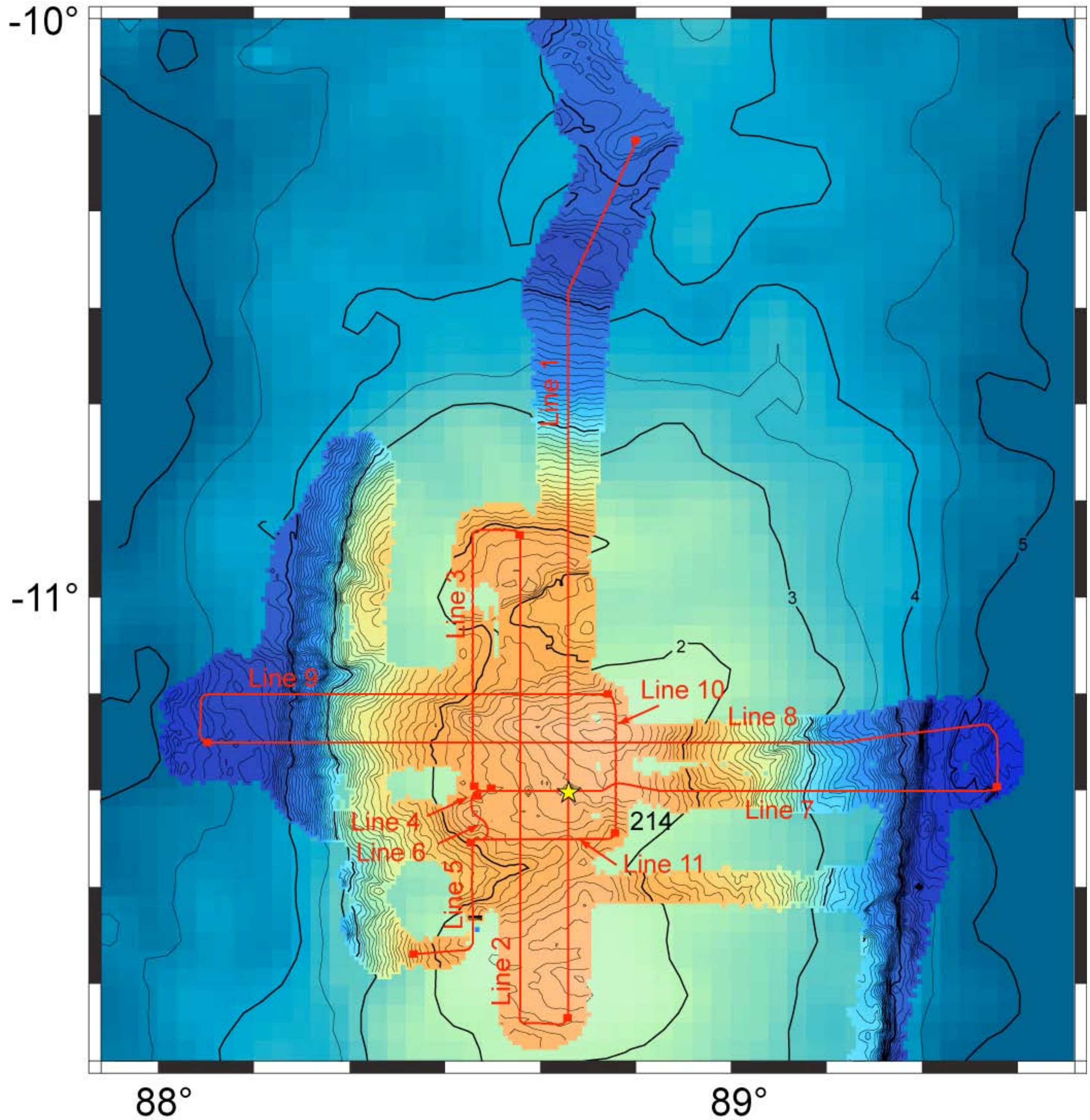


Fig. 21. Site 214 seismic lines, shown by heavy red lines. Red squares show line beginning/end points. Background as in Figure 20.

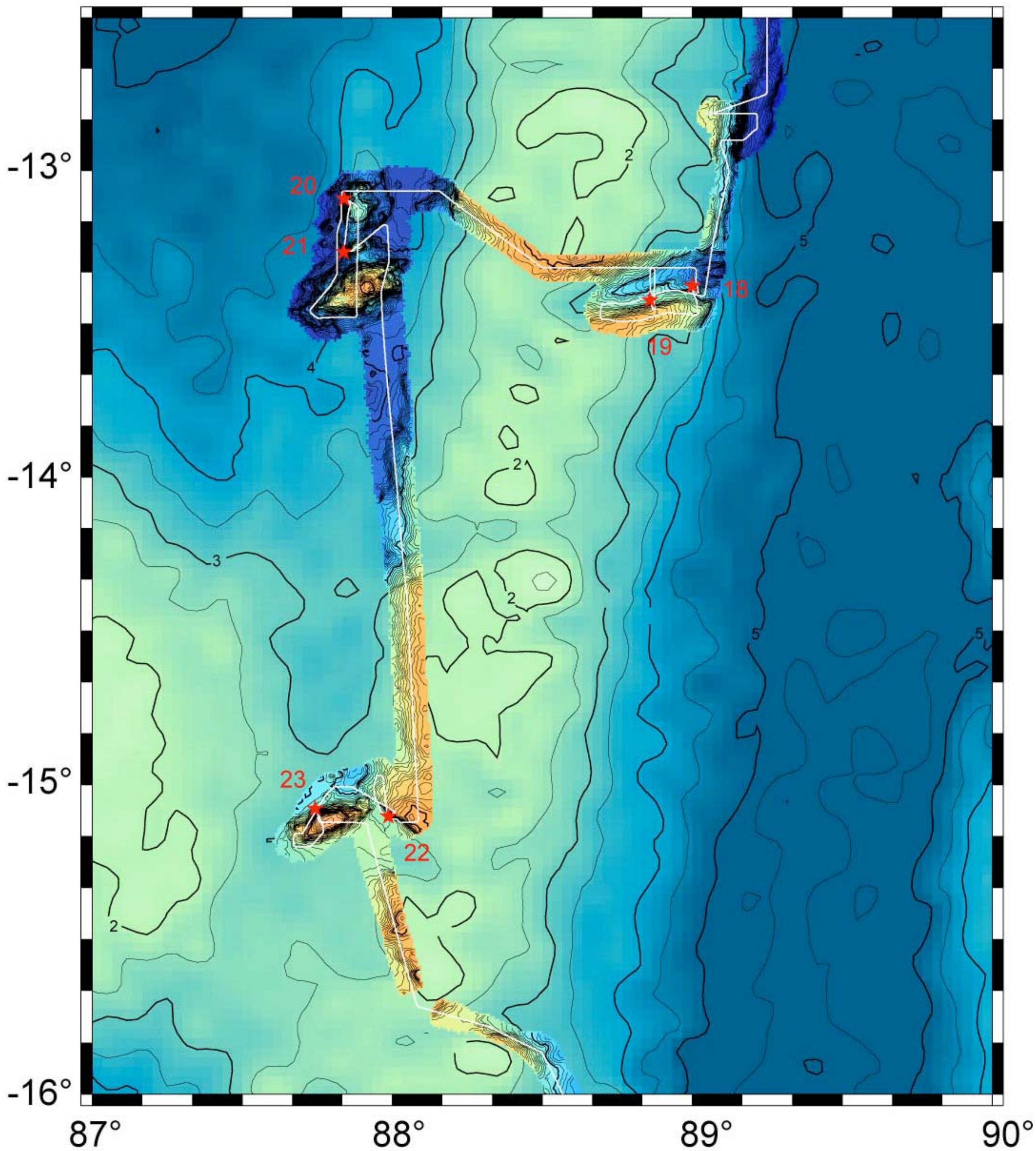


Fig. 22. KNOX06RR dredges 18-23. Multibeam bathymetry color shaded in swath beneath ship track (white line) and contoured at 50-m intervals. Red stars show dredge locations. Background shading is satellite-derived bathymetry, contoured at 500-m intervals.

Week 5: 17-23 July

After leaving the linear seamount group, *Revelle* steamed south to the location of a Russian seismic line (Pilipenko, 1996) that showed what appeared to be bare, steep, west-facing slopes on the central NER and a seamount in between NER and Osborn Knoll (Fig. 22). At the location shown to be a steep slope on the central NER, we found a steep, northwest-southeast trending escarpment over 500 m in height. This feature was sampled in dredge #22, which brought back >50 kg of basalt (Table 1). Proceeding westward, *Revelle* mapped a seamount that also appeared on the Russian seismic line. Dredge #23 sampled its northwest flank but recovered only blocks of sedimentary rock (Table 1). This seamount has a small, flat top that apparently collected the carbonate sediments, which later tumbled down the slope.

At this point in the cruise, several choices had to be made. First, we decided not to investigate Osborn Knoll. Although this large, domal edifice is poorly known and any data collected there would be valuable, we felt that taking several days to go there would mean not being able to go all the way south to Site 253 as planned. Furthermore, from the satellite-predicted bathymetry maps it did not look like we would be able to find an escarpment with a favorable orientation for dredging with strong southeast tradewinds. The second choice was about dredging. If we continued to dredge only west-facing slopes, we would miss the high, east-facing escarpments on NER that partly prompted this cruise. Moreover, examination of the satellite-predicted bathymetry of the southern NER showed few opportunities for steep slopes with favorable orientations for bow-to-the-wind dredge courses. Because the US Navy swell forecast predicted a lull in the rough seas, we convinced Captain Desjardins to let us try the east-facing escarpment by dredging on a westward course.

Headed east, *Revelle* crossed the NER and then sailed southward down the escarpment at 16°S, east of ODP Site 757 (Fig. 23). We found a steep escarpment and made two dredges at nearly the same location, one on the mid-escarpment (#24) and one nearer the base (#25). When planning these dredges, we considered turning bow-into-the-wind for the technicians to deploy and recover the dredge and pinger and doing the rest of the dredge with the stern facing the wind. However, after consideration of the dredge geometry, it was decided that the deep depth and high slope angle would not cause a large deflection of the trawl wire from the vertical. So these two dredges were accomplished "backwards" with the stern and a-frame leading the ship up the dredge track and with the bow pointed windward. This technique worked well and both dredges were highly successful.

Encouraged by these results, we repeated the backwards dredging at three more sites farther south on the escarpment. Dredge #26 was taken at 18°S whereas dredges #27-28 were collected from the escarpment east of site NER4 (Fig. 24). In this area, the escarpment split into long linear terraces and these two dredges each targeted a different terrace. Dredge 27 sampled the lower escarpment whereas dredge #28 sampled a higher portion.

Up to this point, the plan was to wait until the Site 253 location to do the final seismic survey; however, the linear terraces on the east side of site NER4 appear tectonically interesting, so we decided to shoot a single seismic line crossing these features and running up to the NER summit. On 22 July, a 14.5 hour seismic profile was collected, covering approximately 161 km (Fig. 25; Table 2).

Toward the end of the seismic line, near the NER summit, we crossed a graben with sediment free sides in places. We decided to dredge the north wall of the graben at relatively shallow depth (beginning at 2208 m). That dredge (#29) recovered mostly volcaniclastic rocks;

although, at least one such rock contained a basalt cobble that appears suitable for geochronology study.

After dredge 29, Revelle departed southward, headed for the seamount upon which DSDP Site 253 is located.

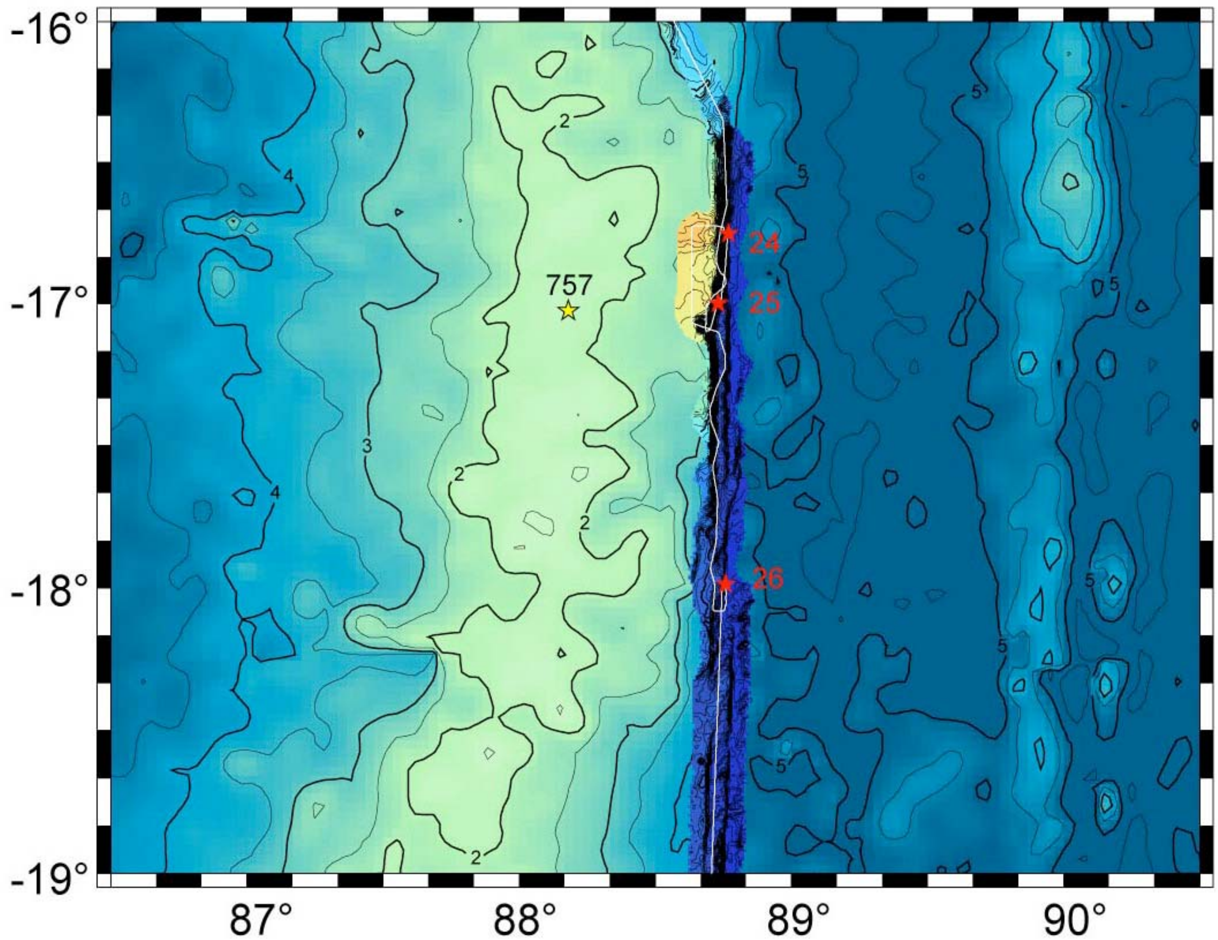


Figure 23. Bathymetry and dredges collected during KNOX06RR on the east escarpment near ODP Site 757. Yellow star is Site 757 and red stars are dredge locations. KNOX06RR multibeam bathymetry shown color shaded with 50-m contours. Background satellite-predicted bathymetry shown at 500-m contour intervals, labeled in km.

