Integrated Ocean Drilling Program Expedition 324 Scientific Prospectus

Testing plume and plate models of ocean plateau formation at Shatsky Rise, northwest Pacific Ocean

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Abstract

One of the most fundamental questions of modern geodynamics is the process of mantle convection and its impact on Earth's surface through volcanism. The greatest source of nonocean-ridge volcanism appears to be massive eruptive episodes that formed oceanic plateaus, volcanic passive margins, and continental flood basalts. A widely accepted hypothesis for such volcanism is that it results from the head of a starting plume, which rises from the deep mantle, spreads out beneath the lithosphere, and melts cataclysmically in a massive outpouring of volcanic activity. Despite the wide acceptance of this hypothesis, a convincing case for a plume head origin has not been made for any oceanic plateau; rather, significant complexities have been revealed by recent drilling of the Kerguelen and Ontong Java plateaus. One great difficulty with research of oceanic plateaus is that the original setting, relative to mid-ocean ridges and plate tectonics, is poorly known for most plateaus because they were formed during the mid-Cretaceous when no magnetic reversals formed ridge-parallel anomalies to record spreading ridge locations. Shatsky Rise, located ~1500 km east of Japan, is unique in being the only large oceanic plateau formed during a time of magnetic reversals, permitting its tectonic setting to be resolved. Magnetic lineations show that the plateau formed along the trace of a triple junction, intimately related to ridge tectonics. Existing data demonstrate that several aspects of Shatsky Rise's history (e.g., massive, rapid initial growth; transition from large to small magma flux; capture of ridges) fit the plume head model. On the other hand, the coincidence of volcanism with the triple junction, ridge jumps, and the lack of isotopic evidence for a hotspot-type mantle source can all be taken as favoring a plate-controlled origin. Its unique combination of features makes Shatsky Rise the best location on Earth to test plume versus plate-tectonic hypotheses of ocean plateau formation. During Integrated Ocean Drilling Program Expedition 324 we propose to core ~800 m of igneous basement at five sites on Shatsky Rise to examine the history, source(s), and evolution of this plateau. From the results of this expedition, we hope to be able to put to rest the question of whether oceanic plateaus like Shatsky Rise were formed from deep-sourced mantle plumes or interaction of plate boundaries and the lithosphere with the shallow mantle.

Schedule for Expedition 324 (Shatsky Rise)

Integrated Ocean Drilling Program (IODP) Expedition 324 to the Shatsky Rise oceanic plateau is derived from IODP Proposal 654-Full2. Expedition 324 (proposal available at **iodp.tamu.edu/scienceops/expeditions/shatsky_rise.html**) is planned for the riserless R/V *JOIDES Resolution,* operating under contract with the U.S. Implementing Organization (USIO). At the time of publication of this *Scientific Prospectus* the expedition is scheduled to begin on 4 September 2009 in Yokohama, Japan, and end in Townsville, Australia, on 4 November 2009, providing 56 days at sea to achieve the expedition's scientific objectives. Any changes to this schedule will be posted at **iodp.tamu.edu/scienceops.** Supporting site survey data for Expedition 324 are archived at the IODP-Management International (IODP-MI) Site Survey Data Bank (**ssdb.iodp.org**). Details on the facilities aboard the *JOIDES Resolution* can be found at **iodp-usio.org.**

Introduction and background

Knowledge about large igneous provinces (LIPs) has played a fundamental role in shaping the prevailing view of mantle geodynamics, that of largely upper mantle plate-driven flow punctuated by rising thermally driven plumes from the lower mantle (e.g., Davies, 1992). The largest LIPs, the oceanic plateaus, continental flood basalts, and volcanic passive margins, reach volumes of several 10^6 to several 10^7 km^3 and are apparently the product of relatively short lived massive magmatic episodes that represent the largest nonridge volcanic process on Earth (e.g., Coffin and Eldholm, 1994). In terms of magma flux, volume, and extent, such LIPs dwarf even the most prodigious present-day hotspots, such as Iceland and Hawaii. Magma production rate for the largest LIPs rivaled or even surpassed that of the global mid-ocean-ridge system for short periods of time (e.g., Tarduno et al., 1991; Duncan and Richards, 1991; Mahoney et al., 1993; Coffin and Eldholm, 1994). Moreover, because many of the largest LIPs formed during the Mesozoic, they may represent a mantle convection regime different from that of the ridge-dominated Cenozoic (e.g., Stein and Hoffman, 1994; Machetel and Humler, 2003).

A widely accepted explanation for plateaus and continental flood basalts is the plume head hypothesis, which posits large (from several hundred to ~2000 km in diameter), bulbous, primarily thermal diapirs that are created at depth in the mantle, probably within the core/mantle boundary zone, and which rise toward the surface, causing cataclysmic volcanism when they impact the lithosphere (e.g., Richards et al., 1989; Griffiths and Campbell, 1990). Like the related plume hypothesis for volcanism at hotspots (Morgan, 1972, 1981; Sleep, 2007), the plume head hypothesis has been accepted by many workers because it provides a simple framework that seems to tie together many observations. Moreover, the plume head phenomenon occurs naturally in numerical and laboratory experiments, given appropriate rheologic conditions (e.g., Whitehead and Luther, 1975; Griffiths and Campbell, 1990, 1991). The trouble is that there is currently no unequivocal geological evidence proving that the plume head mechanism has operated within Earth. Many existing data are indirect indicators of eruptive rate and magmatic volume and could be explained by alternative hypotheses. A growing debate about the number, characteristics, and even existence of mantle plumes (e.g., Smith and Lewis, 1999; Anderson, 2001; Foulger, 2002, 2007; Courtillot et al., 2003; Sleep, 2003; Foulger and Natland, 2003; DePaolo and Manga, 2003) makes it desirable to consider alternative explanations for plateaus. Because ocean plateaus are argued to be the most direct expression of mantle plume heads (i.e., unlike continental LIPs, where magmas must pass through continental lithosphere), understanding oceanic plateau formation is thus critical to understanding mantle dynamics.

Operations during Ocean Drilling Program (ODP) Legs 183 and 192 drilled Kerguelen and Ontong Java plateaus, respectively, seeking evidence that would test the plume head hypothesis (Frey et al., 2003; Fitton et al., 2004). These two plateaus were targeted because they are the largest, and prior data suggested that each formed within a narrow range of ages, as predicted by the plume head model. However, both expeditions uncovered complications that do not fit the simple plume head model (e.g., Coffin et al., 2002; Fitton et al., 2004), so debate over plume heads continued.

In order to address the plume head versus alternative hypotheses, it is necessary to study a plateau for which the relation of the plateau to contemporaneous mid-ocean ridges is known. Unfortunately, this condition is not met for plateaus formed during the Cretaceous Long Normal Superchron (also known as the Cretaceous Quiet Period), such as the Ontong Java, Manihiki, and Kerguelen plateaus, because of the lack of magnetic reversals and thus linear seafloor magnetic anomalies to mark the locations of spreading ridges. Shatsky Rise, located in the northwest Pacific (Figs. **F1, F2**), is the only large intra-oceanic plateau formed at a time of magnetic reversals. Contemporaneous magnetic lineations exist around and within the plateau, providing a framework that allows development of a tectonic model (Nakanishi et al., 1999; Sager et al., 1999). This model is currently based on geophysical inference with little solid geological evidence from sampling.

Shatsky Rise is also unique because it has characteristics that suggest both plume head and ridge-controlled origins (Sager, 2005). The plateau's size, morphology, apparent eruption rate, and age progression are consistent with a plume head origin (Sager and Han, 1993; Nakanishi et al., 1999; Sager et al., 1999). In contrast, the plateau formed at a triple junction during a time of ridge reorganization, which suggests a link to ridge tectonics (Sager et al., 1999; Sager, 2005). Furthermore, existing Nd-Pb-Sr isotopic data for the few basalts cored and dredged from Shatsky Rise show a Pacific mid-ocean-ridge basalt (MORB)–type signature, not the expected ocean island–type signature of a plume head eruption (Mahoney et al., 2005). Whether this MORB affinity is representative of the rise or characterizes only a few minor, late-stage magmas is unknown. However, the fact that existing data for Shatsky Rise can be interpreted both ways suggests that this plateau is uniquely suited for testing plume head versus ridge tectonics models. Moreover, because several, perhaps many, oceanic plateaus formed at triple junctions (e.g., Winterer, 1976; Larson et al., 2002; Sager, 2005; Ishikawa et al., 2005; Smith, 2007), Shatsky Rise probably represents a significant class of ocean plateau, if indeed it is not representative of all.

In the following sections, we briefly review the state of plateau-formation hypotheses, existing knowledge of Shatsky Rise, and why the rise is uniquely suited for testing plume head and ridge tectonics hypotheses. We explain how these hypotheses can be tested by drilling and detail a single-leg nonriser drilling program to sample Shatsky Rise.

Plateau formation hypotheses

Ocean plateaus are remote and difficult to sample. The resulting geological ignorance has led investigators to propose several plateau-formation mechanisms. One class of explanation calls upon anomalous behavior of tectonic plates, such as leaky transform faults (Hilde et al., 1976) or spreading ridge reorganizations (e.g., Anderson et al., 1992; Foulger, 2007). Another class invokes a mantle plume, either as a steady-state plume “tail” beneath a spreading axis or a plume head (Richards et al., 1989; Mahoney and Spencer, 1991; Duncan and Richards, 1991; Coffin and Eldholm, 1994). A third type of mechanism explains plateau formation as a result of a large meteorite impact (Rogers, 1982; Roddy et al., 1987).

The mantle plume hypothesis has been widely accepted, in part because of known shortcomings or lack of development of other hypotheses. The meteorite impact hypothesis was first proposed before discovery of the Chicxulub impact crater (e.g., Hildebrand and Boynton, 1990) and several other large impact sites that were subsequently documented on the continents. Combined with a lack of evidence link-ing plateaus and impacts, the idea lay fallow for many years. However, this hypothesis has been revisited for the Ontong Java Plateau (Ingle and Coffin, 2004; Tejada et al., 2004) because evidence from the plateau does not neatly fit other hypotheses. Plate boundary mechanisms have gained only limited support, partly because they require the assumption of extensive regions of shallow near-solidus asthenosphere that differ geochemically from the shallow asthenosphere that forms mid-ocean ridges and partly because they may not be able to produce the volumes of magma required for the largest plateaus, such as the Ontong Java Plateau. Creating LIPs through cracks, even in a thick part of an oceanic plate, requires that a seemingly small perturbation unleash a massive volcanic event. Consequently, large volumes of anomalously warm asthenosphere or unusually chemically "fertile" (fusible) mantle primed to undergo massive decompression melting must be assumed (Anderson et al., 1992; Foulger, 2007).

Plume-based explanations for plateaus have been bolstered by a wide acceptance of the mantle plume hypothesis for oceanic islands. The idea that thermal (and perhaps chemical) instabilities from the lower mantle rise to the base of the plate and cause hotspot volcanism initially became popular because it provided a neat explanation for age-progressive volcanic chains (Wilson, 1963; Morgan, 1971, 1972; Glen, 2005; Anderson and Natland, 2005). As more age-progressive seamount chains have been found, this explanation has been used repeatedly, with one result being an unlikely large number of proposed plumes. In part, this problem stems from loose application of the plume definition. Recent reexamination of hotspots led Courtillot et al. (2003) and Anderson (2005) to conclude that only a small number fit the original plume concept, that of a thermal diapir originating at or near the core/mantle boundary. Instead, many hotspots, especially smaller ones, likely have shallower sources that may or may not be related to significant thermal upwelling.

The plume head hypothesis arose as an offshoot of the traditional plume hypothesis. It was observed experimentally that if viscosity conditions are appropriate, then perturbations in a gravitationally unstable fluid layer form large bulbous heads that rise through the overlying fluid and that the heads are followed by tails of rising lower-layer material (Whitehead and Luther, 1975; Richards et al., 1989; Griffiths and Campbell, 1990). Such models led to the idea that mantle plumes form near the core/mantle boundary, begin with massive diapirs (plume heads) that rise through the mantle and are fed and followed by a narrow conduit of the same lower-layer material (plume tail). Other versions of the plume head model start plumes from a shallower level, which serves either as the primary source region (e.g., Allègre and Turcotte, 1985; White and McKenzie, 1989; Kellogg et al., 1999) or as a barrier to a lower-mantle plume head, which then creates an upper-mantle plume head by heating from below (Tackley et al., 1993). All of these hypotheses are similar in that they require large thermal (and/or chemical) anomalies that arise at depth and carry deep-mantle material to the base of the plate.

Impingement of a plume head on the lithosphere is thought to lead to voluminous production of basaltic magma, forming an oceanic plateau or continental flood basalt, depending on the type of lithosphere (e.g., Richards et al., 1989; Campbell, 1998). Wide acceptance of this hypothesis rests on radiometric ages indicating that several flood basalts and plateaus were formed rapidly, on the ocean island–like Nd-Pb-Sr-Hf isotopic signatures of many flood basalt sources, and on several long-lived seamount chains that can be traced back to a flood basalt province (e.g., Campbell, 1998). Recently, however, dating results from Leg 183 on Kerguelen Plateau and the Caribbean LIP indicate a longer, more complex emplacement history than previously thought (Duncan, 2002; Coffin et al., 2002; Hoernle et al., 2004). Also, although Ontong Java basalts have an ocean island–type isotopic signature and most of the plateau appears to have formed rapidly (at ~120 Ma), an associated postplateau seamount chain is lacking; plus, the initial depth of much of the plateau was well below that predicted by the plume head model and the amount of posteruptive subsidence has been less than predicted (e.g., Mahoney, Fitton, Wallace, et al., 2001; Fitton et al., 2004, Roberge et al., 2005). The effect of such complications for the plume head model is still being sorted out.