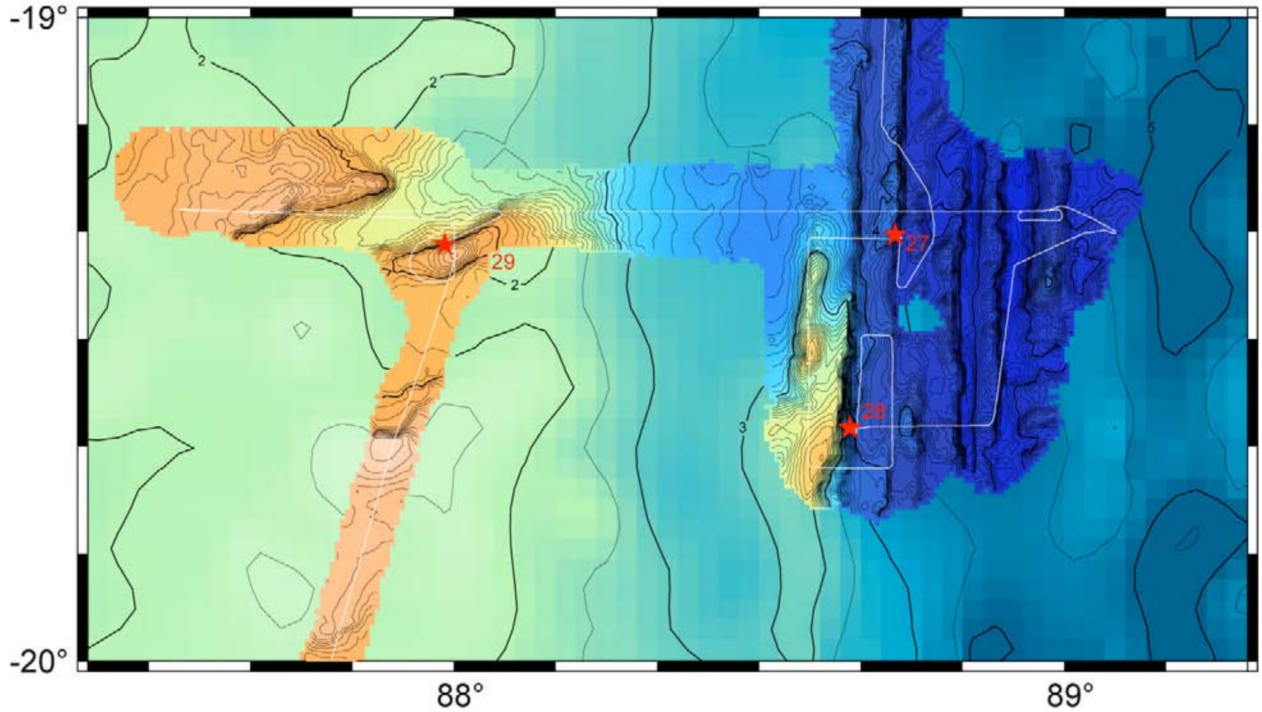


Figure 24. Bathymetry and dredges collected at site NER4 at 19.5°S. Red stars are dredge locations. KNOX06RR multibeam bathymetry shown color shaded with 50-m contours. Background satellite-predicted bathymetry shown at 500-m contour intervals, labeled in km.

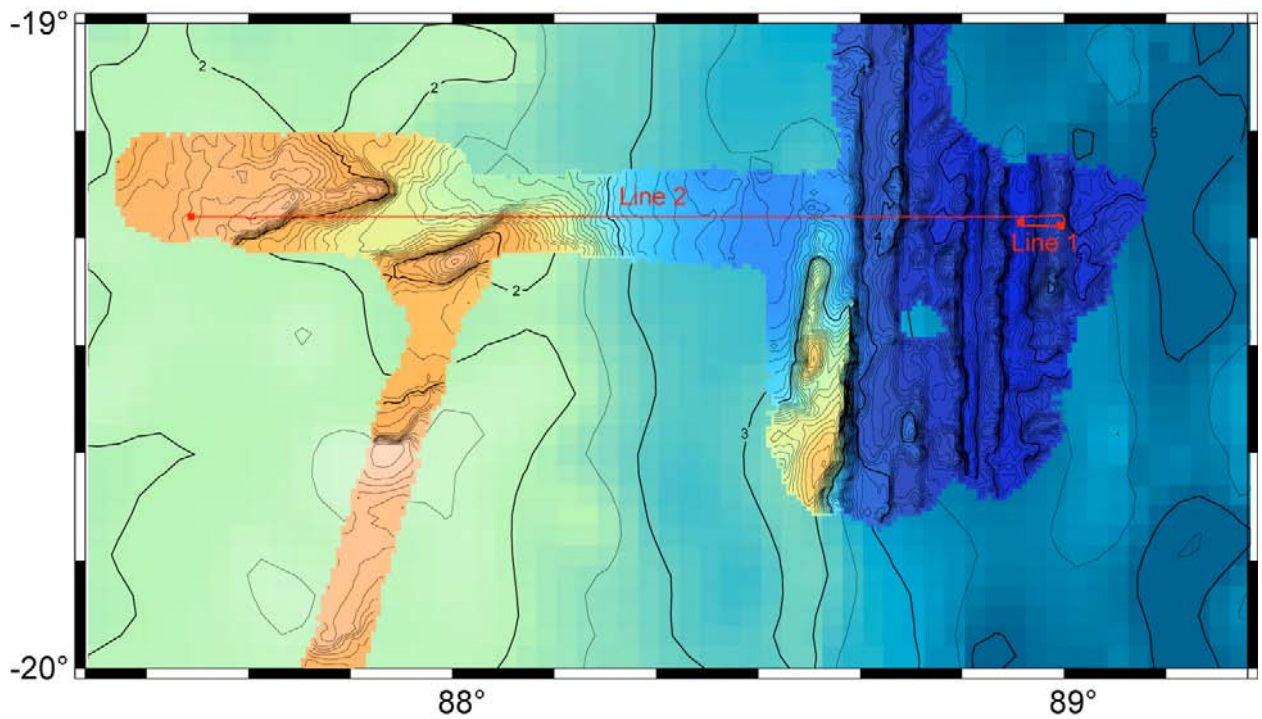


Figure 25. Seismic lines at site NER4. See Table 2 for details. Bathymetry as in Figure 24. Red squares show line beginning and end points.

Week 6: 24-30 July

During the transit between site NER4 and the Site 253 volcano, we expected to find little of interest because this section of the NER is deep and relatively featureless on the satellite-predicted bathymetry maps. However, during transit, we found a u-shaped canyon in a portion of the low ridge that was slightly higher than expected. The canyon has a steep escarpment for its north wall, which was sampled with dredge #30 (Fig. 26) on 24 July. This dredge successfully recovered basaltic samples (Table 1).

Continuing southward, we mapped the northwest corner of the Site 253 seamount because it has closely spaced contours on the satellite-predicted bathymetry map. Rounding this northwest corner, we again found a northwest-southeast trending escarpment and sampled this feature with dredge #31, also on 24 July (Fig. 26). This dredge was also successful, recovering both volcaniclastic sediments and basalt (Table 1).

After this dredge, we proceeded directly to the summit of the Site 253 volcano to begin a 2.5–day seismic survey. The survey does not cross Site 253 itself because we felt that the limited time should survey the canyon incising the seamount as well as the linear ridge to the east (Figs. 27, 28). Without substantially expanding the seismic survey time, we could not include a line across the old DSDP site. The seismic profiling began at 1145 on 25 July, a day which began very calm with only gentle swells.

Before the first line was finished, the calm weather was abruptly interrupted during the middle of the night when the winds kicked up to 35-40 kt. Soon the sea was covered with heavy chop and swells of 8-10 ft. During the following day, the high winds continued from 25-35 kt, piling the seas higher. At 0628 on 26 July, the magnetometer was pulled in so that the starboard air gun could be moved outboard to keep it from being thrown atop the seismic streamer by heavy swells. With the heavy seas and high winds, the multibeam bathymetry and 3.5 kHz echosounder data suffered badly from bubbles under the hull and data on seismic lines 1 (latter end), 2-4, and 5 (beginning) were significantly compromised. By day time on 27 July, the winds moderated to <15 kt and the seas were greatly reduced. Multibeam bathymety quality and quantity improved throughout line 5 and was again excellent through the rest of the survey, lines 6-11. The seismic survey was completed at 0258 on 28 July after 63.4 hours and 704 km of profiling (Fig. 28; Table 2).

With only hours remaining before the deadline to head for Singapore, we turned southeast and mapped bathymetry down to the deep canyon, turning northeast to catch the escarpment with the multibeam sonar swath. On previous crossings, during rough seas, the bathymetry quality was poor. This escarpment is over 2 km in height and is capped on the platform above its north rim by small, volcanoes that appear to be late stage features. At 0930 we stopped for dredge #32, on the lower reaches of this escarpment (Fig. 27). This dredge was successful, recovering 132 kg of rocks, mostly consisting of basalt. We proceeded across the canyon to the linear ridge on the east side of the survey site where we dredged the eastern side of the ridge at a depth of 4742 m at latitude 25°48’S. This dredge was also highly successful, recovering 196 kg of samples, including 37 kg of basalt.

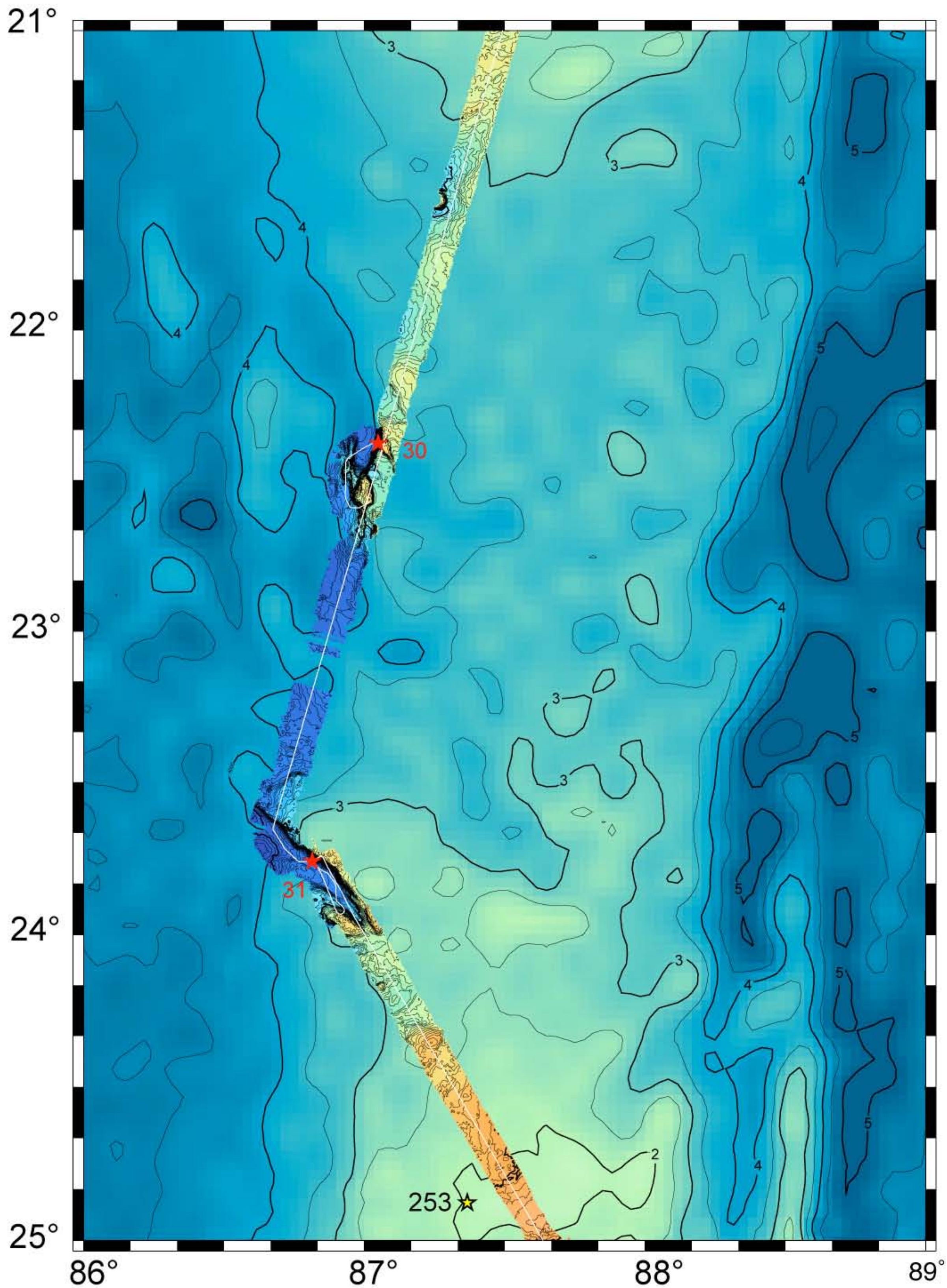


Figure 26. Locations of dredges #30 and #31, between site NER4 and Site 253.