One possible explanation for complex geologic histories for plumes comes from the thermochemical plume hypothesis, in which plume buoyancy is fueled not only by a difference in temperature between the plume and surrounding mantle but also by density differences resulting from chemical composition (Davaille et al. 2003, 2005; Farnetani and Samuel 2005; Lin and van Keken 2006a, 2006b). The primary implications of this type of plume are that it may not behave as would a simple thermal plume, potentially having an extended residence in the lower mantle, perhaps stalling at intermediate mantle depths and not resulting in the magnitude of uplift expected from a thermal plume, and having more than one pulse of flood basalt volcanism.

Why study Shatsky Rise?

During the mid-1990s, ocean drilling studies focused on Kerguelen and Ontong Java plateaus because they are by far the largest, most outstanding examples of LIPs. A serious limitation to understanding the origin of these two plateaus is that they formed mainly during the Cretaceous Long Normal Superchron, so their relationship to contemporaneous spreading ridges cannot be determined. Shatsky Rise is important because it is the only large intra-oceanic plateau that formed during a time of magnetic reversals and the magnetic lineations that run through the plateau (Fig. **F3**) imply that it formed at a triple junction. Knowledge of oceanic plateaus is still so rudimentary that we cannot be certain whether Shatsky Rise and Ontong Java Plateau, for example, formed by the same mechanism. Many other plateaus have formed at triple junctions (Sager, 2005), so Shatsky Rise probably represents a class of ridge-related plateaus, if not all ocean plateaus.

If one wishes to study plume volcanism at a mid-ocean ridge, why not just study Iceland? Several observations imply that the two LIPs have significant differences. Iceland and Shatsky Rise differ in estimated magmatic flux by more than an order of magnitude. If one accepts the plume hypothesis for Iceland (which is not universally accepted; e.g., Foulger, 2002; Foulger et al., 2005), Iceland is well suited for studying present-day plume-ridge interaction; however, Shatsky Rise permits study of the interaction between a plume head and a ridge. Furthermore, Shatsky Rise formed at a triple junction, whereas Iceland did not. In addition, the initial formation of Shatsky Rise appears coincident with a plate reorganization and large (800 km) jump of the triple junction, implying a connection with large-scale plate tectonics. Although small ridge jumps have occurred at Iceland, they have been far smaller than the scale of the jump associated with Shatsky Rise.

Although there are a dozen or so large oceanic plateaus, Shatsky Rise is unique in its setting and holds critical clues to understanding plateau formation. It is a high priority for study for the following reasons:

1. With an area of ~4.8×10^5 km^2 (about the same as Japan or California) and total volume of ~4.3×10^6 km^3, Shatsky Rise is one of the largest ocean plateaus (Sager et al., 1999). Moreover, bathymetric ridges and lava geochemistry suggest Shatsky Rise and Hess Rise (Fig. **F1**) may have arisen from the same source (Bercovici and Mahoney, 1994), which would nearly double the magmatic output. Magmatism of this scale requires something significantly unusual about the physical and/or chemical state of the source mantle.

2. The fact that Shatsky Rise formed during a time of magnetic reversals makes it easier to understand than any other large ocean plateau. Magnetic reversals recorded in Shatsky lavas provide constraint on the rise's structure and original tectonic setting (e.g., Sager and Han, 1993; Sager, 2005). Magnetic anomalies can be used not only to date the plateau and surrounding lithosphere but also to understand how plateau morphology is related to ridge tectonics (e.g., Sager et al., 1999; Nakanishi et al., 1999).
3. Morphology, apparent age progression, and magnetic lineations together indicate that the rise volcanism was spread out laterally, perhaps owing to rapid movement of the Pacific plate over the source mantle (Nakanishi et al., 1999; Sager et al., 1999). In contrast, the volcanic record of larger plateaus formed on a slowly moving plate (e.g., Ontong Java Plateau) may mainly consist of a vertically stacked pile. Therefore, the tectonic and geochemical evolution of Shatsky Rise is easier to address through drilling (i.e., shallow holes distributed laterally).
4. Shatsky Rise formed at a ridge-ridge-ridge triple junction of rapidly spreading ridges; consequently, the lithosphere was young and thin, so lithospheric contamination of magmas should be minimal. Likewise, variations in lithospheric thickness should not have influenced magma compositions significantly and shallow melting beneath a thin lithosphere potentially allowed for greater partial melting.
5. Because of its location exactly along the track of a migrating triple junction and the fact that it appears to share both ridge and plume characteristics, Shatsky Rise is uniquely suited to testing plume head versus ridge-controlled hypotheses of plateau genesis.

Why is drilling required? Although the main edifices of Shatsky Rise have some basaltic outcrops, dredged samples of igneous basement suitable for geochemical and geochronological work have proven difficult to get and harder to study. Because of the Late Jurassic to Early Cretaceous age of the oldest part of the plateau, outcrops on these edifices have probably been exposed for long periods. All outcrops dredged to date are coated with thick ferromanganese oxide deposits that make basement rock recovery difficult. Likewise, all existing dredge samples are highly altered. Although dredged basalts were recovered during the 1994 site survey cruise, the recovered samples are highly altered and did not produce reliable radiometric dates, even with the most modern techniques (M. Pringle, unpubl. data). Likewise, all but a very few samples were unsuitable for chemical or isotopic studies (Tejada, 1998; Tatsumi et al., 1998). In addition, the dredge sites were all promontories, ridges, and other high points that may not be representative of the main plateau-building lavas. In sum, the only way to obtain samples that can address the origin of Shatsky Rise is by drilling a series of holes across the plateau and recovering hundreds of meters of basement igneous rock.

Prior research on Shatsky Rise

By the late 1960s it was known that Shatsky Rise is ancient because Early Cretaceous sediments were cored from its summit (Ewing et al., 1966). Although seismic refraction experiments have not yet imaged the Mohorovicic Discontinuity beneath the high parts of the plateau, they have revealed anomalously thick crust with a similar velocity structure to normal oceanic crust but several times thicker (Den et al., 1969; Gettrust et al., 1980). Seismic profiling showed that the tops of the rise edifices hold thick piles of pelagic sediments (up to 1.2 km), whereas sediments on the rise flanks are thin or absent in places (Ewing et al., 1966; Ludwig and Houtz, 1979; Neprochnov et al., 1984; Sliter and Brown, 1993).

Several Deep Sea Drilling Project (DSDP) and ODP cruises have cored Shatsky Rise over a span of 32 years. In succession, operations during DSDP Legs 6 (Sites 47–50), 32 (Sites 305 and 306), and 86 (Site 577) as well as ODP Legs 132 (Site 810) and 198 (Sites 1209–1214) cored atop the highest southern massif of the rise (Tamu Massif) (Fig. **F2**). Many of the holes had only shallow penetration. Drilling during Leg 32 probed deep into the sedimentary cap, recovering Berriasian (earliest Cretaceous) sediments ~50 m above the expected level of basement at Site 306 (Fig. **F2**). This finding was significant because it implied that Tamu Massif formed during latest Jurassic or earliest Cretaceous time. Recently, operations during Leg 198 cored sediments from all three of the Shatsky Rise massifs (Bralower, Premoli-Silva, Malone, et al., 2002), including Ori Massif (Site 1208) and Shirshov Massif (Site 1207). At the last two sites, only the upper part of the sedimentary section was cored, reaching Late Cretaceous sediments. Igneous basement has been reached only twice. During Leg 6, drilling stopped at the top of supposed basement at Site 50, recovering only a few pebbles of basalt, perhaps from a basal conglomerate (Fischer et al., 1971; Melson, 1971). At Site 1213 on the southwest flank of Tamu Massif (Fig. **F2**), operations during Leg 198 cored a 46 m section of little-altered basaltic sills intruding earliest Berriasian sediments (Shipboard Scientific Party, 2002). These basalts produced the first reliable radiometric date for Shatsky Rise, as well as valuable chemical and Nd-Pb-Sr isotopic data (Mahoney et al., 2005).

Magnetic lineations mapped in the northwest Pacific revealed that Shatsky Rise sits at the confluence of two lineation sets: the northeast-trending Japanese lineations and the northwest-trending Hawaiian lineations (Figs. **F1, F2, F3**) (Larson and Chase, 1972; Hilde et al., 1976). This circumstance indicates that the plateau formed at a triple junction separating the Pacific, Farallon, and Izanagi plates (Larson and Chase, 1972). Subsequent studies revealed that the triple junction jumped repeatedly during the time it occupied the location of the rise and that it must have been geometrically unstable to follow the path of the rise (Sager et al., 1988, 1999; Nakanishi et al., 1999). Furthermore, age constraints (Cretaceous sediments and the Site 1213 radiometric date), seismic stratigraphy, and isostatic compensation all indicate that the age of the rise is near that of the adjacent seafloor (Sager et al., 1999), implying that the triple junction and rise formation are linked. Current thought is that a plume head is the link, a source of heat, uplift, and volcanism that both created the rise and captured the triple junction (Sager et al., 1988, 1999).

Magnetic data were also instrumental in supporting the idea that Shatsky Rise formed from a plume head. Sager and Han (1993) postulated that the rise formed rapidly, based on modeling of the magnetic anomaly over Tamu Massif. They noted that the magnetic anomaly implies mainly reversed polarity, in turn implying that most of the edifice may have formed during a single interval of reversed polarity. With simple calculations using the massif volume and an estimate of the length of the single polarity period, the authors inferred that the massif formed with an eruption rate similar to those of several large flood basalts (~1.8 km^3/y).

Recent analyses have refined and expanded these conclusions. Paleomagnetic analysis of Site 1213 basalt samples gives inclination values that are most consistent with reversed magnetic polarity (Tominaga et al., 2005). Furthermore, the mean ^{40}Ar-^{39}Ar age from two basalt samples from the sills is 144.6 ± 0.8 Ma (2σ error) (Mahoney et al., 2005), a value identical to the age of the Jurassic/Cretaceous boundary and that correlates with magnetic Anomaly M19 in the Gradstein et al. (1995) timescale. This result limits the formation of much of the Tamu Massif to between Anomalies M21 and M19, a period of 1.5 m.y. If Tamu Massif formed during a single polarity interval, it is likely either Anomaly M20 or M19, with durations of 0.4 and 0.75 m.y., respectively. Assuming the volume of the massif between Anomalies M21 and M19 formed in 1.5 to 0.4 m.y. (and making the conservative assumption that it formed on existing [very young] 7 km thick crust) implies volcanic emplacement at rates of 1.2 to 4.6 km^3/y (Sager, 2005). Again, such values are in the range of estimates for several large continental flood basalts (e.g., Richards et al., 1989; Johnson and Thorkelson, 2000).

Although these estimates are intriguing, they were made by very indirect means and require confirmation from radiometric ages of igneous basement samples, particularly from other locations on the rise.

Formation and tectonic history of Shatsky Rise

Much of what is known about the tectonics of Shatsky Rise is based on the magnetic lineations that surround the plateau and in some places transect it (Fig. **F3**) (Sager et al., 1988; Nakanishi et al., 1989, 1999). The lineations range from Anomaly M21 (147 Ma; polarity ages from Gradstein et al., 1995), bordering the southwest edge of the plateau, to M1 (124 Ma) at the northern tip of Papanin Ridge (Figs. **F1, F2**). Magnetic lineations have been mapped on the southeast flank of Tamu Massif, on flanks all around Ori and Shirshov massifs, in the basins between massifs, and all through Papanin Ridge (Fig. **F3**); indeed, little of Shatsky Rise is without magnetic lineations. This observation led to the conclusion that the rise consists of three large edifices (Tamu, Ori, and Shirshov massifs) surrounded by lithosphere that is not greatly modified by plateau-building igneous activity (Sager et al., 1999; Nakanishi et al., 1999).

Shatsky Rise volcanism displays a progression in both age and volume along the trace of the triple junction. Rise volume decreases markedly with distance from Tamu Massif. This edifice has an estimated total crustal volume of 2.5×10^6 km^3, whereas Ori and Shirshov massifs each have volumes of 0.7×10^6 km^3. Papanin Ridge, at the north end of the plateau, has a volume of 0.4×10^6 km^3 and the low ridge implies a low volcanic flux over a long period (Sager et al., 1999). Age also apparently decreases with distance from Tamu Massif, with the ages of the volcanic edifices close to those of the underlying lithosphere, as suggested by isostasy (Sandwell and MacKenzie, 1989). The 144.6 Ma age for the Site 1213 sills is coincident with Anomaly M19, implying the bulk of the massif is Anomaly M19 age or older. The Ori and Shirshov massifs must be younger than Tamu Massif because they reside on lithosphere younger than M19. The youngest magnetic lineation beneath both Ori and Shirshov massifs is M14 (136 Ma), and Papanin Ridge is underlain by Anomalies M10 to M1 (from 131 to 124 Ma). These observations are consistent with a northeastward-younging trend and volcanism following the triple junction path.

Magnetic lineations also show that a geometrically stable triple junction was moving northwest (in a Pacific plate reference frame) prior to Anomaly M22 time (Fig. **F4**). At Anomaly M21 time, the triple junction began to reorganize, with the Pacific-Izanagi isochrons rotating 30°, leading to microplate formation and an 800 km eastward jump of the junction to the location of Tamu Massif (Sager et al., 1988, 1999; Nakanishi et al., 1999). Afterward until Anomaly M3 time (126 Ma) Shatsky Rise formed along the trace of the triple junction. During this time the triple junction jumped repeatedly, at least nine times (Fig. **F4**) (Nakanishi et al., 1999). In addition, the main volcanic massifs have sides parallel to spreading ridges and transform faults. Together, these observations imply that the rise of volcanism was episodic and tied to ridge jumps (Sager et al., 1999).

Geochemical data

Chemical and isotopic data from igneous rocks are important for understanding the formation of ocean plateaus because such data provide key information on mantle sources and the conditions of magma genesis. For Shatsky Rise, such data are few. Only a small number of dredges have recovered basalt, and all of the samples are highly altered, making the interpretation of geochemical data difficult. Tatsumi et al. (1998) concluded from Nb-Zr-Y data that a seamount within the rise has an ocean island–like composition similar to volcanoes of the South Pacific Superswell region, a finding that was interpreted as evidence for a plume head lower-mantle source. Whether or not Superswell mantle sources come from the lower mantle is a subject of debate (e.g., Janney and Castillo, 1999; Lassiter et al., 2003; Natland and Winterer, 2005), but in any case the seamount is located in a basin between the Tamu and Ori massifs (dredge D11; Fig. **F3**) and may have been formed after the rise itself.

In contrast, the Site 1213 basalts and two of the least-altered dredge samples from the Tamu and Ori massifs (dredges D9 and D14; Fig. **F3**) display distinctly MORB-type isotopic characteristics (Mahoney et al., 2005). Age-corrected Nd and Pb isotope ratios of these rocks (e.g., $\varepsilon Nd_{(t)}$ = +9.8 to +8.6) are within the range for Pacific MORB and, despite seawater alteration effects, Sr isotope values (0.70269–0.70280) are also MORB-like (Fig. **F5**). Furthermore, the Site 1213 basalts have broadly MORB-like incompatible element patterns (Fig. **F6**). The plume head model predicts ocean island–like, not MORB-like, isotopic compositions (e.g., Campbell, 1998). Thus, at face value the few existing data do not support a plume head origin. However, Site 1213 basalts are sills and the D9 and D14 dredge hauls sampled summit ridges; such late-stage volcanic products may not be representative of the main plateau-building lava pile beneath.

Sea level indicators

A plume head should produce both dynamic and constructional uplift, implying that much of the area atop a plateau will initially be subaerial, particularly if formed on young lithosphere, as with Shatsky Rise (e.g., Griffiths and Campbell, 1990, 1991). For most of Shatsky Rise, evidence on basement paleodepth is lacking; however, a dredge from the upper flank (dredge D12; Fig. F3) of Tamu Massif recovered shallow-water fossils (rudist casts and corals) (Sager et al., 1999). Because the summit of Tamu Massif is higher, it must have been at or above sea level. Furthermore, a flat summit on Shirshov Massif (beneath the sediment cap) as seen in seismic profiles (Sager et al., 1999) indicates erosion by wave action. Thus, it appears likely that conditions during emplacement were sufficient to raise some areas of the rise above sea level. The anticipated recovery of sediments (including benthic fossils) resting immediately above the igneous basement during Expedition 324 may help to constrain paleodepths of the rise summits. However, as indicated on the seismic profiles (see **"Site summaries"**), the oldest sediment layers often thin toward the proposed drill sites (selected to have least sediment cover) and therefore the recovered overlying sediments might be not contemporaneous to the latest volcanism.

What formed Shatsky Rise—a plume head or ridge tectonics?

Shatsky Rise was initially attributed to plume volcanism because it is a very large, somewhat linear igneous construct (Sager et al., 1988; Nakanishi et al., 1989). Indirect evidence of a rapid eruption rate led to the proposal that the plateau formed from a plume head (Sager and Han, 1993; Nakanishi et al., 1989; Sager et al., 1999). At first blush, this explanation seems a good one. It predicts a trail of age-progressive volcanism tracking the motion of the plate over a nearly fixed source (Morgan, 1971, 1972). Shatsky Rise seems to fit this criterion because existing age constraints imply that the rise becomes younger northeastward. Aseismic ridges and seamount chains connect Shatsky Rise with Hess Rise, apparently continuing the eastward-younging trend. Moreover, a similarity of ages and trends between the Shatsky and Hess rises and the Mid-Pacific Mountains even suggests that the volcanic tracks record the motion of the Pacific plate over nearly fixed mantle sources (Sager, 2005).

Arrival of a plume head should cause voluminous flood basalt–type magmatism, with peak volcanism occurring over a brief period (<2 m.y. in several continental flood basalts) and significant amounts of initial uplift (e.g., Richards et al., 1989; White and McKenzie, 1989; Campbell and Griffiths, 1990; Duncan and Richards, 1991). As summarized above, existing evidence indeed suggests that at least the highest portions of Tamu Massif were initially shallow. Although emplacement rates are not known for most of Shatsky Rise, the radiometric age of the Site 1213 basalts combined with the nearby seafloor magnetic lineations suggests that Tamu Massif was constructed at a very high average rate between 1.2 and 4.6 km^3/y. The upper value is more than a quarter of the 16.8 km^3/y of new ocean crust (e.g., Larson, 1991) estimated to be formed worldwide today at ocean ridges. Moreover, the estimated 1.8×10^6 km^3 volume of the initial Tamu Massif eruption implies a source volume equivalent to a sphere 224–408 km in diameter, assuming a mean melt fraction between 5% and 30% (cf. Coffin and Eldholm, 1994), a volume consistent with supply by an actively upwelling plume head.

The geometry of Shatsky Rise also appears to support the plume head hypothesis. Apparently, the emplacement rate of igneous rock waned with time, as shown by the northeastward decrease in size coupled with the ages inferred from magnetic lineations; this decrease is consistent with a transition from plume head to plume tail (Sager et al., 1999). A plume-type hypothesis is likewise an attractive explanation for the odd behavior of the Pacific-Farallon-Izanagi triple junction during the ~20 m.y. that the plateau was forming. The arrival of a plume head, a major source of heat and tensional stress on the lithosphere, is a potential reason for the initial 800 km jump of the triple junction. Heat and flux of upwelling mantle from a plume might have "pinned" the triple junction near the plume head (and later, tail), explaining the repeated triple junction jumps and the observation that the triple junction did not migrate away from the rise as it should have given the velocities of surrounding plates (Sager et al., 1988). In short, a plume head is a plausible explanation for many Shatsky Rise characteristics.

However, some important observations are not explained easily, if at all, by the plume head model. The MORB-type isotopic signature of the existing Shatsky basalts already has been noted. Another nagging point is the ridge reorganization that occurred near the time that Shatsky Rise formed. Just after Anomaly M21 time, synchronous with the beginning of Shatsky Rise eruptions, the Pacific-Izanagi Ridge rotated ~30° (Sager et al., 1988). It is generally accepted that plate motion is driven primarily by subduction (e.g., Lithgow-Bertelloni and Richards, 1998), so it is unclear how a plume head could cause plate velocity to change by acting on the trailing boundary at the ridge. Although a plume may tend to "capture" nearby ridges because it is a major source of heat and actively upwelling mantle (e.g., Kleinrock and Phipps Morgan, 1988), the ridge reorientation occurred >800 km from the alleged plume center. If plume activity and plate motions are independent or only loosely coupled, as is widely believed (e.g., Eldholm and Coffin, 2000), the temporal proximity of these two events would have to be a coincidence.

Another apparent coincidence is the proximity of plume head and triple junction. Although a ridge or triple junction may jump or reorganize to stay near a plume (e.g., Kleinrock and Phipps Morgan, 1988), this assumes that the ridges are already near the plume. How likely is a plume head to rise within 800 km of a triple junction? Assuming plumes form randomly, the probability of one striking within 800 km of a triple junction is only ~0.4%. If more than one plume head erupted within a given period, the probability can be increased by a factor of *N*, where *N* is the number of plumes. This simple calculation ignores mantle convection or basal lithosphere topography that might help steer plumes toward a ridge (e.g., Courtillot et al., 1999; Jellinek et al., 2003; Braun and Sohn, 2003). Nevertheless, having a plume head “find” a triple junction would seem a low-probability event.

Curiously, western Pacific bathymetry and magnetic lineations seem to imply that other similar plume-ridge coincidences occurred. Some other plateaus formed along or near the paths of the Pacific-Farallon-Izanagi triple junction as well as the Pacific-Farallon-Phoenix triple junction, located on the east end of the Pacific plate. Moreover, many of these plateaus are located near proposed ridge reorganizations. After Shatsky Rise, Hess Rise may have formed near the track of the Pacific-Farallon-Izanagi triple junction as it jumped eastward. Similarly, Magellan Plateau, the oldest part of the Mid-Pacific Mountains, and probably the Manihiki Plateau were all formed near the track of the Pacific-Farallon-Phoenix triple junction (Sager, 2005). Explaining all of these plateaus by plume heads independent of ridge dynamics requires many recurrences of a low-probability event. To remain plausible, the plume head hypothesis must assume that plumes and triple junctions are somehow attracted to each other.

How could ridge tectonics lead to plateau formation? Triple junctions could be the key. Ridges that meet at a triple junction are a focal point for strong upwelling (e.g., Georgen and Lin, 2002), but present-day triple junctions are clearly not sites of plateau formation. The discrepancy between the excess volcanism associated with Late Jurassic and Early Cretaceous Pacific triple junctions and the paucity of such activity during the Late Cretaceous through Cenozoic may be explained by the “fertile” mantle hypothesis (also known as the “perisphere” hypothesis) (e.g., Anderson et al., 1992; Anderson, 1995; Smith and Lewis, 1999; Smith, 2003; Foulger, 2007). This hypothesis states that extensive regions of the shallow asthenosphere have a lower melting point (because of higher volatile content, a more mafic composition, and/or higher potential temperature) than the asthenosphere beneath the present-day ridge system. Although the fertile mantle hypothesis is rejected as a general explanation by many, the Late Jurassic–Early Cretaceous Pacific may be a very special case. During this period, much of the Pacific plate (which was then far smaller than at present) may have been located over an anomalously hot region of asthenosphere that now lies beneath the South Pacific Superswell and which has long been an area of oceanic island and seamount production (e.g., McNutt and Fischer, 1987; Staudigel et al., 1991). Today, this region is far from a spreading center and is characterized by several short-lived, poorly understood hotspots that may represent shallow-sourced plumes or entirely nonplume processes (e.g., Janney and Castillo, 1999; Lassiter et al., 2003; Courtillot et al., 2003; Koppers et al., 2003). Triple junction formation in such an area may have promoted excess melting of anomalously fusible mantle and thus plateau formation. The MORB-type isotopic ratios of the few existing Shatsky samples, all of which are from the last stages of volcanism at their sites, are explicable in this context because isotopically normal MORB-source mantle is predicted to underlie the shallow asthenosphere and to well up and gradually replace it as it melts out and advects away from the melting region (e.g., Anderson, 1995).

Finally, could the rise have been formed by meteorite impact, as Rogers (1982) suggested? This hypothesis readily accounts for the MORB-type isotopic ratios of the Shatsky Rise basalts, as removal of the lithosphere by the impacting object would cause massive melting of the underlying mantle, which normally should be MORB-type mantle (in contrast, the Ontong Java basalts all lack a MORB-like isotopic signature). However, this hypothesis requires the coincidence of a large impact (itself a rare event) within 800 km of a preexisting triple junction, and it fails to explain the 30° Pacific-Izanagi ridge reorientation at Anomaly M21 time and the lack of any evidence for the predicted massive destruction and disruption of seafloor over a very large area surrounding the impact site (Mahoney et al., 2005).

In summary, Shatsky Rise clearly formed in association with plate-velocity changes and ridge and triple junction reorganizations during a period when several plateaus appear likely to have formed near ridges in general and triple junctions in particular. Although the plume head hypothesis can explain many features of Shatsky Rise, it requires significant ad hoc coincidences or modifications. Alternatively, the rise may be explained by anomalous volcanism induced by changes in plate boundaries and lithospheric stress over a region of anomalously fusible mantle. Such a hypothesis requires no coincidence of triple junction location and site of plume impingement and can explain the

MORB-type signature of late-stage basalts from Shatsky Rise. However, it also relies on unusual circumstances. Indeed, no matter what the hypothesis, unusual circumstances of some sort appear to be required, as illustrated by the dichotomy of Pacific plateau formation in the Late Jurassic and Early Cretaceous versus the paucity of such features since. At present, data for and against each hypothesis are incomplete and largely circumstantial. As a result, the mystery of how Shatsky Rise formed is still an open question.

Site survey data and stratigraphic interpretation

Data acquisition

The primary data used for selection of sites are low-fold seismic reflection profiles collected during Cruise TN037 of the R/V *Thomas G. Thompson* in 1994. This data set was also used for Leg 198 and is described in some detail in the Leg 198 *Initial Reports* (Klaus and Sager, 2002), including plots of most ship tracks and seismic lines. Cruise TN037 also collected swath bathymetry, gravity, and magnetic data. Bathymetry and magnetic anomaly analyses are described in Sager et al. (1999) and Nakanishi et al. (1999), respectively.