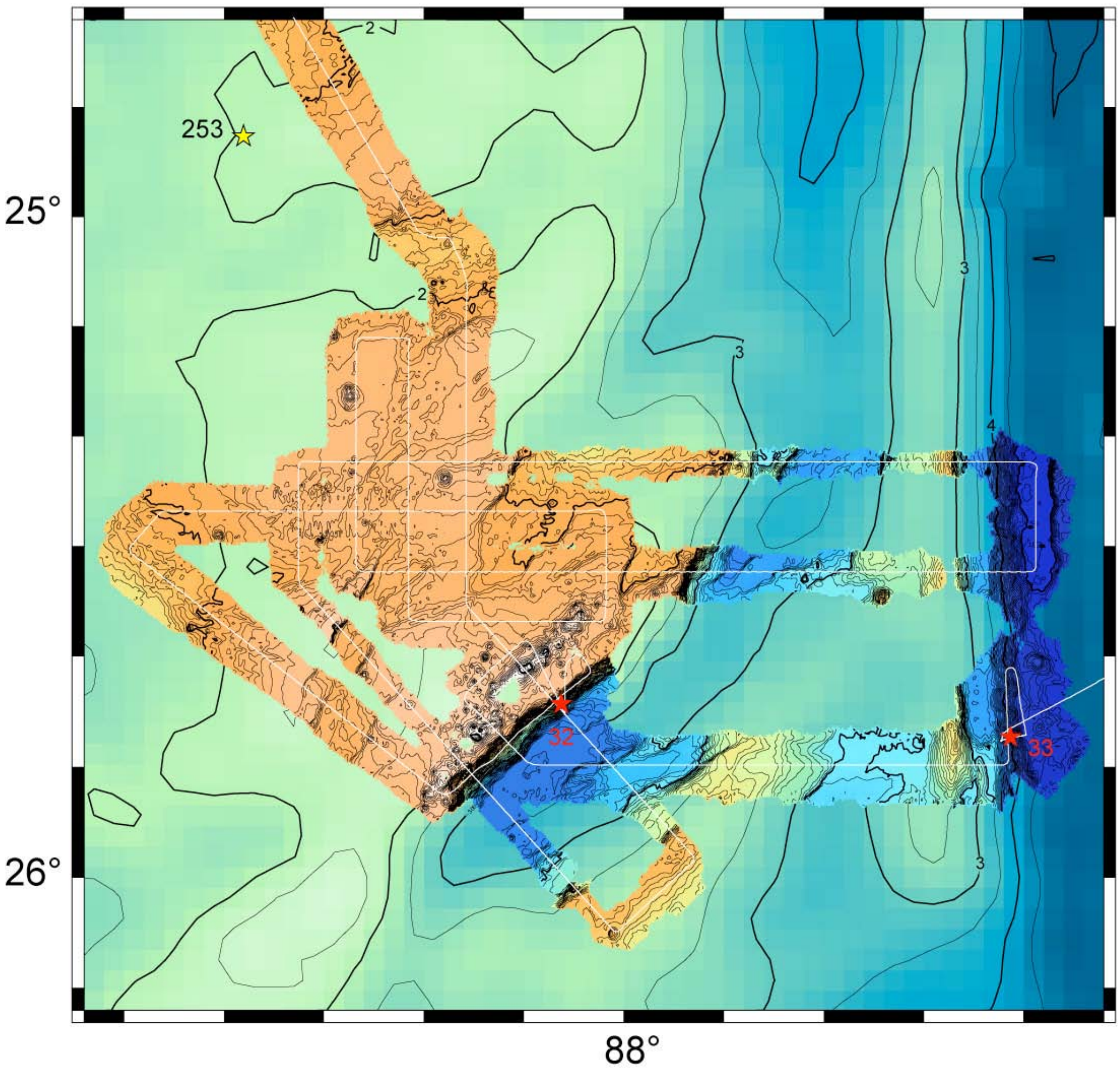


Figure 27. Site 253 multibeam bathymetric survey and dredge locations. Red stars are dredge locations whereas yellow star shows location of DSDP Site 253. KNOX06RR multibeam bathymetry is shown color shaded with 50-m contours with thick 1000-m contours. Background satellite-predicted bathymetry is shown at 500-m contour intervals and labeled in km.

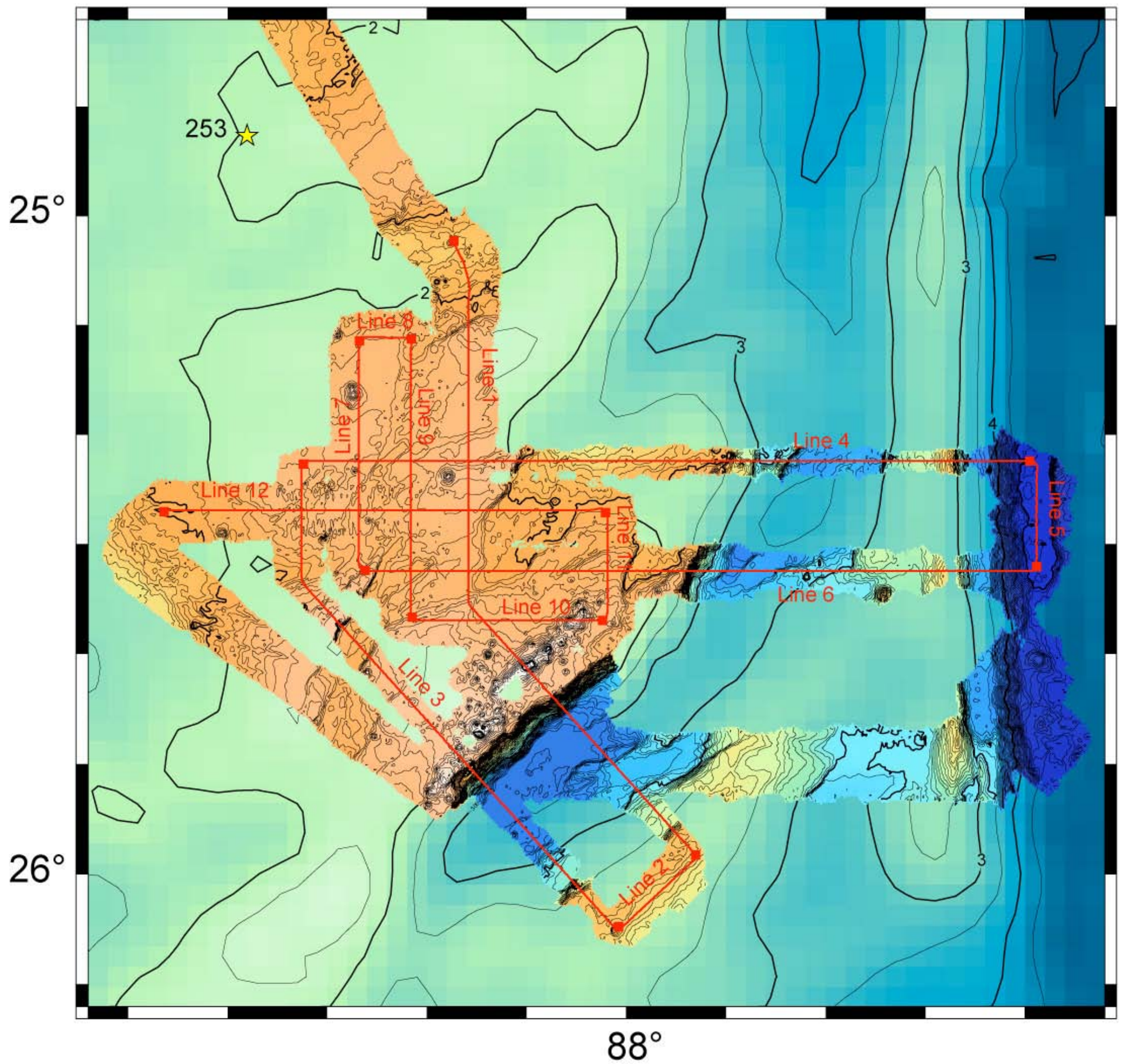


Figure 28. Site 253 seismic lines. Background as in Figure 27. Red squares show line beginning and end points.

After dredge 33 was recovered, at 1058 on 29 July, only a few hours remained before time to begin the transit to Singapore. We had hoped to run a magnetic profile north-south, on the abyssal seafloor up the east side of the southern NER to map the magnetic anomalies in this region where they are poorly known. Although we began the profile from 25° 19.1'S, 89° 30.0'E at 1611 on 29 July, we could only extend the north-south line to 23° 15.0'S before it was time to head toward Singapore. At 0217 on 30 July, *Revelle* turned to a northeast course toward the straight between Java and Sumatra.

The transit to Singapore took nearly a week. At 0531 on 1 August, Revelle reached the EEZ southwest of Keeling Island, and the recording of geophysical data was curtailed. After five more days of uneventful transit, including potentially pirate-infested waters east of Sumatra, the ship arrived at Singapore and docked at approximately 0800 local time on 6 August.

Weather Problems

Despite being in a tropical location, weather was a constraint in many KNOX06RR operations. The cruise occurred at the height of the southern hemisphere winter, which is the most challenging time for sea operations in the southeastern Indian Ocean. Although *Revelle* encountered few organized storms, the weather constraints arose from the strong southeast tradewinds that occur in this season. Consequently, it was usual during KNOX06RR to be operating in nominally “fair” weather, with partly cloudy skies and high pressure, but with tradewinds blowing constantly from the same direction at >20 kt (Fig. 29). Those tradewinds were evident even at our sites north of the equator. With strong winds blowing from the same direction for extended periods, we often experienced rough seas.

Although KNOX06RR did not lose any ship days to bad weather, the rough seas had several effects that compromised data collection. The greatest effect was on the EM120 multibeam sonar bathymetry. When seas were less than about 6 ft, the multlibeam sonar collected good, repeatable data with a wide swath. Starting at about 6 ft wave height, the multibeam bathymetry suffered in quality on headings with a component of ship’s velocity into the direction of the swell. From about 6-10 ft swell height, it was possible to obtain good data on courses that did not have a component of velocity into the swell, but data were compromised on headings into the sea. The problems with data on such headings were probably caused by “aeration,” in other words bubbles forming under the hull that interfere with the sonar detecting signals. Usually this problem caused the sonar swath to be less in width and it also caused the sonar to lose its lock on the bottom for one or several successive pings. With seas >10 ft height, the multibeam sonar data were significantly compromised and at times it was difficult to obtain data at all. With such rough seas, there were often significant gaps where the sonar could not lock onto the sea bottom for extended periods and the swath might be narrowed to only 30-40° width. In such conditions, with the loss of ping data and swath width, the sonar was probably losing 75% of the data compared to normal, calm water conditions. It is difficult to quantify how much data was lost in this manner on KNOX06RR because there was a gradation in data loss severity. Nevertheless, a rough estimate is that there were significant problems in multibeam data acquisition over approximately 20% of the cruise days.

Rough seas also compromised other geophysical data. Although the gravity data have not yet been processed, rough weather causes greater heave and acceleration, which translates into greater errors and uncertainty in the final gravity data. The rough weather also precluded the collection of magnetic data on several days when seismic profiling data were also being collected. The problem arose because of the limited space for towing gear off the fantail. In calm weather seismic operations, the magnetometer was towed off the starboard crane while the starboard air gun was towed from the base of the a-frame on that side of the ship. In heavy seas, there was danger of the air gun tangling with the seismic streamer or the magnetometer, so we had to choose either to profile with only one air gun or without collecting magnetic data. Usually, the latter was the choice and so the magnetic data are missing. Rough seas also hampered the seismic data collection. In one instance at Site 214, the seismic technician felt the weather was too rough for seismic data collection, so there was a hiatus of ~10 hours in the seismic profiling.