Seismic data were collected with a six-channel Teledyne streamer with 25 m active sections. On any given seismic line, one of two alternate seismic sources was used: (1) a single generator-injector (GI) air gun (45/105 in^3) or (2) a four–air gun array (80, 108, 150, and 200 in^3). The GI air gun was mainly used for seismic lines shot between the main bathymetric edifices. It was towed at ~7 nmi/h and achieved twofold seismic data. The air gun array was used primarily on the mountain tops to penetrate the thicker sediment cover in those locations. The array was typically towed at ~5 nmi/h and it provided threefold data. Data were digitized at a 1 ms rate and recorded in Society of Exploration Geophysicists (file format "Y"), or SEG-Y, format. Final shot spacing was 25–37 m. The data were processed through to migration using *Sioseis* and *ProMax* software (see Klaus and Sager, 2002). Included in the processing train was band-pass filtering (30–150 Hz to 0.25 s two-way traveltime [TWT] below seafloor, 20–150 Hz from 0.25 to 1.0 s TWT, and 6–70 Hz below 1.0 s TWT), deconvolution, normal moveout correction, stacking, and finite difference migration.

Seismic stratigraphy

Interpretation of the seismic layering is relatively straightforward because of the drilling that has been done on Shatsky Rise. A review of the stratigraphy cored during Leg 198 as well as previous cruises is contained in the Leg 198 *Initial Reports* (Brawlower, Premoli-Silva, Malone, et al., 2002). In general the summits of the high edifices of Shatsky Rise contain thick sections (up to ~1.2 km thickness) of pelagic sediments. Over the flanks, this sedimentary section is often attenuated.

The sediment pile is mainly Cretaceous chalk and limestone covered by Cenozoic ooze. Sliter and Brown (1993) divided the section into five units, and this was found to be consistent with Leg 198 drilling results (Bralower, Premoli-Silva, Malone, et al., 2002). Lithologic Units I and II consist of foraminifer nannofossil ooze with minor clay. Unit I is Neogene in age (often Miocene–Holocene), whereas Unit II is of Paleogene age. Both have similar seismic character, with parallel-continuous layers, and are often separated by a seismic horizon of modest strength. Units III–V consist of Cretaceous chalk and occasional limestone layers with minor clay and abundant layers and nodules of chert and porcellanite. Indeed, the soft chalk layers interspersed with hard chert and porcellanite have frustrated efforts to recover cores from the top of Shatsky Rise since the beginning of scientific ocean drilling. The three Cretaceous units are often divided by two prominent seismic horizons, named R1 and R2 by Sliter and Brown (1993). In addition, the Leg 198 scientific party used R0 for the horizon nearest the top of the Cretaceous section. The uppermost and lowermost Cretaceous layers show depositional character that is most uniform; however, the middle unit is more sculpted and often shows evidence of erosion and onlap with instances of slumping. The uppermost Cretaceous layer (Unit III) is Turonian–Maastrichtian in age and lies between R1 and R0. The middle Cretaceous layer (Unit IV) is Aptian–Cenomanian in age and is bounded by R2 and R1. At the bottom of the pile is Unit V, which is Berriasian–Barremian in age and resides between igneous basement and R2 on seismic profiles. Although the sedimentary layers atop Shatsky Rise have the potential to provide important paleoceanography and other data, recovering extended sedimentary sections is not an objective of Expedition 324 (see **"Coring and drilling strategy"**).

The Cruise TN037 seismic data occasionally show some character in the portion of the record interpreted as igneous basement. Usually, seismic basement is a strong, irregular reflector below which few coherent reflections are seen. In some places on the Ori Massif, dipping reflectors were noted in acoustic basement. These are likely to be dipping lava flows. On the southwest flank of Tamu Massif igneous basement has a surprising appearance. All along the seismic line over that flank of Tamu Massif seismic basement has an odd, layered appearance for ~0.25 s TWT below the interpreted top of the igneous section. Drilling at Site 1213 during Leg 198 cored through 46 m of igneous rock, which was described as diabase sills (Shipboard Scientific Party, 2002). Because the character of the igneous basement is similar all the way down the southwest flank of Tamu Massif, these units may be sheet flows rather than true sills. At most proposed sites on Shatsky Rise, acoustic basement is strong, has no consistent internal reflectors, and is interpreted as the top of the lava pile. Nevertheless, the characteristics of igneous basement for each site is described in the site descriptions.

Scientific objectives

Primary objectives

1. *Determine the basement age to constrain the temporal evolution of the plateau.*

The timing and duration of volcanism at Shatsky Rise is one of the primary data types that can constrain the origin of the plateau. The drilling plan calls for sampling at three sites on Tamu Massif, which is the hypothesized product of plume head eruption. Along with the preexisting radiometric date from Site 1213, geochronologic data will show whether Tamu Massif erupted in a short period, as is currently hypothesized. A short time span would imply a plume head–like eruption, whereas a longer time span may indicate lower rates of effusion inconsistent with a plume head. If diachronous ages are found, the distribution will give constraints on the type of mechanisms that can explain the initial Shatsky Rise eruptions. In addition, dates from the other Shatsky Rise edifices, the Ori and Shirshov massifs, will show whether these edifices were constructed at or near the time of crustal formation and whether the northern part of Shatsky Rise shows an age progression. New geochronologic data will come from studies of igneous rock samples acquired at the proposed sites.

2. *Determine geochemical and isotopic compositions of igneous rocks cored from Shatsky Rise.*

Much of what we know about mantle source rocks and magma genesis are from interpretations of geochemistry and isotopic chemistry from rock samples. Although the signature of a lower-mantle source is still debated, in general it is expected that mantle plumes give rise to igneous rocks with ocean island basalt (OIB) composition and isotopic characteristics of the lower mantle. Furthermore, high ratios of $^3He/^4He$ are also taken by many as evidence for a lower-mantle source (e.g., Courtillot et al., 2003). Currently, such evidence is missing from the Shatsky Rise rock samples that have been studied, but this could result from a sampling bias because of the small number of samples that have been studied. If OIB chemistry or other mantle indicators are found in the rocks cored at the proposed new sites, the plume model will be supported or, conversely, if new drilling fails to produce evidence of lower-mantle involvement, the plate model will be strengthened. In addition, the patterns of geochemical variation across Shatsky Rise will also help establish the formation mechanism. Will new samples show geochemical variability consistent with evolution or zoning of the magma source, or will the geochemical characteristics be homogeneous, as is the case for Ontong Java Plateau? Will new drilling provide evidence for exotic, high-temperature igneous rocks, such as the high-Mg Kroenke-type basalts from Ontong Java Plateau (Fitton and Godard, 2004) that may indicate higher mantle temperatures associated with a plume source? These answers will come from geochemical and isotopic studies of the igneous rocks cored from the proposed sites.

3. *Determine the source temperature and degree of partial melt that produced Shatsky Rise lavas.*

Estimation of source temperatures and the degree of partial melting could be critical to distinguish between an upper- or lower-mantle source or to test abnormal mantle fertility models for Shatsky Rise lavas. In general, high degrees of partial melt would be expected for a plume head eruption that is associated with high mantle temperature. For example, partial melting of 30% is interpreted for Ontong Java Plateau eruptions from phase petrology and pattern of incompatible element abundances from igneous rock samples (Fitton et al., 2004). On the other hand, regions of abnormally high mantle fertility tapped by the triple junction could result in similar high melt extraction rates (e.g., Foulger and Anderson, 2005). Evidence for source temperatures above ambient mantle, however, may be an important indicator for the existence of thermal (deep) mantle plumes. Recently, Putirka (2008) proposed an improved method of olivine thermometry to estimate mantle source temperature. Herzberg et al. (2007) also proposed a method to estimate the mantle temperature by using major element composition and phase equilibria. These approaches might be particularly powerful if combined with other methods such as combined He and Os isotope studies (e.g., Brandon et al., 2007).

Secondary objectives

1. *Determine the physical volcanology of Shatsky Rise eruptions.*

Above all, Shatsky Rise is a monster volcanic construct. Although they share many characteristics with the thousands of seamounts scattered across the Pacific plate, the Shatsky Rise volcanic edifices exhibit some important differences. One of the more notable is the slope of the rise volcano flanks, which is much lower (~1°) than those of typical seamounts (~5°) (Sager et al., 1999). Another is the apparent mantling of the Tamu Massif southwest flank by sills or sheet flows, as interpreted from Site 1213 data and the seismic character of acoustic basement. Both observations may be indicative of high effusion rate eruptions. Thus the volcanic stratigraphy may provide important clues about the eruptions of Shatsky Rise igneous rocks. This stratigraphy will be developed from descriptions of igneous rock cores and comparison with logging data.

2. *Determine the magnetic polarity of Tamu Massif and paleolatitudes of Shatsky Rise.*

From a study of the magnetic anomaly of Tamu Massif, Sager and Han (1993) concluded that the edifice is largely of reversed magnetic polarity and was therefore erupted in a short period of time during a period of reversed magnetic polarity. Although inconclusive owing to the small number of independent samples of the magnetic field and the low paleolatitude, the paleomagnetism of igneous samples from Site 1213 is consistent with a reversed magnetic polarity. Paleomagnetic studies of proposed Tamu Massif sites will establish whether other sites are also of reversed polarity, which would support the hypothesis that this massif formed in a short period of time. In addition, the Jurassic and Early Cretaceous paleolatitude of the Pacific plate is uncertain, so paleomagnetic samples from Shatsky Rise have the potential to help establish the paleolatitude of the rise and the Pacific plate. Paleomagnetic studies will be done mostly from basalt samples cored on Shatsky Rise; however, if the coring recovers sufficient numbers of oriented samples from the sedimentary section, those samples can also be used to determine paleolatitude. In that regard, new results will be important for comparison from paleomagnetic results from Berriasian sediments cored at Site 1213 (Sager et al., 2005).

3. *Determine paleodepths of Shatsky Rise.*

Plume head models predict significant uplift associated with introduction of a large starting plume head beneath oceanic lithosphere (e.g., Olson and Nam, 1986). The associated constructional volcanism also creates a much thicker crust than normal. Indeed, there is evidence that the Kerguelen Plateau formed subaerial landmasses that later subsided below sea level as they moved away from the plume head source (Wallace, 2002). Seismic profiles of Shatsky Rise also imply that summits of Tamu Massif and Shirshov Massif were above sea level at eruption and subsided to the present depth, but the prediction has yet to be confirmed by drilling. Sampling the rise summits during Expedition 324 will establish whether they were originally shallow or subaerial or were emplaced in a deepwater environment. Paleodepths will be established from examination of microfossils and measurement of volatile abundances in basaltic glass (if preserved) (e.g., Roberge et al., 2005). If the summits of Shatsky Rise were shallow marine or above sea level, the classic plume head model is supported or, conversely, if the basement tops consist of deep submarine basalt, other models such as melting of a wet spot and/or melting of recycled crust have to be considered (Schilling et al., 1980; Korenaga, 2005).

4. *Determine magma evolution and magma chamber process of Shatsky Rise*

Geochemical studies of oceanic plateaus suggest that compositional variations in extrusive lavas are probably controlled by magma evolution processes (fractional crystallization, magma mixing, assimilation, and reaction with cumulates) in a large-scale magma chamber. Understanding magma evolution processes in large magma chambers will also help to understand the formation of the cumulative part of the lower oceanic crust. For example, a primary magma lost 20%–80% minerals by fractionation in shallow magma chambers to produce Ontong Java Plateau basalts (Fitton et al., 2004; Sano and Yamashita, 2004). Current geochemical data from Shatsky Rise also show that basement rocks experienced significant fractionation before their eruption. However, the magma chamber scale and evolution mechanism of oceanic plateau are not clear compared to well-studied MORBs (e.g., Sinton and Detrick, 1992). Systematic basement sampling on this expedition could provide information about magma evolution processes by using chemical variations of whole rocks. Examination of chemical zoning profiles of phenocryst phases (olivine, plagioclase, and clinopyroxene) and recording physiochemical properties (temperature, pressure, and magma compositions) during their growth can further contribute to reconstruct the history of magma evolution.

Coring and drilling strategy

General operations plan

The Expedition 324 operations plan (Table **T1**) is based on previous experience in coring LIPs, such as Kerguelen Plateau (Leg 183), Ontong Java Plateau (Leg 192), and the Emperor Seamounts (ODP Leg 197). Such operations are reasonably well understood, having been accomplished numerous times in the past, and relatively simple in that they do not require special equipment or advanced coring techniques.

At each of the drill sites, the *JOIDES Resolution* will drop a beacon and establish position over the site, lower the drill string to the seafloor, and proceed with drilling and coring until unable to continue or allotted time runs out. At all sites, only rotary core barrel (RCB) drilling is anticipated. By not coring with the advanced piston corer (APC)/extended core barrel (XCB) bottom-hole assembly (BHA), several days at each site are saved by not having to run the APC/XCB BHA to the bottom and core the upper sedimentary section. The consequence of coring only with the RCB is that soft sediments will be deformed by the coring process. This is deemed an acceptable loss because the sedimentary section has been cored on each of the Shatsky Rise massifs (and many times at Tamu Massif), coring sediments is not an objective of the expedition, and the drill sites have been chosen in places where the sediment section is thin. In addition, as another time-saving method, we are seeking Environmental Protection and Safety Panel approval not to core the sediment section until reaching a penetration depth of ~50 m above basement. The rationale is that the upper sedimentary section has been cored at other nearby locations, so there is not much to be learned by additional sediment coring.