Dredging was also affected by rough seas, principally by limiting options in choosing a course for dredging. Without a functioning bow thruster, we had to dredge with *Revelle* lined up close to the wind direction. At first, the captain would only allow us to dredge with the stern into the wind, but in rougher seas, only with the bow into the wind. At many sites we had to look for outcrops that had a good orientation for dredging with the wind, which made us pass up some good dredging opportunities. Although it has to be said that dredging was overall very successful and the captain and crew were accommodating in trying new approaches to dredging, nevertheless, most of the dredges that returned empty or did not produce good basalt samples were at less-than-ideal locations that were dictated by the wind and swells. Although we never crossed over the line into weather that was deemed too rough for dredging, there was perhaps a week of days total in which we were very close to the safety limit for dredging.

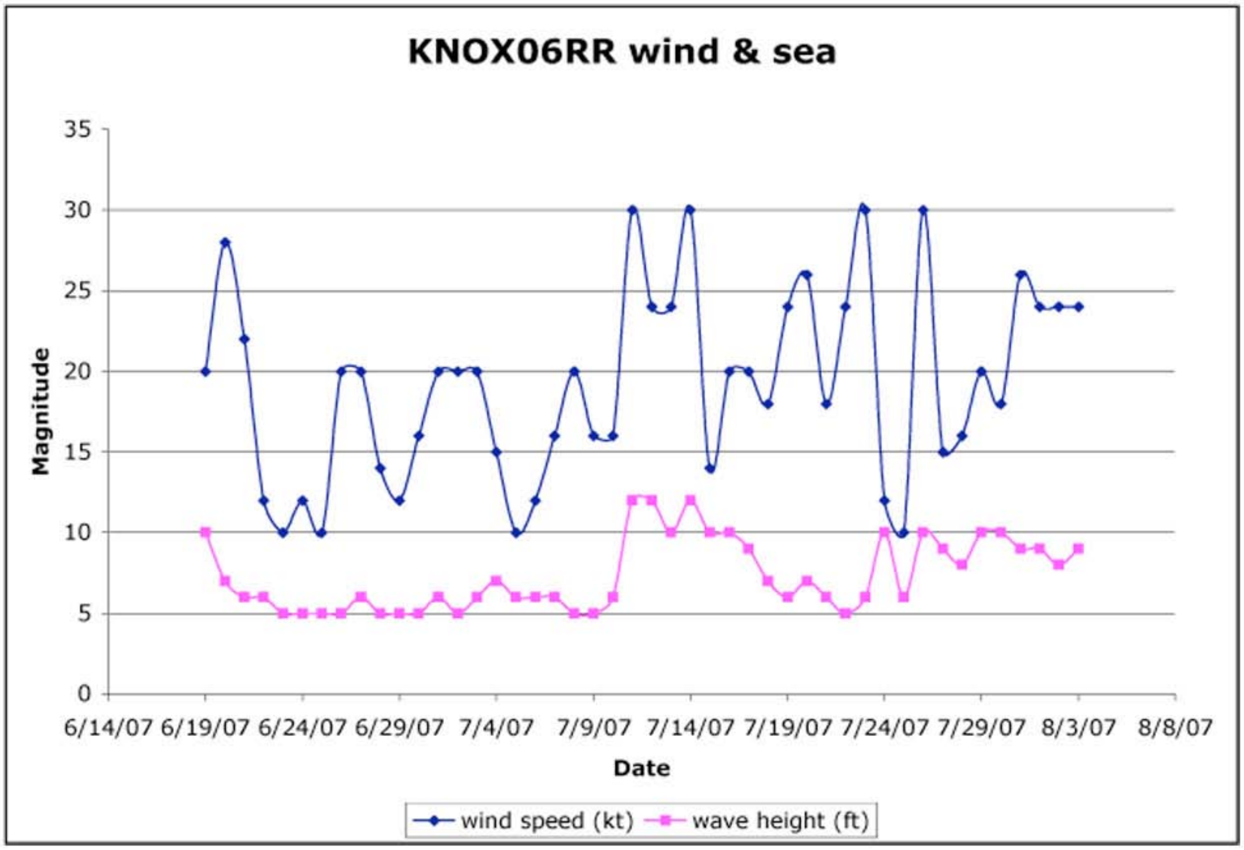


Figure 29. Wind speed (knots) and wave height (ft) for cruise KNOX06RR. Noon observations logged on the bridge of the R/V *Roger Revelle*. Note that winds were ≥20 kt for 25 out of 46 days logged.

IV. Preliminary Observations

Geophysics

A first look at the geophysical data, principally the multibeam bathymetry and seismic data, reveal a NER that is has been more tectonically active than generally appreciated. The traditional western view of NER is of a long, linear volcanic track whose shape was dictated by the motion of the Indo-Australian plate over a plume in the mantle. Several investigators have written articles that imply the NER is not so simple. The ridge may not preserve a simple, monotonic age progression because of shifts in the ancient Wharton ridge position (Krishna et al., 1999). Moreover, segments of the ridge may have been shaped by faulting (Pilipenko et al., 1996) and furthermore, faulting may continue, related to the ongoing deformation in the central

Indian Ocean (e.g., Krishna et al., 2001). One of the reasons that these interpretations have not previously taken root in the generally accepted picture of NER is poor documentation by geophysical data. Indeed, it is clear from ship track maps of the region that KNOX06RR represents the most geophysical data collected over NER in a single cruise.

The morphology detailed by the EM120 multibeam echosounder shows significant changes along the length of the NER. In the north, we find large, separate seamounts. Proceeding south, the volcanoes become less separate until the high, southern ridge is reached, and it is nearly continuous for ~17° (1900 km). We see these broad trends reflected in the multibeam bathymetry data. In the Site 758 and Site 216 surveys, the volcanoes appear more-or-less rounded in plan. In the sites NER2 and NER3 surveys, we found volcanoes that were more linear and which have a definite bathymetric grain, likely caused by horst and graben structures (Fig. 30). The high, south ridge is surprising in its morphology. The east side is often a sharp, linear, steep escarpment 1-2 km in height. This morphology is almost certainly the result of strike-slip faulting that has shaped this side of the NER. In contrast, the west side of the ridge has a low, volcanic slope that appears to be a normal, volcanic morphology.

The most surprising aspect of faulting is the obvious traverse fabric seen in most of the NER from the central part south through the high ridge. We see some of this faulting in the trends at sites NER2 and NER3 (Fig. 30). In those locations, the volcanoes appear split by east-west and northeast-southwest trending basins. Seismic sections show that these basins are fault related. The high, south ridge is also permeated with basins of this type, noted also in the surveys at Site 214, site NER4, and Site 253.

Seismic reflection profiles show the faulting mentioned above as well as revealing a sediment cover that generally decreases southward. Igneous basement faulting is seen in the north, at Sites 758 and 216 (Fig. 31). At these northern sites, the faulting is generally more widely spaced than in the south. In the middle of the NER, at sites NER2 and NER3, faulting is more pervasive, with distances between fault blocks generally less than in the north. In the southern ridge, the faulting is both pervasive and often with large throw. One of the most notable features of the south NER faulting is the large fault basins, sometimes forming large canyons that dissect the ridge. These fault basins are often filled with sediment, causing the thickest sediment deposits on the ridge.

Sediment thickness generally decreases from north to south. One factor is certainly burial by Bengal Fan sediments, which mantle the large volcanoes in the north of NER. However, this is not the only sediment source. Pelagic sediments appear thickest in the north, with typical thicknesses of ~400-500 m on volcano tops. The pelagic layer thins southward and at the far south it is typically <100 m in thickness. The underlying sediments, probably deposited near the time of volcanic formation and probably consisting mostly of volcaniclastics, are variably thick at all locations. The thickness of this sediment layer seems mostly controlled by local sources and topography.

Looking forward to geophysical research to be done with the data collected on KNOX06RR, the data will provide important insights into the formation of NER. In conjunction with previous results from ocean drilling, the seismic data will be used to develop a sedimentation model. This will help constrain the timing of faulting events. The seismic and multibeam bathymetry data will allow us to examine the extensive faulting and its relationship with past and current tectonic events that have and are shaping NER. Other data, such as magnetic and gravity data, will be useful for compilation with other similar data from past cruises in synthesis studies of regional tectonics.

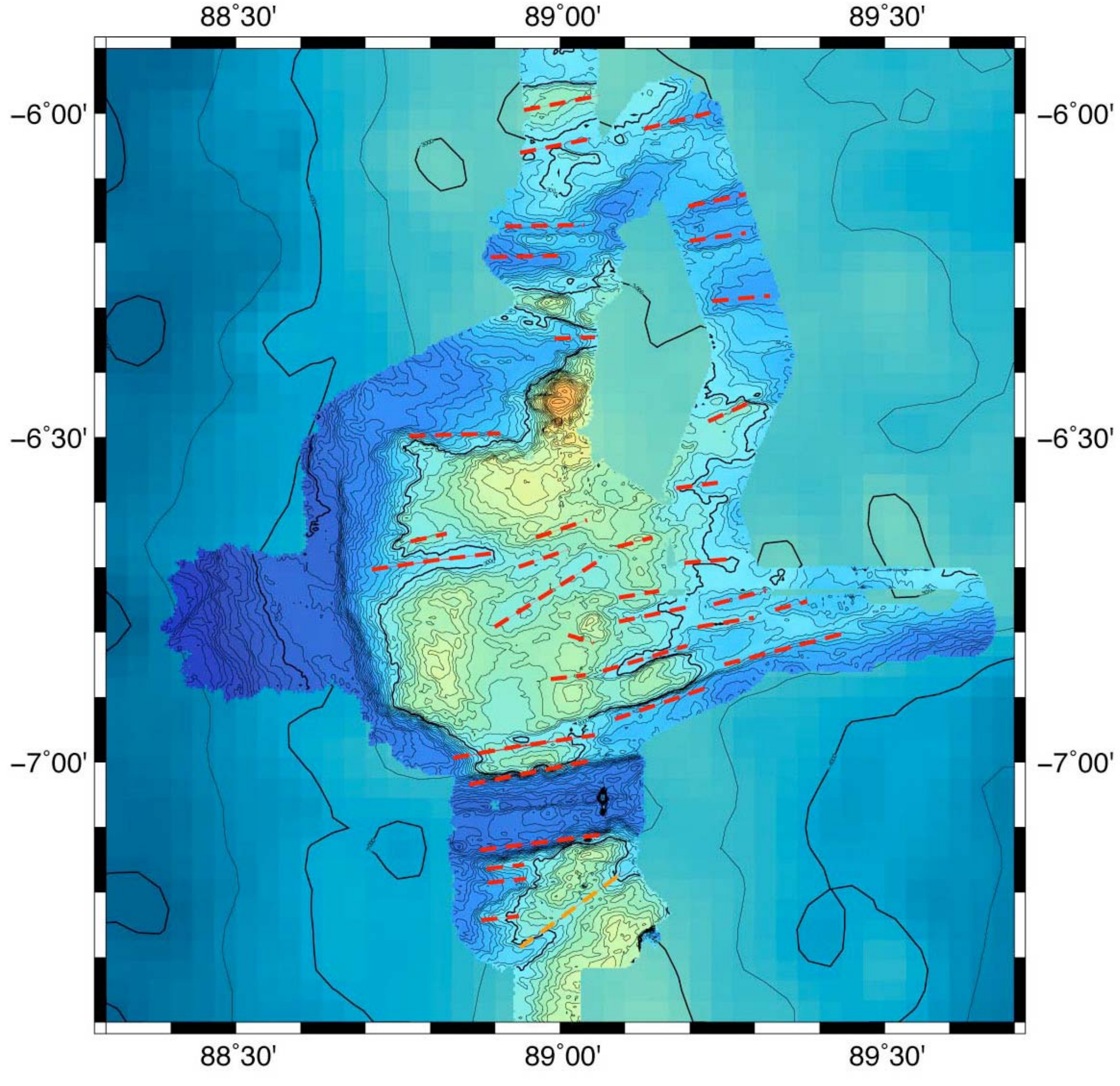


Figure 30. Tectonic lineations noted in the multibeam bathymetry of the site NER2 seamount. Dashed lines highlight bathymetric basins, ridges, or escarpments.

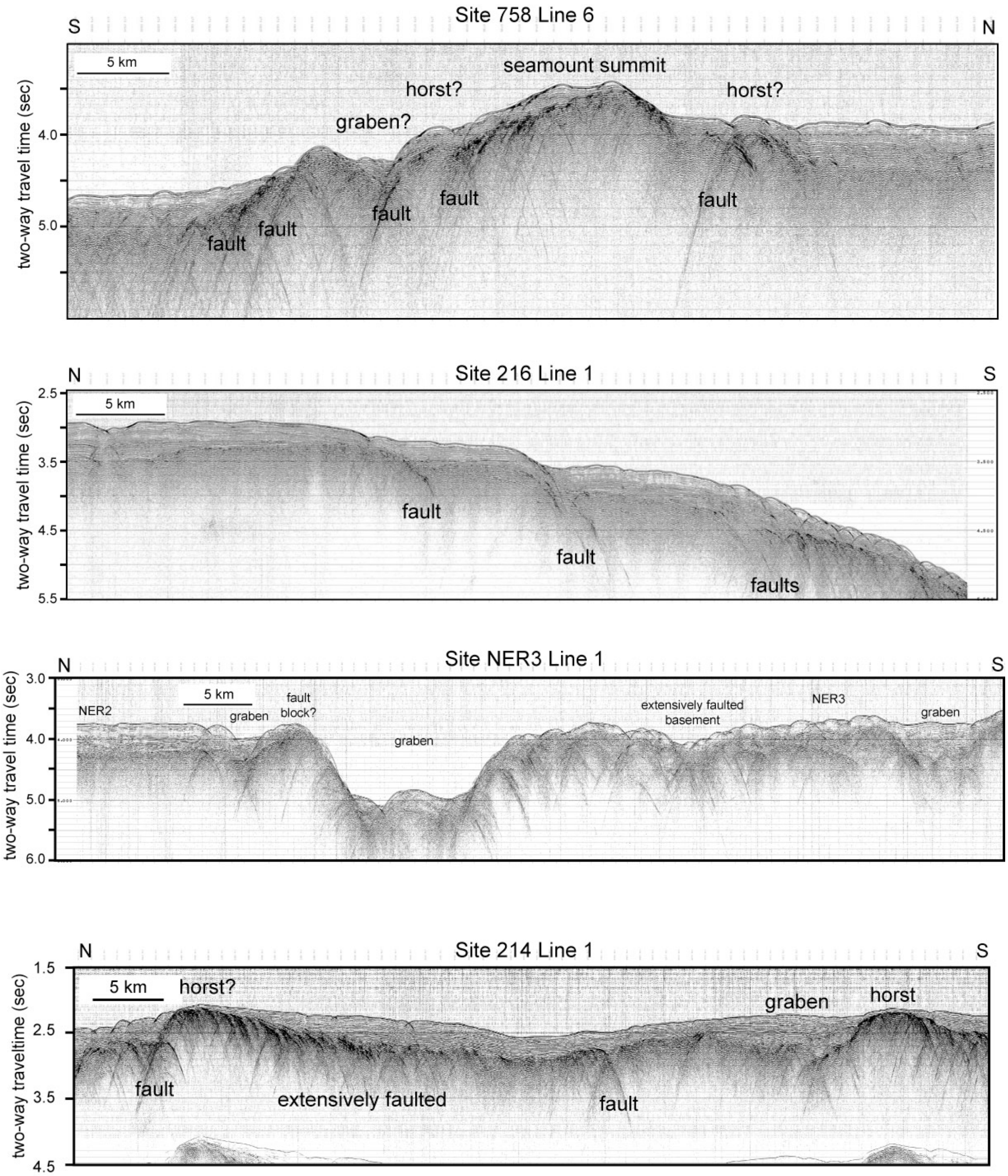


Figure 31, part 1. Example seismic reflection profiles from NER sites. From top to bottom, a profile segment is shown from Site 758, Site 216, site NER2-NER3, and Site 214.

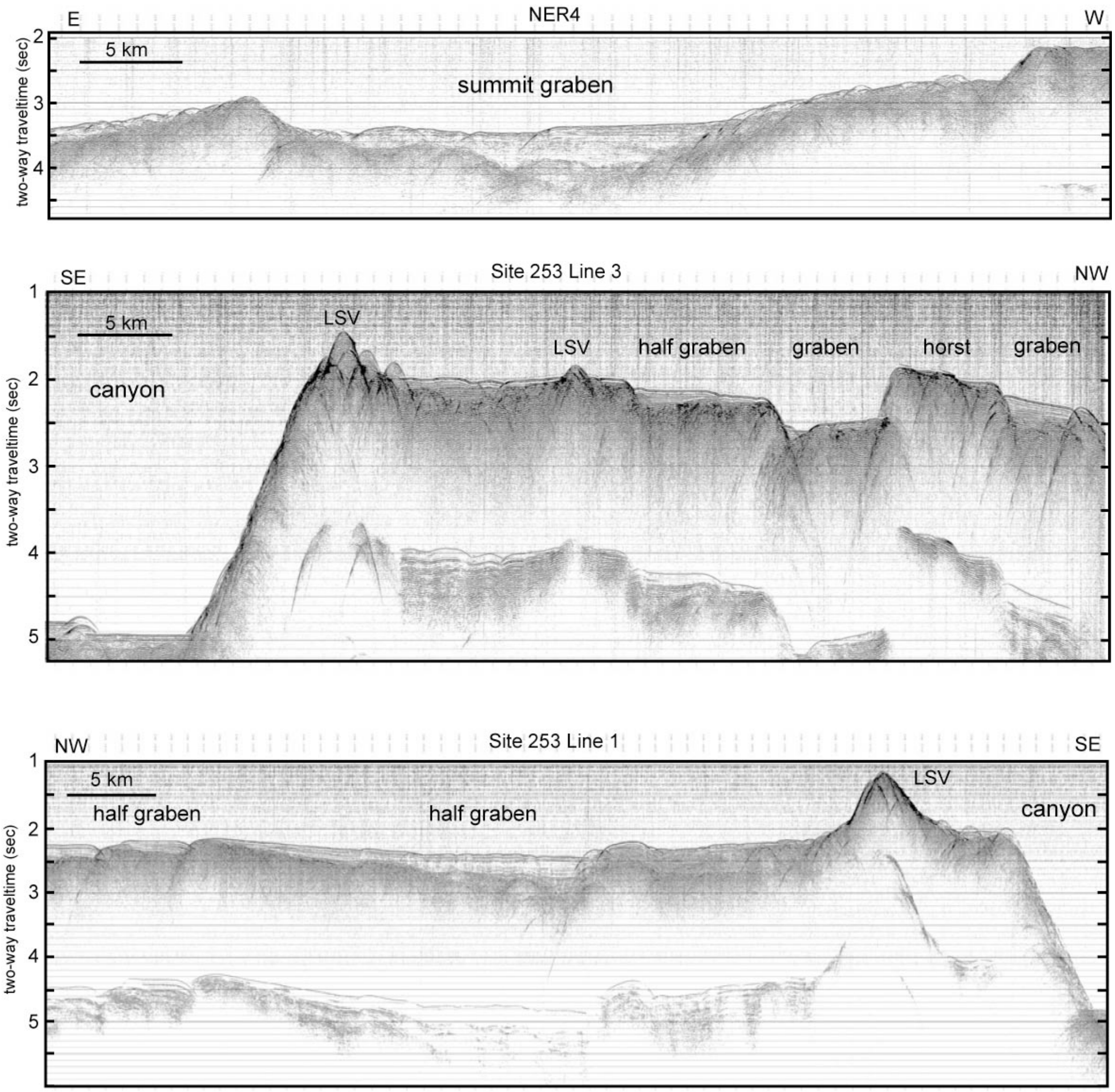


Figure 31, part 2. Example seismic reflection profiles from NER sites. Top profile is from site NER4, showing the summit graben. Middle and bottom profiles show the extensive faulting at Site 253.

Rock samples

From the vicinity of ODP Site 758 in the north to ODP Site 253 in the south of the Ninetyeast Ridge (Fig. 10), twenty three of thirty three dredges recovered 2238 kg of basalt; two garnet-bearing mantle rocks (0.4 kg) were also recovered in dredge 13. In addition, several dredges contained lithified carbonate, phosphorite, chert, Fe-Mn crust and volcaniclastic rocks for a total rock recovery of 3135 kg. Most of our successful dredges, i.e., with basalt recovery, were deep, starting at >3500 mbsl. Many of these deep dredges contained pillow basalt with quenched pillow rims, commonly with both altered and unaltered glass, and well developed pipe vesicles; pillow margin breccias were abundant.

Most dredges included several petrographically distinct types of basalt that were classed as separate groups based on grain-size, aphanitic to medium-grained, and phenocryst assemblage, ranging from aphyric to plagioclase- and olivine-phyric with rare clinopyroxene-phyric samples. These groups are likely to have had different petrogenesis. In order to select the most appropriate samples for geochemical studies, ~350 billets were cut on the ship for shore-based preparation of thin and polished sections. Also prepared on the ship were slabs, 100 to 200 grams, of petrographically distinct samples from each dredge containing basalt; these ~250 samples were hand carried to MIT so that the shore-based geochemistry program, i.e., whole rock analyses of major and trace elements could begin as soon as possible. Pillow basalts with apparently fresh glass were also selected for microprobe analyses of major and trace elements. In addition, about 100 samples were chosen, about 3 samples for each dredge, because they have the characteristics, e.g., plagioclase phenocrysts or unaltered groundmass, suitable for dating by ^{40}Ar/^{39}Ar geochronology. These data, as well as the whole-rock analyses will be part of the PhD thesis of Evelyn Mervine, a MIT/WHOI Joint Program student who participated in the cruise. Another MIT student, H. Owens, will chose samples containing large magnetite grains to evaluate U+Th/He geochronology as a dating technique independent of the K-Ar system. These samples will also be shipped by air to MIT.

The basalt samples collected are suitable for addressing our two major objectives:

(1) Determination of eruption age as a function of latitude along the south to north striking Ninetyeast Ridge; in particular are the ages consistent with a simple age progression along a hotspot track, or is the age progression more complex because of southerly spreading ridge jumps thereby causing reversals in a simple age progression or is a hotspot interpretation inappropriate?

(2) What is the relative role of different mantle sources, hotspot- and MORB source-related, contributing to the generation of Ninetyeast Ridge basalt as a function of age and proximity of a spreading ridge offset by large, north-south fracture zones, to the independent hotspot sources that formed the Kerguelen Archipelago and Amsterdam/St Paul Islands?

V. Education and Outreach

Project Summary (R. Wilson, teacher-at-sea)

This section reviews the planning, expedition outreach and projected post-cruise activities for the KNOX06RR Expedition to the Ninetyeast Ridge aboard the R/V *Roger Revelle*. During the latter two weeks of April, I applied for the Teacher at Sea project from *JOI Learning*. I had learned about this opportunity from the President of CAST (Colorado Association of Science Teacher) who I co-teach with. My students were closely involved with project planning from the start, as was the school district administration. When I was selected, I began detailed planning activities that included significant interaction with students during the actual expedition. Travel to Thailand began on June 10th and I return to Colorado from Singapore on August 8th. Activities related to the cruise are expected to continue for a period of up to two years.

Planning

Initial project planning involved middle school students doing research into ocean exploration and the Integrated Ocean Drilling Program. As a part of the early discussions, students tried to imagine themselves going on this site survey expedition. Would they want to and what would they look for? This exploratory was then followed with actual work preparing the JOI application, writing short answer essays for questions and thinking of how the teacher would be selected. Once the application was sent in, we then prepared our approach for the interview, who should be included, and what are the questions?

It was important to have the full support of the school district for this project. We wanted to have significant student involvement and our immediate students were able to help identify student interests and help with the web site design. We held a contest with students to brainstorm and select the best web site name.

Using Epals and other resources, I began to search for other schools to participate, particularly in Thailand and India. By May 10th, I had a list of seven schools that wanted to participate at some level with students in the expedition. They were Colorado, Texas, Washington State (Makah Indian Reservation), British International School in Phuket, Thailand, India, and W. Australia. In total, I completed mailing and distribution lists of 120 addresses by May 30th and was sending updates with news about the project from my web-based mail system, which I intended to continue to use during the expedition.

I also sent a weekly status report to JOI and to Will Sager, the chief scientist for the expedition, and we had weekly conference calls to discuss planning. Once I had a list of the scientists, I sent out an introduction email to explain my role in the project, and had several email exchanges with scientists during the period just prior to departure.

Immediate Pre-Cruise Activities

There was a working session for two days prior to departure from Denver, Colorado where I worked directly with the web site developer. He had done an initial configuration in Adobe Dreamweaver based on the concept design and specifications that I had sent to him on May 15th. The concept design was based on student input. During the sessions in Denver, we modified the website as needed, loaded initial content about the project, configured the statistics counters and loaded this onto the JOI server. A development site version was kept in the MacBook Pro to then access the remote server for later ship-board updates.

I departed Denver on June 12th and eventually joined up with Will Sager and his team in Phuket on June 15th. I did direct updates to the web site from the hotel in Thailand with travel notes. We boarded the ship on Sunday, June 17th and I began to test the satellite connection, firewall and access on board the ship. Our outreach goal was to continue to involve online students real-time in several aspects of our scientific research.

Computer and Technical Connectivity

The educational outreach program relied primarily on the website updates, and secondarily on student emails and videoconferences. It was clearly understood that the outreach plan would stretch the technical capability of computer and network capabilities at sea.

Although I came on board two days prior to departure, we were not successful in establishing file transfers through the firewall before leaving the port. Once we left port, the satellite connection was not available for the two-day transit to the Ninetyeast Ridge due to interference of the mast with the satellite reception on a westerly course. Once on station, connectivity was restored and during the next week, we worked through ftp and firewall configuration to allow web site update access through the firewall. During this period, I was able to send email attached html files for the shore-based developer to load to the active web site. This significantly delayed initial web site updates and later required full re-synchronization between the databases.

There are known constraints for connectivity on the *Revelle*. First, the limiting factor is the satellite connection. Maximum configured bandwidth up is 88 kbps and down is 96 kpbs. Although this is adequate for text-based Internet and files, email and partial voice, it is the absolute minimum for graphics or video. The obstruction due to the mast height causes loss of connectivity on courses for up to 90 degrees out of 360 degrees relative to the satellite location.
It is understood that Pacific area coverage is to a different satellite, which would change this limitation. When on station while dredging, if the ship swings course, the satellite loses lock-on and is intermittent.

For the primary use of ship-based to web server updates, the satellite in most cases is adequate as long as graphics are strictly limited and carefully sized. Email for student communication is also adequate as long as mail is forwarded to the *Revelle* ship mail server and is not to a web-based mail account. This limitation required rebuilding of all student distribution lists and folders. After the cruise I will also then need to reconvert archived mail and combine all student mail files.