Coring igneous rocks is often time consuming and wearing on the drill bit. In coring time calculations, an igneous rate of penetration (ROP) of 2–3 m/h has been assumed, based on similar results from Leg 192 (Ontong Java Plateau) (Mahoney, Fitton, Wallace, et al., 2001). Lesser or greater penetration at Shatsky Rise sites will depend on the average ROP at each site. In general, during igneous coring an RCB drill bit will last ~40–60 h (rotating time). At a rate of 3 m/h, for example, this implies a penetration of 120–180 m before the bit is too worn to continue. This will place a limit on the total igneous penetration at sites where only a single bit is planned. Changing the bit requires raising the entire drill string, changing the bit, sending the drill string back to the seafloor, and reentering the hole. This typically takes on the order of 1 day of operations time with a free-fall funnel (FFF). During Expedition 324, the use of FFFs is planned for multibit hole reentry at proposed Site SRSH-3B and possibly at proposed Site SRCH-5. Lesser penetration may actually occur owing to unfavorable hole conditions or unavoidable operations problems, such as not being able to find and reenter the FFF.

The general coring plan is to core at three sites on Tamu Massif, so age and geochemical trends across the putative plume head eruption can be examined, and one site each on the Ori and Shirshov massifs to study the age and geochemical evolution of the younger part of the plateau. Because Expedition 324 departs from Yokohama and must end in Townsville it is necessary to work from north to south, thus beginning at proposed Site SRNH-2 and ending at proposed Site SRSH-8. This is not necessarily the best approach (one could argue that Tamu Massif sites have higher priority), but because the cruise must end to the south, working from north to south saves ~1.5 days of transit time.

Proposed drill sites

Tamu Massif sites

The program envisions coring at three sites on Tamu Massif, the massive volcano that formed from initial Shatsky Rise eruptions. One site is located at the summit, whereas two are situated on the lower reaches, one on the southwest (oldest) flank, and one on the northeast (youngest) flank. Primary sites were chosen where sediments are thin and the reflector thought to represent igneous basement is clear. For each primary site, at least one nearby alternate site was chosen.

Primary sites

Site SRSH-8

Proposed Site SRSH-8 is located on the southwest flank of Tamu Massif at 4670 m water depth, ~50 km downslope from Site 1213 where igneous rocks were cored on Leg 198. Like Site 1213, the interpreted upper igneous section on the Cruise TN037 seismic profile has a curious layered signature that is seen all along the seismic profile traversing the southwest flank. This site was chosen at a location where erosion has partly stripped away the sediment cover, leaving only a thin layer of sediments overlying igneous basement. From the seismic profile a total sediment thickness of 155 m is anticipated, with 116 m of ooze overlying 39 m of probable chalk with chert. The purpose of drilling at this site is to recover igneous rocks from the southwestern flank of Tamu Massif, which is thought to be the oldest part of Shatsky Rise. At proposed Site SRSH-8, the plan is to core igneous rock with a single bit, ending with bit destruction or when allotted time is exhausted. This should achieve ~100 m penetration of igneous basement.

Site SRSH-3B

Proposed Site SRSH-3B is situated on the upper slope of the east side of the summit of Tamu Massif at 3477 m water depth. It is located on Cruise TN037 seismic Profile 14C at 1625 on 23 August 1994. The objective of proposed Site SRSH-3B is to core a long section of igneous rocks from the Tamu Massif summit for comparison of geochronology, geochemistry, and isotopes with other locations on Tamu Massif and elsewhere on Shatsky Rise. A deep hole is planned at this site, using two drill bits to achieve the planned penetration of ~300 m into the igneous basement (assuming each RCB bit penetrates ~150 m). A FFF will be emplaced at the top of the hole to allow reentry after bit changes.

Originally chosen as an alternate to proposed Site SRSH-3, which is located at the intersection of two seismic lines, proposed Site SRSH-3B was elevated to primary status for two reasons. First, sediments are thinner at proposed Site SRSH-3B. The total sediment thickness at this site is estimated to be 169 m, with 78 m of ooze and 91 m of chalk with chert, in contrast to the 311 m sediment thickness estimated for proposed Site SRSH-3. Second, at proposed Site SRSH-3B, the character of the upper igneous basement is different than at most other Tamu Massif sites. In most locations on the summit and south flank of Tamu Massif, the upper igneous basement appears layered, much like sediment, and this layered section has a thickness of ~0.25 s TWT. At Site 1213, igneous material with this signature was cored, recovering apparent sills. At proposed Site SRSH-3B, this layered basement is thin and more normal-appearing basement (lower frequency, less coherent reflectors) is closer to the surface. Assuming a seismic velocity of 4000 m/s, this surface layer is estimated to be 90 m thick. Since deep penetration is planned at this site, it should be possible to penetrate through the upper basement layer into the lower layer.

Site SRSH-6

This site is located on the north flank of Tamu Massif at 3285 m water depth. Appearing on Cruise TN037 seismic line 13 at 0225 on 22 August 1994, the site is situated on a basement high where the thick pelagic sediment cover atop the high plateau is thinned, allowing drilling of igneous basement with minimal cover. The purpose of drilling at this site is to recover igneous rocks from the northern extent of Tamu Massif for comparison with the summit and southwest flank sites. Proposed Site SRSH-6 has been chosen where the overlying sediments are ~177 m thick, with ~58 m of ooze atop ~119 m of cherty chalk and limestone. Coring of basement will be done with a single bit, giving an estimated igneous section penetration of ~100 m.

Alternate sites

Site SRSH-2A

Proposed Site SRSH-2A is an alternate for primary proposed Site SRSH-8. It is located in deep water (4743 m) at the foot of the Tamu Massif southwest flank, just to the east of the M21 magnetic lineation. The objective for this site is to sample igneous rocks from the oldest part of Shatsky Rise. The proposed site is located on Cruise TN037 seismic Profile 17D at 0115 on 29 August 1994. At this location, the drape of pelagic sediments covering the Tamu Massif flank becomes thinner as it goes over a basement high, located to the southwest of the proposed site. Based on the seismic layers, there is a covering of 297 m of sediment of which the upper ~41 m is predicted to be ooze and the rest is likely to be cherty chalk. Basement will be cored to refusal, bit destruction, or allotted time running out. This is estimated to provide ~100 m penetration of the igneous section.

Site SRSH-2B

Proposed Site SRSH-2B is located in deep water (4783 m) on the lower southwest flank of Tamu Massif and is an alternate for primary proposed site SRSH-8. It is situated on Cruise TN037 seismic Line 17C at 2301 on 28 August 1994. Unlike the other southwest Tamu Massif flank sites, this site has a thick sediment cover, estimated at ~511 m. The overall objective is the same as at proposed Site SRSH-8 and other nearby prospective sites: to sample ~100 m of basalt from the southwest flank for geochemical, isotopic, and geochronologic study. However, the sediment column at proposed Site SRSH-2B contains an unusual feature. At ~0.075 s TWT above the igneous basement, the sediments show a thin, strong reflector. This reflector is limited in areal extent and appears to connect to a zone of chaotic reflections that appear to be side-swipe from a buried volcanic cone. The strong, mid-sediment reflector is interpreted as a lava flow from this cone that must have occurred long after shield-building volcanism stopped forming the south flank. Thus, a second objective for this site is to study this post-shield volcanism. Drilling with a single bit is planned at this site, which should give ~100 m penetration of the igneous basement.

Site SRSH-3

Proposed Site SRSH-3 is an alternate for proposed primary Site SRSH-3B. This site is situated on the east side of the summit of Tamu Massif at 2987 m water depth. The objective of this hole is to core a long section of igneous rocks from the Tamu Massif summit. The proposed site is located on Cruise TN037 seismic Profile 14B at 1207 on 23 August 1994. At this site, sediments are predicted to be 311 m thick with ~50 m of ooze overlying ~261 m of cherty/shaley chalk and limestone. Coring at this site is planned for two bits and two round trips of the drill string with reentry into a FFF; however, depending on penetration, we might need three bits to reach target depth. If each bit gives ~150 m of penetration into the igneous section, the total igneous section drilled will be ~300 m.

Site SRSH-5

Proposed Site SRSH-5 is located near the summit of Tamu Massif in a channel on the west side of a summit ridge. The water depth is 3499 m. The site was chosen at the axis of a channel, at 2246 on 25 August 1994 on Cruise TN037 seismic Line 15C. The objective at this site is to core igneous rocks from the summit of Tamu Massif but at a location on the other side of the summit from proposed Site SRSH-3. Seismic data indicate a vanishing cover of ooze and ~210 m of Cretaceous cherty chalks and limestone. The total igneous penetration is planned for one bit, which should give ~100 m of igneous section. This site was moved to alternate status because of time constraints and because another hole is planned for the Tamu Massif summit.

Site SRSH-7

Proposed Site SRSH-7 is an alternate for proposed primary Site SRSH-6, which is located ~35 km upslope on the northeast flank of Tamu Massif. It is located on Cruise TN037 seismic Line 13 at 2350 on 21 August 1994. This site was chosen because it is a spot on the seismic line where acoustic basement is clear and appears to show the normal flank slope and the sediments are thin. In contrast, basement at proposed Site SRSH-6 is a high of undetermined origin, so proposed Site SRSH-7 would allow drilling of apparently normal flank slopes. The coring objectives and drilling plan at this site are the same as for proposed Site SRSH-6.

Ori Massif

Primary site

Site SRCH-5

Proposed Site SRCH-5 was chosen as primary over other Ori Massif sites because it is located atop a volcanic ridge at the summit of the volcanic edifice where sediments are thin. Proposed Site SRCH-3 was originally proposed as the primary site and it was chosen because it has a basement high at the intersection of two seismic lines. However, it displays poorly defined basement structure on seismic lines, perhaps caused by rough basement topography. In contrast, proposed Site SRCH-5 shows a strong, coherent acoustic basement reflector that apparently represents the almost-flat top of a summit ridge. Furthermore, pelagic sediments on the flat ridge top have apparently been sculpted by currents, giving rise to a tapering sediment cover that allows us to choose a location with as much covering sediment as desired.

Proposed Site SRSH-5 is located on Cruise TN037 seismic Line 8 at 0005 on 15 August 1994 where sediments have a thickness of 184 m with 54 m of ooze and 130 m of chalks and chert. The objective of coring at this site is to recover igneous rocks from Ori Massif, specifically at the summit of this large volcanic structure, for the purpose of geochronologic, geochemical, and isotopic studies. Proposed Site SRSH-5 is one of two sites where drilling deeper than ~100 m is the plan (the other is proposed Site SRSH-3B). To achieve this extra depth, two RCB bits might be needed, which should allow ~200 m penetration into igneous material. In this case, a FFF will be used to facilitate reentry of the hole after the bit change.

Alternate sites

Site SRCH-3

Proposed Site SRCH-3 is an alternate site for proposed Site SRCH-5 that is located at the summit of the Ori Massif at 3243 m water depth. Proposed Site SRCH-3 was chosen at a location where two seismic lines intersect over a basement volcanic high. The site is located on Cruise TN037 seismic Line 11 at 1741 and seismic Line 9 at 0801Z. The seismic line indicates ~133 m of sedimentary cover with the upper ~25 m consisting of ooze and the remainder of cherty chalk and limestone. The scientific goals and operational plan for proposed Site SRCH-3 are the same as for proposed Site SRCH-5.

Site SRCH-4

Proposed Site SRCH-4 is also an alternate site for proposed Site SRCH-5. It was chosen to provide a site located on the lower flank of Ori Massif. Proposed Site SRCH-4 is situated on the lower east flank of Ori Massif at 4079 m water depth. It is found on cruise Cruise TN037 seismic Line 8 at 1537 on 14 August 1994. At this location, the seismic profile shows a sediment cover that thins downslope. The scientific goals and operational plan for this site are the same as for proposed Site SRCH-5.

Shirshov Massif

Primary site

Site SRNH-2

Proposed Site SRNH-2 is located on Cruise TN037 seismic Line 5A at 2130 on 09 August 1994 at 3654 m water depth. Originally this site was proposed as an alternate to proposed Site SRNH-1, which is located near the intersection of two seismic lines. It was elevated to primary status because the sediment is thinner than at proposed Site SRNH-1 and the acoustic basement is simpler. At proposed Site SRNH-2, the acoustic basement is relatively flat near the edge of the summit platform of Shirshov Massif, whereas there is a basement high of uncertain origin near the location chosen for proposed Site SRNH-1. The seismic profile indicates that at proposed Site SRNH-2, the sediment cover is 194 m thick with the uppermost ~54 m being Cenozoic ooze and the remainder being cherty chalk and limestone. As at other Expedition 324 sites, the objective for proposed Site SRNH-2 is to core igneous rock for geochronologic, geochemical, and isotopic studies in comparison to other Shatsky Rise sites. Drilling with a single bit is planned at this site, which should give ~100 m penetration of the igneous basement.

Alternate sites

Site SRNH-1

Proposed Site SRNH-1 is located on the summit of Shirshov Massif at 3339 m water depth. The site location has been chosen where currents have eroded the uppermost sedimentary layers and therefore the sedimentary cover is thinner than elsewhere. The site is situated on Cruise TN037 seismic Line 5C at 0030 on 11 August 1994. The sedimentary cover appears to be 285 m thick, with the upper ~83 m being ooze and the remainder being cherty chalk and limestone. The scientific objectives and drilling plan are the same as at proposed Site SRNH-2.