Another technical factor impacted the effective utilization of ship-based computer resources. Since all of the science team and part of the crew were new to the ship, initial setup and training were a significant technical support commitment. Although there is a set-up guide for users, set-up issues continued well into July since general network support is secondary to the primary science setup needed for instrumentation and data collection. In addition to the satellite, technical computing resources and network resources, there are an estimated 35 laptops and personal use computers for that require support. As a result, access to shipboard computer services is limited.

Overall, the educational outreach goals for connectivity were met with the web site updates and for email with students. Voice or video communications via Skype were blocked by the firewall unless explicitly unblocked for a conference. With limited technical support resources, this significantly constrained this aspect of the educational outreach; this outreach goal was only marginally met. One potential way to improve this for future expeditions may be to delegate some aspects of user support to a second person on the science or technical support team.

Work Plan

During the initial days of transit, I discussed a content work plan with the several people on the ship. The first week was devoted to understanding the overall layout, ship procedures, resolving technical issues, and to meeting the science team and crew.

The primary work during the next three weeks was on the geophysics group. During this time, Will Sager and the team wrote several background articles and devoted time to help with the outreach work. I then allocated two weeks to the petrology group, and worked closely with them to understand the sorting and grouping of rock samples before taking the final two weeks to work on profiles and integration. The time during integration also was used to continue with articles completed by science team members in the petrology group.

The actual work sessions with the science team and crew were very productive. It was helpful to become a part of each work team for some block of time, and then to also have time to summarize and organize my notes and material. Attention to structure and keeping materials organized were critical during these sessions.

Summary Results as of August 1, 2007

The web site was implemented online June 15th. Since that time, we have averaged 80 visitors each day and an average of 300 page views per day. Updates through the firewall were possible from June 28th and have been daily, with a few exceptions. At this point, there are about 700 html and picture files in the active web site.

At three times during the expedition, an update email was sent out to the 120 students and teachers. Since participation was voluntary, this helped keep the focus and we did see an increase in web visits for the three to five days following the emails. JOI Learning also released the web site link in an email to 1300 teachers early in July. I have received 700 emails on board the *Revelle* and have sent 400 emails. As noted above, for project purposes, mail has been archived and will be merged with web-mail after the expedition.

There have been 2 videoconference meetings and two school videoconferences during the expedition. These were arranged in advance and included several people on board. Skype was used for these sessions and the quality was generally acceptable for most sessions and testing. During two conferences, the quality was fair to poor and the connection had to be re-established a few times.

There have been five science challenge questions during the expedition. We had from 5-20 responses on each question. These form the base for the classroom resources and were also a way to hold student attention during summer vacation since there were prizes awarded to the top students for each question.

Because graphics were important to the project and to subsequent expansion of the website, there was a focused effort to collect images and video during the trip. I now have a chronological library of 7000 images and videos, plus and estimated 3000 images taken by other members of the science team and crew.

Overall, the goals were met for the educational outreach during the expedition. To summarize: the website was effective and was maintained on a daily basis with the connectivity from the ship. Email with students was effective and also allowed some interaction between scientists and students. Videoconferences were partially effective, again allowing interaction between the scientists, educators and students on a real-time basis.

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Table 1. KNOX06RR dredge locations.

No.	Site	Begin Date	On sta. Time	End Date	On deck Time	Depth on bott.	On bottom location Latitude		Longitude	
1	Site 758 Smt	20-Jun	21:45	21-Jun	4:00	3556	5	7.00	90	26.00
2	Unnamed Smt	23-Jun	4:00	23-Jun	8:35	3047	3	14.99	90	34.10
3	Site 216	26-Jun	4:04	26-Jun	9:45	4401	1	24.30	90	42.40
4	Site 216	26-Jun	14:30	26-Jun	20:57	4480	0	54.50	90	30.09
5	Unnamed Smt	27-Jun	9:45	27-Jun	13:45	2782	-0	27.20	89	29.20
6	Unnamed Smt	28-Jun	2:24	28-Jun	9:59	4531	-2	1.50	89	28.70
7	Unnamed Smt	28-Jun	16:00	28-Jun	10:25	3807	-2	13.29	89	2.58
8	NER1	29-Jun	9:26	29-Jun	15:25	2967	-3	33.99	89	7.00
9	NER2	3-Jul	12:11	3-Jul	18:30	3026	-6	24.00	88	59.30
10	NER2	3-Jul	19:20	4-Jul	1:03	2951	-6	24.20	88	59.10
11	NER2	4-Jul	3:45	4-Jul	12:31	3988	-6	42.37	88	39.24
12	NER3	7-Jul	1:00	7-Jul	8:45	4133	-7	57.00	88	40.97
13	NER2	7-Jul	13:40	7-Jul	20:28	3663	-7	2.00	88	59.00
14	NER3	7-Jul	21:15	8-Jul	3:45	3659	-7	6.50	89	0.00
15	NER3	8-Jul	16:00	8-Jul	22:17	4053	-8	22.40	88	40.30
16	NER3	9-Jul	8:52	9-Jul	16:15	3964	-9	28.70	88	32.10
17	Site 214	14-Jul	4:45	14-Jul	12:15	4954	-11	15.99	89	21.00
18	Canyon	15-Jul	11:38	15-Jul	18:34	3334	-13	22.58	88	59.99
19	Canyon	15-Jul	20:38	16-Jul	2:06	2909	-13	25.95	88	51.60
20	Linear Smt	16-Jul	14:24	16-Jul	19:59	3859	-13	5.50	87	50.40
21	Linear Smt	16-Jul	21:15	17-Jul	4:36	3974	-13	15.90	87	50.30
22	NER summit	17-Jul	19:47	18-Jul	1:06	2728	-15	6.09	87	59.41
23	Unnamed smt	18-Jul	4:45	18-Jul	12:00	2868	-15	4.64	87	44.59
24	E scarp	19-Jul	3:58	19-Jul	12:20	4100	-16	59.90	88	43.91
25	E scarp	19-Jul	14:30	19-Jul	23:15	4718	-16	45.10	88	46.15
26	E scarp	20-Jul	8:28	20-Jul	14:54	4939	-17	59.12	88	45.49
27	E scarp	21-Jul	0:00	21-Jul	9:24	4642	-19	20.52	88	43.96
28	NER 4 E scarp	21-Jul	14:57	21-Jul	23:10	4116	-19	38.60	88	39.50
29	NER4 summit	23-Jul	2:23	23-Jul	6:13	2208	-19	20.89	87	59.10
30	Unnamed	24-Jul	1:35	24-Jul	9:06	3734	-22	22.50	87	2.16
31	NW Site 253	24-Jul	19:07	24-Jul	2:30	3597	-23	45.50	86	48.91
32	Site 253	28-Jul	9:30	28-Jul	18:13	3588	-25	45.50	87	53.90
33	Site 253	29-Jul	1:30	29-Jul	10:58	4752	-25	47.30	88	40.00

Table 2. KNOX06RR Seismic lines.

Line	BOL Time	BOL Date	EOL Time	EOL Date	BOL SP#	EOL SP#	BOL Lat deg	BOL Lat min	BOL Lon deg	BOL Lon min	EOL Lat deg	EOL Lat min	EOL Lon deg	EOL Lon min
Site 758														
1	8:47	21-Jun	12:57	21-Jun	1001	2503	5	12.87	90	33.11	5	12.99	90	6.97
1 (1A)	13:03	21-Jun	14:35	21-Jun	2542	3091	5	13.27	90	6.49	5	22.49	90	6.41
1 (2)	14:43	21-Jun	20:01	21-Jun	3140	5050	5	22.89	90	6.95	5	22.98	90	38.52
3	20:05	21-Jun	23:21	21-Jun	5051	6225	5	23.21	90	38.78	5	30.80	90	22.66
4	23:24	21-Jun	4:18	22-Jun	6226	7991	5	30.81	90	22.36	4	57.92	90	22.00
5	4:19	22-Jun	5:14	22-Jun	7992	8322	4	57.71	90	16.96	4	57.69	90	16.97
6	5:16	22-Jun	10:28	22-Jun	8326	12201	4	57.79	90	16.96	5	27.44	90	17.00
7	10:38	22-Jun	12:10	22-Jun	10202	10749	5	27.97	90	17.67	5	27.99	90	26.49
8	12:19	22-Jun	14:43	22-Jun	10750	11606	5	27.44	90	27.02	5	11.97	90	27.00
Site 216														
1	22:16	23-Jun	8:49	24-Jun	11609	15402	1	55.72	90	20.10	0	58.24	90	30.01
2	8:56	24-Jun	10:33	24-Jun	15403	15987	0	57.56	90	30.12	0	48.56	90	23.63
3	10:40	24-Jun	21:13	24-Jun	15988	19792	0	48.45	90	22.96	1	22.09	89	33.88
4	21:15	24-Jun	22:14	24-Jun	19793	20146	1	22.24	89	33.76	1	27.39	89	33.88
5	22:14	24-Jun	9:30	25-Jun	20147	24194	1	27.39	89	33.88	1	27.70	90	43.20
6	9:39	25-Jun	10:20	25-Jun	24195	24437	1	27.05	90	43.73	1	22.39	90	43.64
7	10:24	25-Jun	16:31	25-Jun	24438	26638	1	22.02	90	43.38	1	22.00	90	4.89
8	16:35	25-Jun	18:26	25-Jun	26639	27307	1	22.24	90	4.55	1	33.46	90	4.49
9	18:27	25-Jun	21:02	25-Jun	27308	28252	1	33.56	90	4.50	1	33.99	90	19.38
10	21:05	25-Jun	23:52	25-Jun	28253	29254	1	33.99	90	19.67	1	17.11	90	20.02
NER2														
1	4:29	1-Jul	9:57	1-Jul	29255	31221	-6	15.26	88	58.89	-6	44.95	88	0.01
2	9:58	1-Jul	15:00	1-Jul	31222	33032	-6	45.06	89	0.01	-6	48.98	88	28.84
3	15:00	1-Jul	15:54	1-Jul	33033	33356	-6	48.98	88	28.84	-6	43.53	88	28.37
4	15:55	1-Jul	3:17	2-Jul	33357	37454	-6	43.43	88	28.39	-6	43.05	89	37.96
5	3:18	2-Jul	4:09	2-Jul	37455	37760	-6	43.10	89	38.05	-6	47.99	89	38.00
6	4:09	2-Jul	9:13	2-Jul	37761	39580	-6	47.99	89	38.00	-6	47.98	89	6.96
7	9:13	2-Jul	10:44	2-Jul	39581	40123	-6	47.98	89	6.96	-6	38.28	89	6.71
8	10:45	2-Jul	13:58	2-Jul	40124	41275	-6	38.18	89	6.69	-6	38.01	88	47.53
9	13:59	2-Jul	16:44	2-Jul	41276	42263	-6	38.03	88	47.43	-6	53.69	88	49.94
10	16:44	2-Jul	17:10	2-Jul	42264	42423	-6	53.69	88	49.94	-6	53.98	88	52.53
11	17:11	2-Jul	20:19	2-Jul	42424	43552	-6	53.97	88	52.64	-6	35.25	88	53.01
12	20:20	2-Jul	22:10	2-Jul	43553	44211	-6	35.15	88	53.02	-6	34.51	89	3.55
13	22:10	2-Jul	4:08	3-Jul	44212	46352	-6	34.51	89	3.55	-7	10.20	89	4.01
NER3														
1	15:43	4-Jul	3:54	5-Jul	46353	50735	-6	50.67	88	59.05	-8	5.44	88	58.98
2	3:55	5-Jul	8:19	5-Jul	50736	52323	-8	5.54	88	58.94	-7	59.99	88	32.99
3	8:20	5-Jul	17:39	5-Jul	52324	55681	-7	59.98	88	32.89	-7	55.00	89	27.03
4	17:47	5-Jul	1:56	6-Jul	55682	58623	-7	54.47	89	27.52	-7	47.91	88	41.76
5	1:57	6-Jul	6:03	6-Jul	58624	60049	-7	47.90	88	41.66	-7	40.51	89	3.59
6	6:04	6-Jul	10:51	6-Jul	60050	61775	-7	40.54	89	3.68	-8	8.65	89	3.98
7	10:52	6-Jul	13:20	6-Jul	61776	62670	-8	8.74	89	3.94	-8	9.01	88	49.41
8	13:25	6-Jul	16:58	6-Jul	62709	63982	-8	8.72	88	49.02	-7	47.28	88	49.08
9	18:31	6-Jul	22:18	6-Jul	63983	65327	-7	45.27	88	53.75	-8	7.32	88	54.01

Table 2. KNOX06RR Seismic lines (cont.).