SRNH-2A

Proposed Site SRNH-2A is an alternate for proposed primary Site SRNH-2, situated where sediment thins on the north rim of the Shirshov Massif summit. This site is found on Cruise TN037 seismic Line 5A at 2144 on 09 August 1994. It is situated ~2 km south of proposed Site SRNH-2 at a location where the basement is better defined than at the primary site. Because the sediment dome on top of Shirshov Massif thickens toward the center of the edifice, sediments at this site are significantly thicker than at the primary site. The estimated sediment thickness for proposed Site SRNH-2A is 328 m, with 41 m of Cenozoic–Late Cretaceous ooze overlying 287 m of Cretaceous chalk, limestone, and chert. Because of the better basement definition at this site, it could be moved to primary status if the expedition is allowed to drill through the uppermost sediments without coring. The objectives for proposed Site SRNH-2A are the same as those for the primary site: to core igneous rock for geochronologic, geochemical, and isotopic studies in comparison to other Shatsky Rise sites. Drilling with a single bit is planned at this site, which should give ~100 m penetration of the igneous basement.

Prospects for recovery of different lithologies

Table **T1** and the attached site summaries summarize the expected penetration at each of the Shatsky Rise sites. In general, the objective of Expedition 324 is to core igneous rock, so sediment coring is secondary. Many of the expedition drill sites were chosen at locations where sediment cover is thick enough to provide stability for the BHA when it contacts the igneous rock interface. In such locations the sedimentary section is often condensed and large parts of the sedimentary history found elsewhere are missing. Among the primary sites, the greatest sediment penetration is predicted at proposed Site SRNH-2 (194 m) and the least at proposed Site SRSH-8 (155 m). The sediment column has been divided into two parts that are generally recognizable in seismic sections: an upper, Cenozoic ooze section and a lower, Cretaceous section that likely consists of chalk with stringers and nodules of chert and porcellanite. The estimation of the thickness of the Cretaceous chalk is difficult because it is highly dependent on the exact, but unknown, percentage of high-velocity chert and porcellanite within the otherwise much lower seismic velocity chalk.

Actual recovery is likely to be greatly different from the predicted penetration thicknesses. In the sedimentary section, recovery of the ooze section should be high, perhaps close to 100%. However, because all Expedition 324 coring will be done with

RCB bits, unconsolidated sediments will be highly deformed. Furthermore, because this upper ooze section has been cored in many places and is likely to be deformed by coring, we propose to drill through most of the sediments without coring in order to save time for coring deeper in the section. In the Cretaceous chalks, recovery is typically very low because of the interbedded chert and porcellanite. Whereas the RCB bit grinds these hard sedimentary rocks, the much softer chalk is usually washed away and the resulting recovery is very low (see Brawlower, Premoli Silva, Malone, et al., 2002).

Recovery in the igneous section is also likely to be much less than the penetrated length. Typical average recovery rates in submarine lava flows is 35%–50%. This number represents an average and recovery can be much higher or lower. Cores from submarine igneous sections provide a biased sample of the true igneous section (Tominaga et al., 2009). Usually it is the interiors of massive flows that are preferentially recovered, whereas fractured rocks are usually poorly recovered. Indeed, this bias is one of the reasons that downhole logging data are important for the scientific party's understanding of the true lithologic succession.

Logging/downhole measurements

The main objectives of the downhole measurement program are to document crustal physical properties, define structural and lithologic boundaries as a function of depth, and reconstruct the volcanic stratigraphy of Shatsky Rise, which could be used for assessing the evolution of this plateau and testing the hypotheses of a plume head versus plate-controlled origin of volcanism. In addition, wireline logging data can be compared to results of laboratory analyses of discrete samples and should help delineate alteration patterns, fracture densities, and structural orientations and determine how these correlate with current and paleostress environments. These measurements will complement core measurements by determining the thickness of lithologic units in intervals where core recovery is poor.

Wireline logging

A series of wireline tool string deployments are planned for all sites drilled during this expedition. These tool strings will provide measurements including natural gamma ray, density, magnetic susceptibility, sonic velocities, microresistivity, and borehole images. The operational time estimates for all deployments are given in Table **T1.** Detailed descriptions of all wireline tools and applications are provided at **iodp.ldeo.columbia.edu/TOOLS_LABS/index.html.**

The first tool string deployment in each hole will consist of at least total and spectral gamma ray (HNGS), density, photoelectric effect factor, caliper, and potentially, magnetic susceptibility measurements. These measurements will be used for characterization of stratigraphic sequences, assessment of alteration, and reconstruction of the volcanic stratigraphy. Depending on borehole conditions, subsequent deployments could consist of a Formation MicroScanner (FMS), Dipole Sonic Imager (DSI), HNGS, and if tools are commercially available, an ultrasonic borehole imager (UBI). The FMS and UBI will provide high-resolution borehole images of lithostratigraphic sequences and boundaries, oriented fracture patterns, and structural features that could be related to current and paleostress environments. These images can also be used for reconstruction of the volcanic stratigraphy and reorientation of core pieces. The DSI measurements will include a full set of compressional and shear wave forms and cross-dipole shear wave velocities measured at different azimuths. These types of measurements can be used to determine preferred mineral and/or fracture orientations, fracture densities, and paleostress directions. The velocity and density downhole measurements can also be used for constructing synthetic seismograms and tying the core-log measurements to regional seismic lines.

Risk and contingency strategy

General contingency plan

Three principal factors could affect the implementation of the drilling plan:

1. Adverse hole conditions (e.g., an unstable section of the borehole wall that collapses into the hole or broken pieces of hardware lodged in the hole),
2. Weather conditions that limit the ability to continue coring (e.g., high seas) or to stay on station (e.g., approaching typhoon), and
3. Time delays (e.g., arising from equipment breakdowns, inclement weather, and measures taken to respond to hole conditions).

Hole conditions

In general, unusually adverse hole conditions are not expected during Shatsky Rise drilling. Prior drilling has shown that chert layers may cause drilling difficulties, but sites have also been chosen to minimize sediment cover where possible. Hole conditions in the igneous section depend on the type and consolidation of the igneous rocks. It is common to encounter fractured, friable zones while drilling lava flow sections, usually between flows. Occasionally rock pieces from the borehole wall cave into the hole after being knocked loose by the drill string. Loose rocks above the drill bit can cause the drill string to bind and may require clearing the hole. On rare occasions, such debris causes so much difficulty that the hole must be abandoned. Depending on time estimates and the importance of the site for archiving the overall objectives of this expedition, a new "B" hole could be drilled. To save valuable time, coring of the new "B" hole would not start before reaching the maximum penetration depth of the abandoned "A" hole.

Weather

Another potential issue that may shorten operations time is weather. Expedition 324 will take place in September and October, which are months in the middle of western Pacific typhoon season. Although many typhoons track to the south of Shatsky Rise on their way westward, they may turn around east of Japan and head to the east, thus threatening northern Shatsky Rise, even though it is at a northerly latitude. A drillship with thousands of meters of drill pipe hanging from the derrick is highly vulnerable to being overtaken and damaged by a cyclone, so the captain will be conservative and stay well away from projected storm paths. ODP Leg 191, which occurred in the same months (September–October 2000) lost 4.3 days while waiting out a typhoon. Leg 32 lost 2.1 days in similar fashion, and operations at Site 810 during Leg 132 were terminated early because of an approaching storm. The implication is that Expedition 324 could lose several operation days because of nearby typhoons. If a hole must be abandoned because of an approaching typhoon, we might deploy a FFF if return to the site and reentry is deemed worthwhile.

Timing

If significant time is consumed by responding to poor hole conditions, slow penetration rate, or weather-related delays, a decision would have to be made to drop a primary site from the schedule. We consider proposed Sites SRSH-3B and SRSH-8 (and their respective alternates) located on the summit and southern flank of Tamu Massif (and supposed to reflect the early stages of Shatsky Rise volcanism/possible plume head arrival) as our highest priority sites. Proposed Sites SRNH-2 and SRCH-5 on the northern and central massifs reflect the later stages of Shatsky Rise activity and are therefore of intermediate priority. Proposed Site SRSH-6 at the northern flank of Tamu Massif has the least priority.

Sampling and data-sharing policy

Shipboard samples and data acquisition

Following core labeling, nondestructive whole-core measurements, and core splitting, samples will be selected from the working halves of cores by members of the shipboard party for routine measurement of physical and magnetic properties and bulk chemical and mineralogical analyses by, as needed, inductively coupled plasma–atomic emission spectrometry and X-ray diffraction spectrometry. Thin sections of samples will be prepared for identification of minerals, determination of mineral modes (by point counting), and studies of texture and fabric. Detailed visual core description will be conducted on the archive halves.

Personal sampling for shore-based research

Shipboard and shore-based researchers should refer to the IODP Sample, Data, and Obligations Policy (**www.iodp.org/program-policies**). This document outlines the policy for distributing IODP samples and data. It also defines the obligations incurred by sample and data recipients. All requests for data and core samples must be approved by the Sample Allocation Committee (SAC). The SAC is composed of Co-Chief Scientists, Staff Scientist, and IODP Curator on shore and curatorial representative in place of the Curator on board ship.

Scientists must submit their research plans using the Sample/Data Request form (**smcs.iodp.org:8080/smcs**) no later than 3 months before the expedition. This planning process is necessary to coordinate the research to be conducted and to ensure that the scientific objectives are achieved. Based on the sample requests (shore based and shipboard), the SAC and Shipboard Scientific Party will formulate a tentative expedition-specific sampling and data-sharing plan for shipboard and postexpedition activities. This plan will be subject to modification depending upon the actual material recovered and collaborations that may evolve between scientists during the expedition. Modifications to the sampling plan during the expedition require the approval of the SAC.

All personal sample frequencies and sizes must be justified scientifically and will depend on core recovery, the full spectrum of other sample requests, and the cruise objectives. Generally, the size of individual samples will be <15–25 cm^3 and will be taken from the working halves of the core. Some redundancy of measurements is unavoidable, but minimizing the duplication of measurements among the shipboard party and identified shore-based collaborators will be a factor in evaluating sample requests. All shipboard scientists and approved shore-based requesters will be expected to collaborate and cooperate within the framework of this plan.

Personal sampling will take place on board during the expedition. If critical intervals are recovered (e.g., small sills or dikes, veins, ores, erosion horizons, beach pebbles, fresh glasses, or ash layers), there may be considerable demand for samples from a limited amount of cored material. These intervals may require modifications to the sampling plan (e.g., special handling, reduced sample size, or deferring of sampling to postcruise).

Following Expedition 324, cores will be delivered to the IODP Gulf Coast Core Repository at Texas A&M University, College Station (USA). All collected data and samples will be protected by a 1 y postcruise moratorium, during which time data and samples are available only to the Shatsky Rise expedition science party and approved shore-based participants.

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Table T1. Operations plan. (**Continued on next page.**)

Site No.	Location (Latitude Longitude)	Sea Floor Depth (mbsf)	Operations Description	Transit (days)	Drilling Coring (days)	Log (days)
Yokohama, Japan						
			Transit 1115 nmi to Site SRNH-2 @ 10.5 kt	4.4		
SRNH-2	38° 04.400'N	3654	Locate site, measure tubulars, and trip drill string to mudline		0.4	
	162° 38.710'E		Drill to 144 mbsf		0.2	
			RCB from 144 mbsf to 194 mbsf in sediment		0.5	
			Wiper trip and flush hole with mud			
			RCB from 194 mbsf to 294 mbsf (100 m into bsmt)		2.0	
			Wiper trip and displace hole with mud			
			Release bit w/MBR and set end of pipe at 80 mbsf		0.5	
			Log hole with triple combo and FMS-sonic			0.8
			Recover drill string and secure drilling equipment		0.4	
			Sub-Total Days On-Site: 4.8			
			Transit 232 nmi from Site SRNH-2 to SRCH-5 @ 10.5 kt	0.9		
SRCH-5	36° 06.944'N	3148	Locate site and trip drill string to mudline		0.4	
	158° 27.526'E		Drill to 134 mbsf		0.2	
			RCB from 134 mbsf to 184 mbsf in sediment		0.4	
			Wiper trip and flush hole with mud			
			RCB from 184 mbsf to 384 mbsf (200 m into basement)		4.0	
			Wiper trip and displace hole with mud			
			Release bit w/MBR and set end of pipe at 80 mbsf		0.6	
			Log hole with triple combo and FMS-sonic			0.7
			Recover drill string and secure drilling equipment		0.4	
			Sub-Total Days On-Site: 6.7			
			Transit 112 nmi from SRCH-5 to SRSH-6 @ 10.5 kt	0.4		
SRSH-6	34° 25.320'N	3285	Locate site and trip drill string to mudline		0.4	
	159° 22.932'E		Drill to 127 mbsf		0.2	
			RCB from 127 mbsf to 177 mbsf in sediment		0.4	
			Wiper trip and flush hole with mud			
			RCB from 177 mbsf to 277 mbsf (100 m into basement)		2.1	
			Wiper trip and displace hole with mud			
			Release bit w/MBR and set end of pipe at 80 mbsf		0.4	
			Log hole with triple combo and FMS-sonic			0.7
			Recover drill string and secure drilling equipment		0.3	
			Sub-Total Days On-Site: 4.5			
			Transit 115 nmi from SRSH-6 to SRSH-3B @ 10.5 kt	0.5		
SRSH-3B	32° 30.474'N	3477	Locate site and trip drill string to mudline		0.4	
	159° 14.082'E		Drill to 119 mbsf into sediment		0.2	
			RCB from 119 mbsf to 169 mbsf into sediment		0.4	
			Wiper trip and flush hole with mud			
			RCB from 169 mbsf to 308 mbsf (139 m into basement)		2.7	
			Wiper trip and flush hole with mud			
			Rig up/deploy Free Fall Funnel (FFF), inspect FFF w/VIT			
			Round trip drill for bit change and reenter FFF		1.2	
			RCB from 308 mbsf to 469 mbsf (161 m into basement)		3.7	
			Wiper trip and flush hole with mud			

Table T1 (continued).