Line	BOL Time	Date	BOL Time	Date	BOL SP#	EOL SP#	BOL Lat/Lon deg	min	deg	min	EOL Lat/Lon deg	min	deg	min
Site 214														
1	21:55	9-Jul	13:18	10-Jul	65328	70866	-8	22.98	88	41.39	-9	28.91	88	33.35
2	13:19	10-Jul	22:24	10-Jul	70867	74141	-9	28.91	88	33.36	-10	16.30	88	48.50
3	22:25	10-Jul	3:35	11-Jul	74142	75938	-10	16.38	88	48.45	-10	46.41	88	43.01
4	3:36	11-Jul	3:46	11-Jul	75939	76002	-10	46.51	88	43.01	-10	47.51	88	43.00
5	21:20	11-Jul	0:04	12-Jul	76003	76992	-11	0.22	88	38.00	-10	58.37	88	33.00
6	0:06	12-Jul	1:11	12-Jul	76993	77387	-10	58.56	88	33.00	-11	5.06	88	33.00
7	1:12	12-Jul	11:27	12-Jul	77388	81079	-11	5.16	88	33.00	-11	1.15	88	15.50
8	11:28	13-Jul	1:57	13-Jul	81080	86297	-11	1.02	88	15.50	-11	20.00	88	37.33
9	1:58	13-Jul	10:47	13-Jul	86298	89476	-11	20.00	88	37.44	-11	20.00	89	24.12
10	10:48	13-Jul	13:37	13-Jul	89477	90491	-11	20.00	89	24.21	-11	13.87	89	20.45
11	13:38	13-Jul	16:16	13-Jul	90492	91443	-11	13.89	89	20.35	-11	15.00	89	4.29
NER4														
1	4:44	22-Jul	5:46	22-Jul	1002	1376	-19	17.99	88	56.27	-19	18.02	88	59.63
2	5:47	22-Jul	19:14	22-Jul	1377	6221	-19	17.95	88	59.54	-19	18.01	87	34.10
Site 253														
1	11:37	25-Jul	21:26	25-Jul	6222	9757	-25	7.93	87	44.03	-25	58.10	88	6.60
2	21:28	25-Jul	23:05	25-Jul	9758	10343	-25	58.25	88	6.73	-26	5.03	87	59.22
3	23:06	25-Jul	7:48	26-Jul	10344	13479	-26	5.06	87	59.11	-25	23.64	87	27.25
4	7:49	26-Jul	18:12	26-Jul	13480	17576	-25	23.33	87	27.25	-25	22.50	88	34.01
5	18:13	26-Jul	20:51	26-Jul	17577	18169	-25	22.49	88	34.11	-25	32.03	88	41.01
6	20:52	26-Jul	6:53	27-Jul	18170	21776	-25	32.12	88	41.00	-25	32.49	87	33.62
7	6:55	27-Jul	10:18	27-Jul	21777	22993	-25	32.42	87	33.42	-25	11.52	87	33.05
8	10:19	27-Jul	11:15	27-Jul	22994	23329	-25	11.44	87	33.11	-25	11.46	87	38.37
9	11:16	27-Jul	15:42	27-Jul	23330	24927	-25	11.53	87	38.36	-25	36.51	87	38.25
10	15:43	27-Jul	18:38	27-Jul	24928	25985	-25	36.61	87	38.28	-25	36.97	87	57.55
11	18:39	27-Jul	20:14	27-Jul	25986	26556	-25	36.92	87	57.66	-25	27.00	87	51.75
12	20:15	27-Jul	2:58	28-Jul	26557	28977	-25	27.00	87	51.65				

Table heading abbreviations: BOL = beginning of line; EOL = end of line; SP = shotpoint number.

Appendix 1. Dredge Summaries

****

Overall Grand Totals:
Total Dredge Recovery: ~3135 kg
Total Basalt Recovery: ~2238 kg

****

Dredge #1:

Date: June 20th, 2007

Location: On Bottom- 05º07.82’ N 090º26.82’ E
Off Bottom- 05º05.89’ N 090º24.53’ E

Location Description:
Cone to the southeast of Drill Site 758

Depth: On Bottom- 2950 m
Off Bottom- 2587 m

Total Dredge Recovery: ~2 kg

Total Basalt Recovery: None

Sample Recovered:
2 kg of calcite fragments

****

Dredge #2:

Date: June 23rd, 2007

Location: On Bottom- 03°14.99’ N 090º34.10’ E
Off Bottom- 03°15.72’ N 090º34.82’ E

Location Description:
Between Drill Sites 758 and 216, steep slope that looks like a landslide scarp

Depth: On Bottom- 3035 m
Off Bottom- 2390 m

Total Dredge Recovery: ~44 kg

Total Basalt Recovery: ~22 kg

Sample Recovered:
13 kg of flowtop breccia in vesicular basalt
7 kg of aphanitic, massive basalt
2 kg of plagioclase-microphyric, massive basalt
18 kg of volcaniclastic claystone to sandstone
3 kg of chert
1 kg of calcium carbonate cobbles
****
Dredge #3:

Date: June 26th, 2007

Location: On Bottom- 01º24.30' N 090º42.40' E
Off Bottom- 01º25.29' N 090º42.41' E

Location Description:
Tall seamount to the east of Drill Site 216

Depth: On Bottom- 4377 m
Off Bottom- 3814 m

Total Dredge Recovery: ~82 kg

Total Basalt Recovery: ~82 kg

Sample Recovered:
82 kg of aphanitic, massive, aphyric to sparsely-phyric basalt. Phenocrysts of plagioclase and clinopyroxene are present in the sparsely-phyric samples.

****
Dredge #4:

Date: June 26th, 2007

Location: On Bottom- 00º54.50' N 090º30.09' E
Off Bottom- 00º55.50' N 090º29.31' E

Location Description:
Southeast slope of Drill Site 216 seamount

Depth: On Bottom- 4478 m
Off Bottom- 3850 m

Total Dredge Recovery: ~399 kg

Total Basalt Recovery: ~155 kg

Sample Recovered:
144 kg of aphyric to sparsely-phyric basalt (three subgroups: massive- 72 kg, vesicular- 62 kg, and pillow rims- 10 kg)
11 kg of palagonite (altered glass) breccias
0.30 kg of altered pumice
0.15 kg of phosphoritic carbonate

Also- 182 kg of bulk sample, not examined in detail but most likely all basalt

****

Dredge #5:

Date: June 27th, 2007

Location: On Bottom- 00º27.20'S 089º29.20' E
Off Bottom- 00º27.54' S 089º20.20' E

Location Description:
Unnamed section of the Ninetyeast Ridge between Drill Site 216 and Site NER 4

Depth: On Bottom- 2782 m
Off Bottom- 2418 m

Total Dredge Recovery: ~ 14 kg

Total Basalt Recovery: ~14 kg

Sample Recovered: 4 Rocks Total
2 aphanitic,vesicular, aphyric basalts (5.9 kg, 0.25 kg)
1 aphanitic, massive, aphyric basalt (0.35 kg)
1 fine to medium-grained, massive, aphyric basalt (7.6 kg)

****

Dredge #6:

Date: June 28th, 2007

Location: On Bottom- 02º01.50' S 089º28.70' E
Off Bottom- 02º00.63' S 089º28.28' E

Location Description:
Steep scarp face south of Drill Site 216

Depth: On Bottom- 4525 m
Off Bottom- 3454 m

Total Dredge Recovery: ~566 kg

Total Basalt Recovery: ~566 kg

Sample Recovered:
200 kg of aphanitic to fine-grained, aphyric basalt
160 kg of aphanitic to fine-grained, plagioclase-phyric basalt
66 kg of aphanitic, clinopyroxene-plagioclase-phyric basalt
14 kg of fine-grained, clinopyroxene-phyric basalt
0.15 kg of basalt breccia

Also- 126 kg of bulk sample, not examined in detail but likely all basalt

****

Dredge #7:

Date: June 28th, 2007

Location: On Bottom- 02°13.29' S 089º02.59' E
Off Bottom- 02°12.84' S 089º01.67' E

Location Description:
Steep scarp face, south of Drill Site 216

Depth: On Bottom- 3807 m
Off Bottom- 3016 m

Total Dredge Recovery: ~77 kg

Total Basalt Recovery: ~65 kg

Sample Recovered:
50 kg of aphanitic to fine-grained, aphyric basalt
8 kg of fine-grained, possible ultramafic (olivine-phyric?) basalt
2 kg of very fine-grained, sparsely plagioclase-phyric basalt
5 kg of assorted basalt cobbles
5 kg of assorted manganese-encrusted cobbles
6 kg of phosphoritic conglomerate
1 kg of volcaniclastic/carbonate cobbles

****

Dredge #8:

Date: June 29th, 2007

Location: On Bottom- 03º33.99' S 089º07.00' E
Off Bottom- 03º33.09' S 089º06.65' E

Location Description:
Steep scarp at Site NER 1

Depth: On Bottom- 2967 m
Off Bottom- 2467 m

Total Dredge Recovery: ~75 kg

Total Basalt Recovery: None

Sample Recovered:
75 kg of calcium carbonate boulders and cobbles

****

Dredge #9:

Date: July 3rd, 2007

Location: On Bottom- 006º24.00' S 088º59.30' E
Off Bottom- 006º24.29'S 088º59.46' E

Location Description:
Northernmost seamount of Site NER 2, dredging NW-SE along side of seamount

Depth: On Bottom- 3017 m
Off Bottom- 2812 m

Total Dredge Recovery: ~0.5 kg

Total Basalt Recovery: None

Sample Recovered: 2 Rocks Total
1 carbonaceous conglomerate (0.3 kg)
1 manganese crust on top of a thin layer of carbonaceous conglomerate (0.2 kg)

****

Dredge #10:

Date: July 4th, 2007

Location: On Bottom- 06º24.20' S 088º59.10' E
Off Bottom- 06º24.49' S 088º59.37' E

Location Description:
Northernmost seamount of NER 2, dredge track is 1/5 of a degree SE of dredge track #9

Depth: On Bottom- 2951 m
Off Bottom- 2622 m

Total Dredge Recovery: None

Total Basalt Recovery: None

Sample Recovered: None

Dredge #11:

Date: July 11th, 2007

Location: On Bottom- 06º42.37' S 088º39.24' E
Off Bottom- 06º43.09' S 088º39.97' E

Location Description:
Steep scarp at Site NER 2

Depth: On Bottom- 3988 m
Off Bottom- 3578 m

Total Dredge Recovery: ~17 kg

Total Basalt Recovery: ~17 kg

Sample Recovered:
17 kg of aphanitic to fine-grained basalt. Both vesicular and massive basalt was recovered. Approximately 1/3 of the basalt recovered is plagioclase phyric while the rest is aphyric.

0.4 kg of volcaniclastic breccia
0.02 kg of volcanic tuff

****

Dredge #12:

Date: July 7th, 2007

Location: On Bottom- 07º57.00' S 088º40.97' E
Off Bottom- 07º57.50' S 088º42.50' E

Location Description:
Steep scarp on western side of NER 2

Depth: On Bottom- 4133 m
Off Bottom- 3542 m

Total Dredge Recovery: ~29 kg

Total Basalt Recovery: None

Sample Recovered: 4 rocks and some assorted cobbles
3 calcium carbonate boulders (4 kg, 5 kg, and 15 kg)
Assorted calcium carbonate cobbles (4.8 kg)
1 carbonate crust (0.2 kg)
1 volcanic tuff (0.3 kg)

Dredge #13:

Date: July 7th, 2007

Location: On Bottom- 07º02.00' S 088º59.00' E
Off Bottom- 07º00.64' S 088º59.97' E

Location Description:
Southern scarp of NER 2, along NER 3 seismic line 1

Depth: On Bottom- 3655 m
Off Bottom- 2949 m

Total Dredge Recovery: ~41 kg

Total Basalt Recovery: ~29 kg

Sample Recovered:
14 kg of aphanitic to medium-grained, aphyric basalt
8 kg of fine to medium-grained, olivine-phyric basalt
6 kg of fine to medium-grained, plagioclase-phyric basalt
1 kg of assorted basalt cobbles

11 kg of calcareous/volcaniclastic cobbles
0.5 kg of volcaniclastic sandstone
0.3 kg of volcanic tuff

Also- 2 Mantle Xenoliths:
1 fine-grained, massive, aphyric garnet pyroxenite (0.1 kg)
1 garnet peridotite (0.3 kg)

****

Dredge #14:

Date: July 7th-8th, 2007

Location: On Bottom- 07º06.50' S 089º00.00' E
Off Bottom- 07º07.95' S 089º00.54' E

Location Description:
Northern scarp of NER 3, 1 mile east of NER 3 seismic line 1

Depth: On Bottom- 3655 m
Off Bottom- 2911 m

Total Dredge Recovery: ~204 kg

Total Basalt Recovery: ~143 kg

Sample Recovered:
83 kg of very fine to medium-grained, aphyric basalt
21 kg of fine-grained, plagioclase-phyric basalt
12 kg of aphanitic to fine-grained, clinopyroxene-phyric basalt
1 kg of fine-grained, clinopyroxene-plagioclase-phyric basalt
1 kg of fine-grained, olivine-phyric basalt
25 kg of assorted basalt cobbles
44 kg of calcium carbonate cobbles and boulders
8 kg of volcaniclastic breccia
4 kg of volcaniclastic conglomerate
4 kg of volcaniclastic tuff
1 kg of volcaniclastic claystone

****

Dredge #15:

Date: July 8th, 2007

Location: On Bottom- 08º22.40’ S 088º40.30’ E
Off Bottom- 08º22.89’ S 088º41.28’ E

Location Description:
Southwestern scarp of Site NER 3

Depth: On Bottom- 4053 m
Off Bottom- 3438 m

Total Dredge Recovery: ~122 kg

Total Basalt Recovery: ~ 115 kg

Sample Recovered:
115 kg of aphanitic to fine-grained, aphyric basalt
0.5 kg of hyaloclastic breccia
5 kg of pink (iron-rich?) phosphorite cobbles
1 kg of chert
0.1 kg of pumice cobbles
0.1 kg of volcanic tuff cobbles
0.5 kg of calcium carbonate cobbles

****

Dredge #16:

Date: July 9th, 2007

Location: On Bottom- 09º28.70’ S 088º32.10’ E
Off Bottom- 09º28.96’ S 088º33.73’ E

Location Description:
Western scarp of seamount north of Drill Site 214

Depth: On Bottom- 3957 m
Off Bottom- 3443 m

Total Dredge Recovery: ~145 kg

Total Basalt Recovery: ~110 kg

Sample Recovered:
80 kg of aphanitic to fine-grained, aphyric basalt

9 kg of very fine to fine-grained, olivine-phyric basalt
6 kg of aphanitic to fine-grained, plagioclase-phyric basalt
15 kg of assorted basalt cobbles
14 kg of marl (volcaniclastic and calcium carbonate) cobbles and boulders
10 kg of calcium carbonate cobbles and boulders
8 kg of chert
3 kg of phosphorite cobbles

****

Dredge #17:

Date: July 14th, 2007

Location: On Bottom- 11°15.99' S 089°21.00' E
Off Bottom- 11°15.43' S   089°19.96' E

Location Description:
Eastern basal scarp of Drill Site 214

Depth: On Bottom- 4947 m
Off Bottom- 4435 m

Total Dredge Recovery: ~30 kg

Total Basalt Recovery: ~28 kg

Sample Recovered:
20 kg of aphanitic to fine-grained, aphyric basalt
4 kg of very fine-grained, plagioclase-phyric basalt
3 kg of serpentinized or chloritized basalt
1 kg of fine-grained, olivine-phyric basalt
1 kg of basalt breccia
0.5 kg of chert

****

Dredge #18:

Date: July 15th, 2007

Location: On Bottom- 13°22.60' S   089°00.00' E
Off Bottom- 13°22.58' S   089°59.99' E

Location Description:
North-facing scarp on the eastern side of seamount south of Drill Site 214

Depth: On Bottom- 3334 m

Off Bottom- 2999 m

Total Dredge Recovery: ~10 kg

Total Basalt Recovery: ~4 kg

Sample Recovered:
4 kg of highly-altered basalt
5 kg of volcaniclastic sandstone
0.5 kg of chert
0.25 kg of siltstone

****
Dredge #19:

Date: July 15th, 2007

Location: On Bottom- 13º25.55' S 088º51.60' E
Off Bottom- 13º26.96' S 088º52.10' E

Location Description:
North-facing scarp on the eastern side of seamount south of Drill Site 214

Depth: On Bottom- 2899 m
Off Bottom- 2291 m

Total Dredge Recovery: ~40 kg

Total Basalt Recovery: None

Sample Recovered:
35 kg of calcium carbonate cobbles and boulders
2 kg of chert
1 kg of volcaniclastic claystone to sandstone
1 kg of phosphate-chalk cobbles
0.5 kg of marl (volcaniclastic and calcium carbonate) cobbles

****

Dredge #20:

Date: July 16th, 2007

Location: On Bottom- 13º05.50' S 087º50.40' E
Off Bottom- 13º06.08' S 087º51.50' E

Location Description:
Northwest scarp of north-south trending seamount cluster 20 minutes west of main NER

Depth: On Bottom- 3859 m
Off Bottom- 3236 m

Total Dredge Recovery: 0.40 kg

Total Basalt Recovery: None

Sample Recovered:
0.40 kg of botryoidal manganese crusts

****

Dredge #21:

Date: July 16th, 2007

Location: On Bottom- 13º15.90' S 087º50.30' E
Off Bottom- 13º15.69' S 087º52.06' E

Location Description:
Western scarp of north-south trending seamount cluster 20 minutes west of main NER, about 10 miles south of the location of Dredge 20

Depth: On Bottom- 3974 m
Off Bottom- 2749 m

Total Dredge Recovery: None

Total Basalt Recovery: None

Sample Recovered: None

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Dredge #22:

Date: July 17th-18th, 2007

Location: On Bottom- 15º06.09' S 087º59.41' E
Off Bottom- 15º05.50' S 087º59.41' E

Location Description:
Southwest scarp of seamount on western edge of Ninetyeast Ridge, at same latitude as Osborn Knoll

Depth: On Bottom- 2728 m
Off Bottom- 2157 m

Total Dredge Recovery: ~55 kg

Total Basalt Recovery: ~54 kg

Sample Recovered:
46 kg of aphanitic to fine-grained, massive to vesicular, aphyric basalt
8 kg of aphanitic to very fine-grained, massive, plagioclase-phyric basalt
0.5 kg of volcaniclastic claystone to sandstone
0.5 kg of botryoidal manganese crusts

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Dredge #23:

Date: July 18th, 2007

Location: On Bottom- 15º04.64' S 087º44.59' E
Off Bottom- 15º06.25' S 087º45.47' E

Location Description:
Northwest scarp of tall seamount between NER and Osborn Knoll

Depth: On Bottom- 2868 m
Off Bottom- 1883 m

Total Dredge Recovery: ~ 22 kg

Total Basalt Recovery: None

Sample Recovered:
22 kg of calcium carbonate boulders and cobbles

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Dredge #24:

Date: July 19th, 2007

Location: On Bottom- 16º59.90' S 088º43.91' E
Off Bottom- 16º59.23' S 088º42.73' E

Location Description:
East-facing scarp east of Drill Site 757

Depth: On Bottom- 4100 m
Off Bottom- 2864 m

Total Dredge Recovery: ~192 kg

Total Basalt Recovery: ~130 kg

Sample Recovered:
75 kg of aphanitic to medium-grained, massive, aphyric basalt
29 kg of very fine to fine-grained, massive, plagioclase-phyric basalt
10 kg of very fine-grained, massive, clinopyroxene-phyric basalt
8 kg of very fine-grained, massive, olivine-clinopyroxene-phyric basalt
8 kg of basalt breccia
37 kg chert
25 kg of calcium carbonate boulders and cobbles
0.1 kg of volcaniclastic sandstone

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Dredge #25:

Date: July 19th, 2007

Location: On Bottom- 16º45.10' S 088º46.15' E
Off Bottom- 16º44.40' S 088º44.63' E

Location Description:
East-facing scarp northeast of Drill Site 757

Depth: On Bottom- 4718 m
Off Bottom- 3222 m

Total Dredge Recovery: ~62 kg

Total Basalt Recovery: ~35 kg

Sample Recovered:

26 kg very fine-grained to medium-grained, massive, aphyric basalt
9 kg very fine-grained to medium-grained, massive to vesicular, plagioclase-phyric basalt
26 kg basalt/palagonite breccia
1 kg volcaniclastic sandstone

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Dredge #26:

Date: July 20th, 2007

Location: On Bottom- 17º59.12' E 088º45.49' E
Off Bottom- 17º58.59' E 088º44.62' E

Location Description:
Southeast corner of eastern scarp of Drill Site 757 seamount

Depth: On Bottom- 4939 m
Off Bottom- 4124 m

Total Dredge Recovery: ~47 kg

Total Basalt Recovery: ~40 kg

Sample Recovered:
20 kg of aphanitic, massive, olivine-phyric basalt
20 kg of aphanitic to very fine-grained, olivine-microphyric, plagioclase-phyric basalt
7 kg of basalt/palagonite breccia

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Dredge #27:

Date: July 21st, 2007

Location: On Bottom- 19º20.52' S 088º43.96' E
Off Bottom- 19º19.91' S 088º42.88' E

Location Description:
Eastern scarp of Site NER 4

Depth: On Bottom- 4642 m
Off Bottom- 3770 m

Total Dredge Recovery: ~85 kg

Total Basalt Recovery: ~81 kg

Sample Recovered:
50 kg of aphanitic to very fine-grained, massive to vesicular, olivine-microphyric to olivine-phyric basalt (note: both pillow fragments and flow interiors)
22 kg of aphanitic to medium-grained, massive to vesicular, aphyric basalt (note: both pillow fragments and flow interiors)
9 kg of assorted basalt cobbles
3 kg of assorted basalt breccia cobbles
1 kg of basalt/palagonite breccia

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Dredge #28:

Date: July 21st, 2007

Location: On Bottom- 19º38.60' S 088º39.50' E
Off Bottom- 19º37.88' S 088º38.33' E

Location Description:
Eastern upper scarp of Site NER 4, 20 miles southwest of Dredge 27

Depth: On Bottom- 4116 m
Off Bottom- 3024 m

Total Dredge Recovery: ~135 kg

Total Basalt Recovery: ~132 kg

Sample Recovered:
56 kg of aphanitic to medium-grained, massive, aphyric basalt
32 kg of aphanitic to fine-grained, massive, clinopyroxene-phyric basalt
6 kg of fine-grained, massive, plagioclase-clinopyroxene-phyric basalt
5 kg of fine-grained to medium-grained, massive, olivine-phyric basalt
1 kg of very fine-grained, massive, plagioclase-phyric basalt
32 kg of assorted basalt cobbles
2 kg of basalt-phosphorite breccia
1 kg of volcaniclastic sandstone/ tuff

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Dredge #29:

Date: July 23rd, 2007

Location: On Bottom- 19º20.90' S 087º59.10' E
Off Bottom- 19º21.52' S 087º59.44' E

Location Description:

North-facing scarp, graben east of summit of Site NER 4. 40 miles west of Dredge 27.

Depth: On Bottom- 2208 m
Off Bottom- 1718 m

Total Dredge Recovery: ~127 kg

Total Basalt Recovery: ~0.1 kg

Sample Recovered:
0.1 kg of aphanitic, massive, sparsely feldspar-phyric, evolved? volcanic rock
70 kg of volcaniclastic sandstone / tuff boulders and cobbles
55 kg of phosphorite boulders and cobbles
2 kg of phosphorite breccia
0.3 kg calcium carbonate cobbles

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Dredge #30:

Date: July 24th, 2007

Location: On Bottom- 022º22.50' S 087º02.16' E
Off Bottom- 022º22.80' S 087º03.74' E

Location Description:
Western scarp of Ninetyeast Ridge

Depth: On Bottom- 3734 m
Off Bottom- 2460 m

Total Dredge Recovery:~ 82 kg

Total Basalt Recovery: ~68 kg

Sample Recovered:
45 kg of aphanitic, massive to vesicular plagioclase-phyric basalt
14 kg of aphanitic, massive to vesicular, aphyric basalt
4 kg of aphanitic, massive, clinopyroxene-phyric basalt
1 kg of aphanitic, massive, plagioclase-pyroxene phyric basalt
4 kg of assorted basalt cobbles
8 kg of palagonite breccia
3.5 kg of basalt breccia
1 kg of assorted phosphorite-chalk cobbles
1 kg of volcaniclastic sandstone/tuff cobbles
0.5 kg of basalt-phosphorite breccia cobbles

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Dredge #31:

Date: July 24th, 2007

Location: On Bottom- 23º44.50' S   086º48.91' E
Off Bottom- 23º44.70' S   086º50.40' E

Location Description:
Southwest-facing scarp on northwest corner of Drill Site 253 edifice

Depth: On Bottom- 23º45.50' S 086º48.91' E
Off Bottom- 23º44.70' S 086º50.40' E

Total Dredge Recovery: ~101 kg

Total Basalt Recovery: ~7 kg

Sample Recovered:
6 kg of aphanitic to medium-grained, massive to vesicular aphyric basalt
0.3 kg of fine-grained, massive, plagioclase-phyric basalt
0.5 g of fine-grained to medium-grained, massive, olivine-phyric basalt
0.5 kg of fine-grained, massive, plagioclase-olivine-phyric basalt
81 kg of volcaniclastic conglomerate boulders and cobbles
4 kg of phosphorite cobbles
4 kg of volcaniclastic/biogenic conglomerate boulders and cobbles
2.5 kg of volcaniclastic sandstone/tuff boulders and cobbles
2 kg of carbonate/volcanic claystone cobbles

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Dredge #32:

Date: July 28th, 2007

Location: On Bottom- 25º45.50' S 087º53.90' E
Off Bottom- 25º44.04' S 087º53.29' E

Location Description:
Southeast-facing scarp of graben southeast of Drill Site 253

Depth: On Bottom- 25º45.50' S 087º53.90' E
Off Bottom- 25º44.04' S 087º53.29' E

Total Dredge Recovery: ~133 kg

Total Basalt Recovery: ~122 kg

Sample Recovered:
61 kg of very fine-grained to medium-grained, massive to vesicular, plagioclase-phyric basalt
41 kg of aphanitic to fine-grained, massive to vesicular, aphyric basalt
9 kg of aphanitic to very fine-grained, massive to vesicular, olivine-phyric basalt
2 kg of aphanitic, massive, clinopyroxene-phyric basalt
1 kg of aphanitic, massive, olivine-clinopyroxene-phyric basalt
8 kg of assorted basalt cobbles
8 kg of hyaloclastic / basalt breccia cobbles and boulders
3 kg of volcaniclastic sandstone / tuff cobbles and boulders

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Dredge #33:

Date: July 29th, 2007

Location: On Bottom- 25°47.30' S 088°40.00' E
Off Bottom- 25°47.72' S 088°37.76' E

Location Description:
East-facing scarp of north-south ridge to the east of Drill Site 253 edifice

Depth: On Bottom- 4742 m
Off Bottom- 3475 m

Total Dredge Recovery: ~196 kg

Total Basalt Recovery: ~ 37 kg

Sample Recovered:
13 kg of aphanitic, massive, olivine-plagioclase-phyric basalt
10 kg of aphanitic to very fine-grained, massive, olivine-phyric basalt
7 kg of aphanitic to medium-grained, massive, aphyric basalt
0.5 kg of aphanitic, massive, clinopyroxene-phyric basalt
0.5 kg of aphanitic, massive, plagioclase-phyric basalt
6 kg of assorted basalt cobbles
132 kg of basalt breccia boulders and cobbles
14 kg of volcaniclastic sandstone / tuff boulders and cobbles
11 kg of hyaloclastic / basalt boulders and cobbles
2 kg of assorted manganese crusts