			Displace hole with logging mud, drop bit with MBR			
			Set end of pipe at 80 mbsf		0.6	
			Log hole with triple combo, FMS-sonic, and UBI			1.3
			Recover drill string and secure drilling equipment		0.4	
			Sub-Total Days On-Site: 10.9			
			Transit 145 nmi from SRSH-3B to SRSH-8 @ 10.5 kt	0.6		
SRSH-8	31° 05.752'N	4670	Locate site and trip drill string to mudline		0.4	
	156° 55.981'E		Drill to 105 mbsf in sediment		0.2	
			RCB from 105 mbsf to 155 mbsf in sediment		0.5	
			Wiper trip and flush hole with mud			
			RCB from 155 mbsf to 255 mbsf (100 m into basement)		2.1	
			Wiper trip and displace hole with mud			
			Release bit w/MBR and set end of pipe at 80 mbsf		0.5	
			Log hole with triple combo and FMS-sonic			0.9
			Recover drill string and secure drilling equipment for transit		0.5	
			Sub-Total Days On-Site: 5.1			
			Transit 3129 nmi toTownsville, Australia @ 10.5 kt	12.4		
Townsville, Australia				**19.2**	**27.6**	**4.4**
			Subtotal On-Site Time:	**32.0**		
			Contingency:	**4.8**		
			Total Operating Days:	**56.0**		
			Total Expedition Including Port Call Days= 5	**61.0**		

Figure F1. Location of Shatsky Rise, Hess Rise, and selected magnetic anomaly lineations in the northwest Pacific Ocean. Bathymetric highs of the two rises are highlighted in blue (modified from Sager et al., 1999).

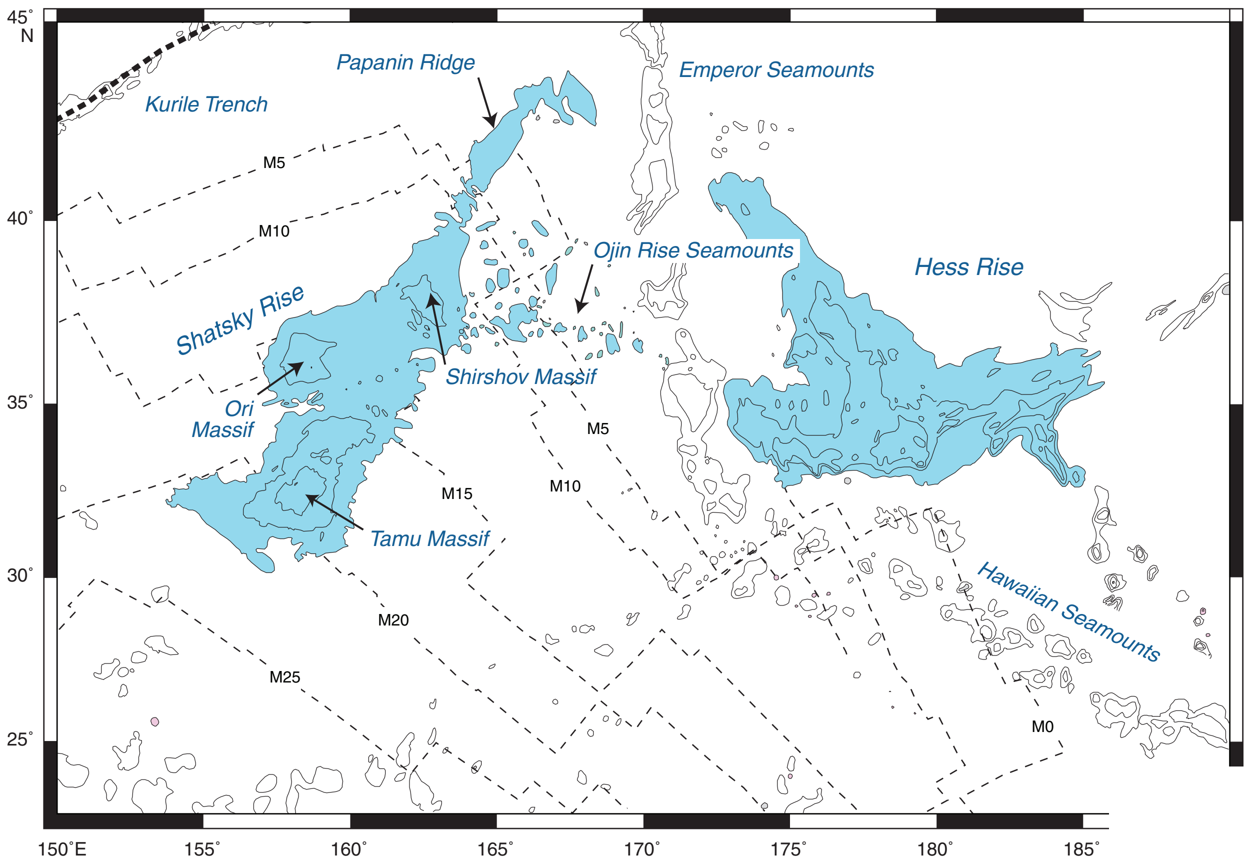


Figure F2. Location chart showing major features (blue shading), the Cruise TN037 site survey seismic tracks (purple lines), DSDP and ODP drill sites (open and solid circles), and proposed Expedition 324 primary drill sites (red circles). Light blue = elevations shallower than 5 km on Shatsky Rise. Black solid circle = Site 1213, where igneous rocks were cored during ODP Leg 198. Inset illustrates the location of Shatsky Rise (gray) in relation to western Pacific magnetic lineations (thin lines), trenches (toothed line), and Japan (black).

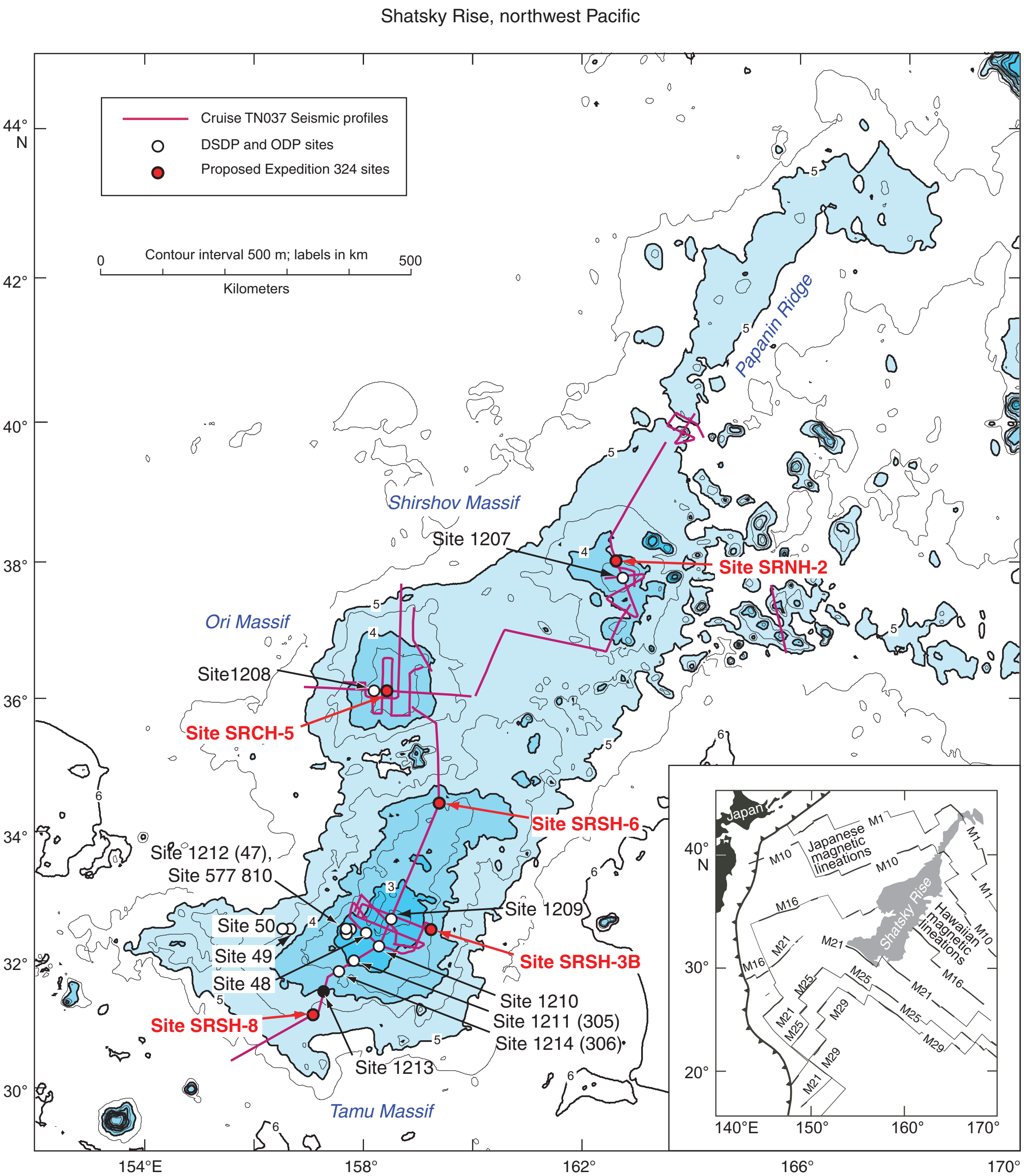


Figure F3. Magnetic lineations within and around Shatsky Rise. Heavy straight lines = magnetic lineations and fracture zones. Bathymetric contours shown at 500 m intervals. Gray shading = depths <5 km. Open circles = DSDP and ODP sites mentioned in the text, open square = dredge location mentioned in the text. Modified from Nakanishi et al. (1999).

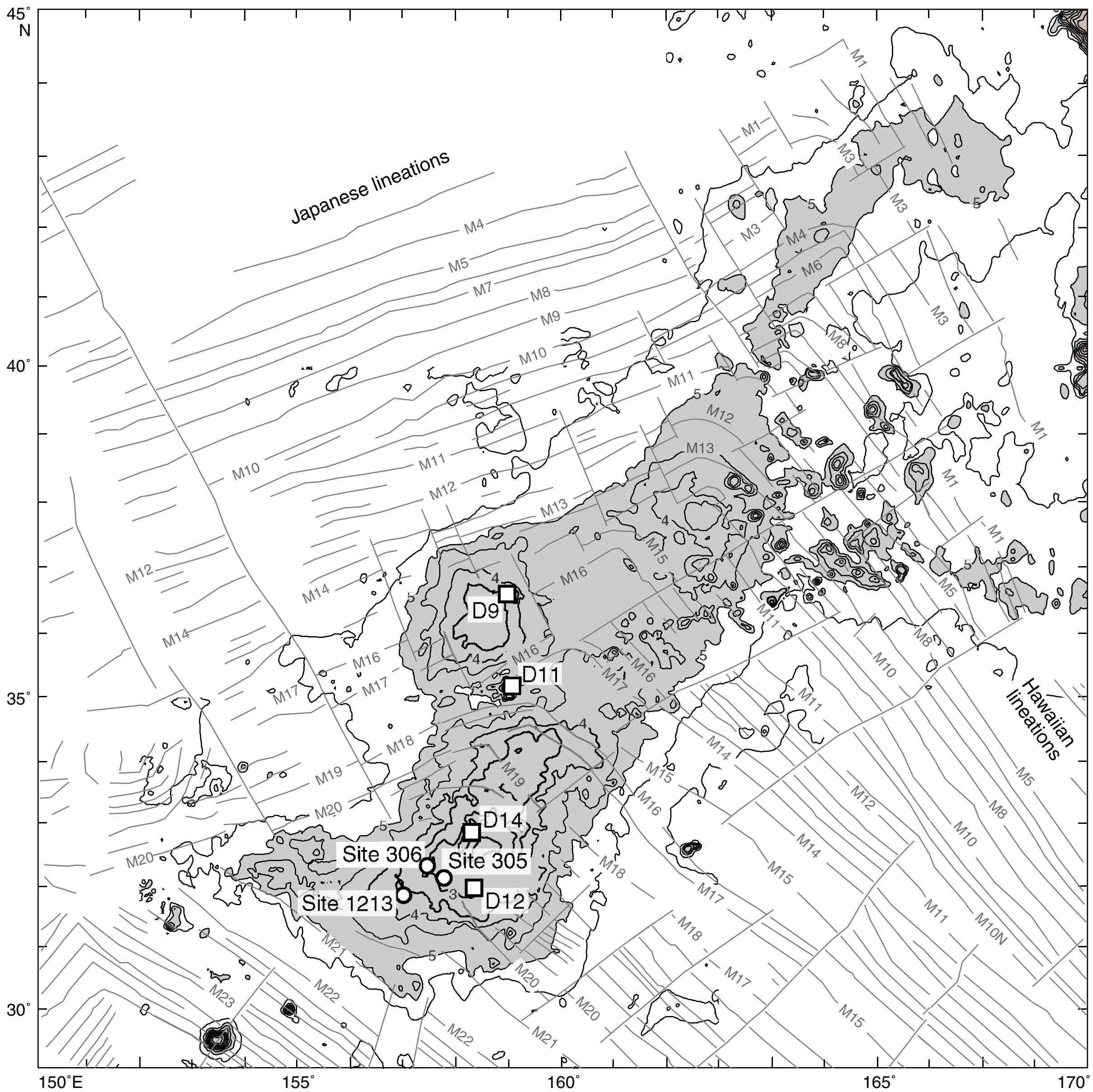


Figure F4. Tectonic history of Shatsky Rise, illustrating the migration of ridges and triple junction (TJ) during formation of the rise. Dark magnetic lineations existed on the Pacific plate at the time given for each panel. Red lines = ridges, light purple lines = future isochrons, blue arrows = path of triple junction, yellow arrows = jumps and changes in direction (modified from Nakanishi et al., 1999).

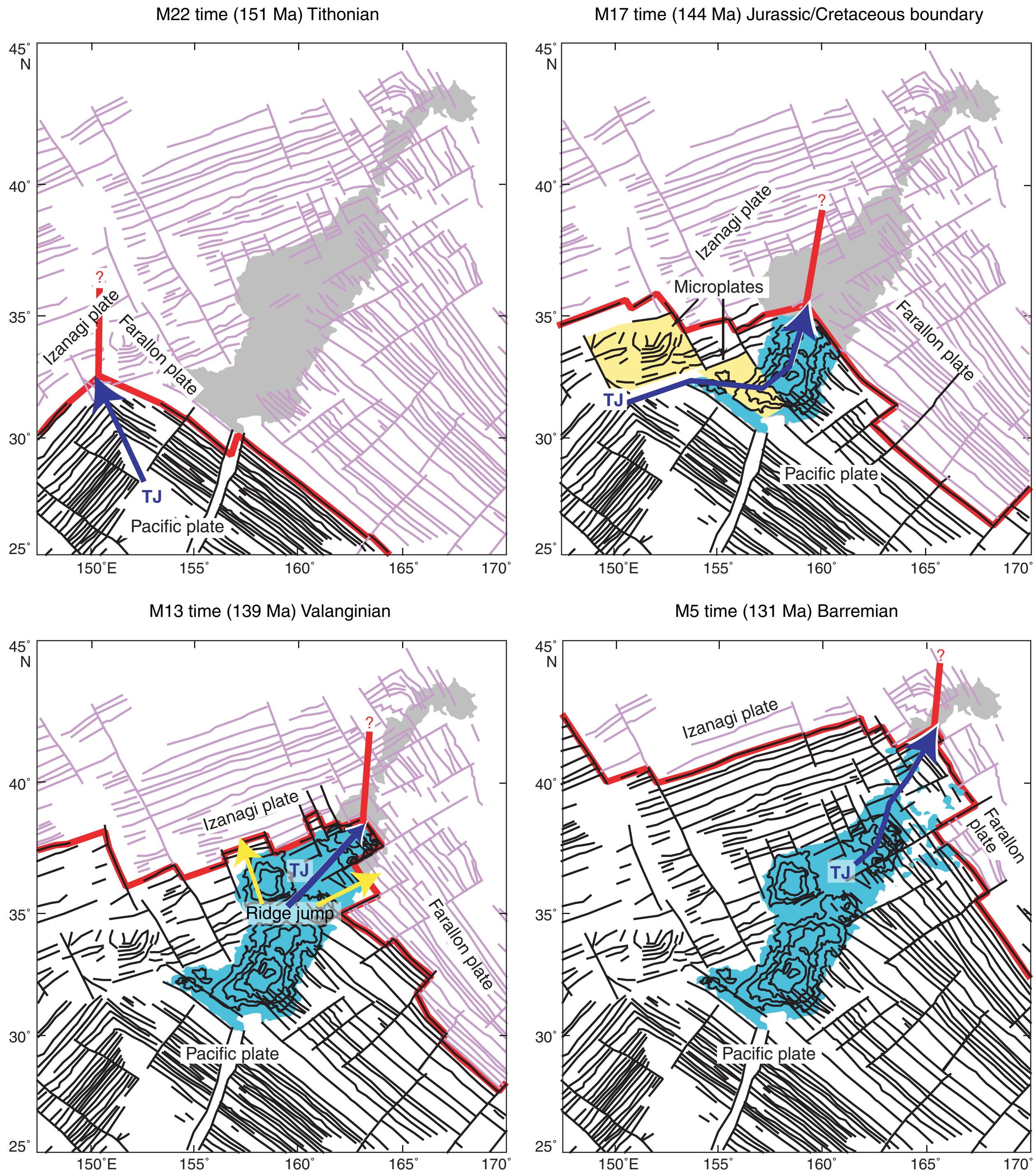


Figure F5. Age-corrected isotope data. Fields for Pacific mid-ocean-ridge basalt (MORB) and the Easter-Nazca Ridge hotspot chain are adjusted for radiogenic ingrowth to the estimated 144 Ma positions of the mantle sources (see Tejada et al., 2004). Pb isotope data for Holes 1213B and 1179D (and Easter-Nazca Ridge) were acquired using a double spike. Fields are from Mahoney and Spencer (1991), Tejada et al. (2004), Ray et al. (2004), and references therein (after Mahoney et al., 2005). SOTW = Southtow Expedition.

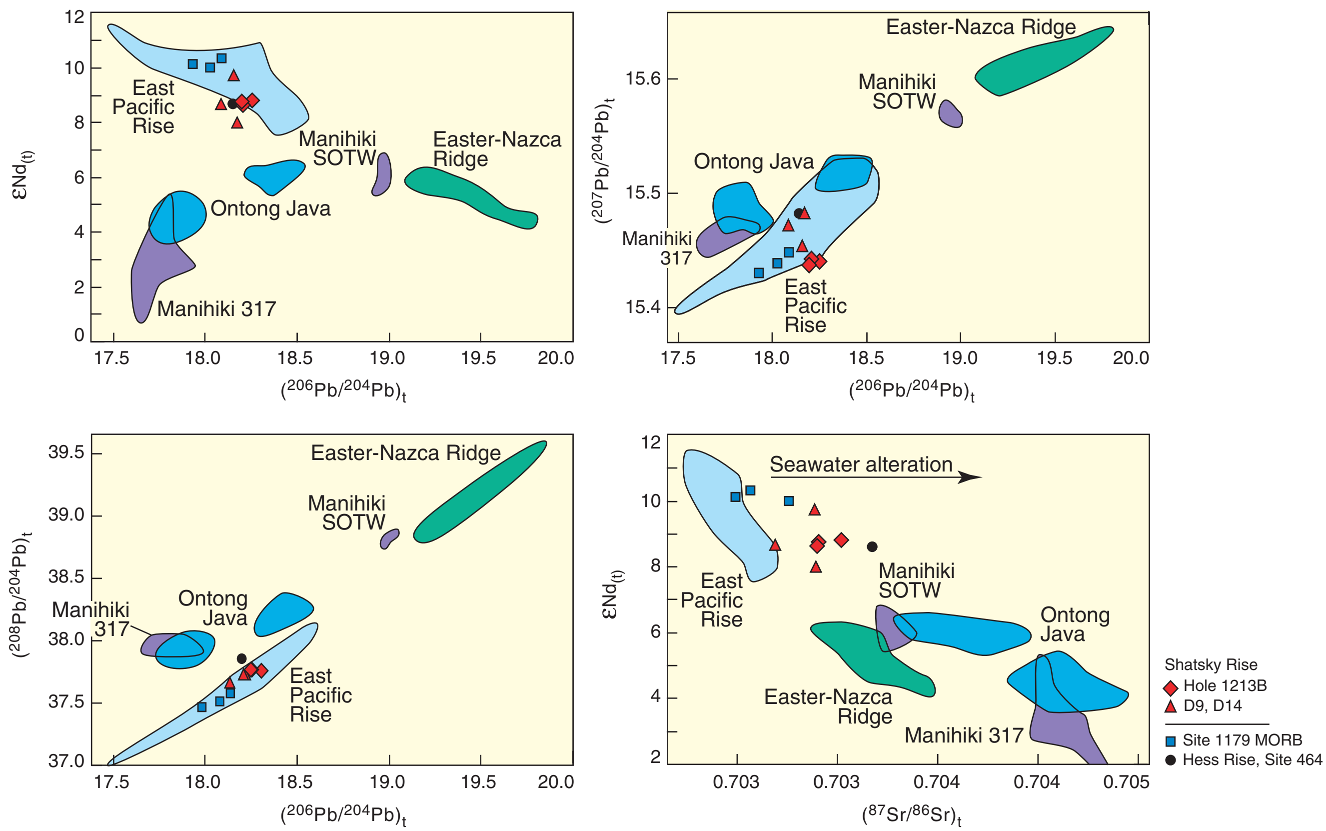
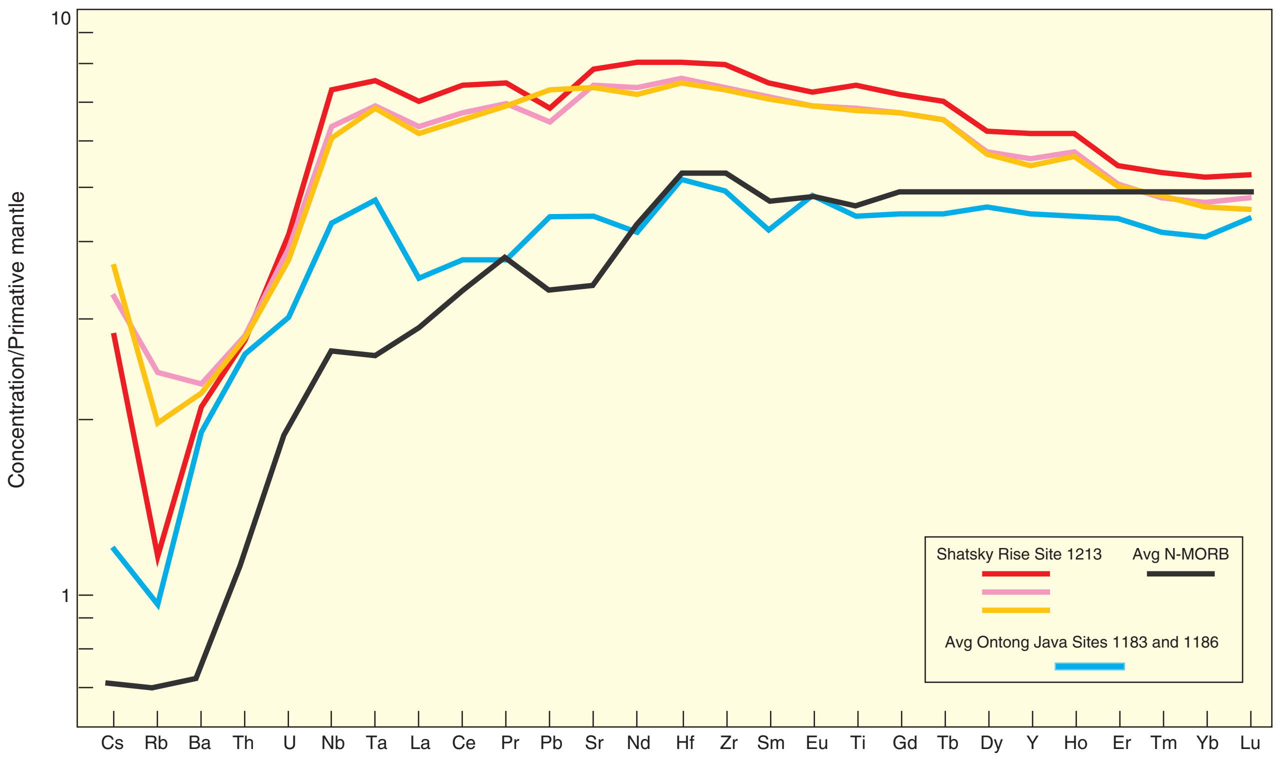


Figure F6. Incompatible trace element patterns. Ontong Java pattern is from Fitton and Godard (2004); average normal mid-ocean-ridge basalt (N-MORB) pattern and normalizing values are from Sun and McDonough (1989) (after Mahoney et al., 2005).



Site summaries

Proposed Site SRCH-3

Priority:	Alternate site
Position:	36°00.516′N, 158°20.970′E
Water depth (m):	3243
Target drilling depth (mbsf):	333 (133 m sediment, 200 m basement)
Requested maximum penetration (mbsf):	~433 (300 m basement)
Survey coverage:	Cruise TN037, R/V *Thomas Thompson* (Klaus and Sager, 2002) • Seismic Line 11 (time: 1741Z, 19 Aug 1994) (Fig. **AF1**) • Seismic Line 9 (time: 0801Z, 16 Aug 1994). (Fig. **AF2**) • Track map (Fig. **AF3, AF4**)
Objective: (see text for details)	• Core igneous basement from Central High summit for petrographic, geochemical, isotopic, radiometric dating, and paleolatitude investigation. • Determine the origin and emplacement history of Shatsky Rise basement rocks.
Drilling, coring, and downhole measurement program:	Hole A • RCB wash to ~50 m above basement, coring to TD (possible need for second bit and FFF deployment?) • Wireline log (triple combo, FMS-Sonic)
Anticipated lithology:	• 0–25 mbsf: pelagic ooze • 25–88 mbsf: chalk with chert • 88–133 mbsf: shaley chalk • >133 mbsf: basalt

Site summaries (continued)

Proposed Site SRCH-4

Priority:	Alternate site
Position:	36°04.492′N, 159°17.065′E
Water depth (m):	4079
Target drilling depth (mbsf):	377 (177 m sediment, 200 m basement)
Requested maximum penetration (mbsf):	~477 (300 m basement)
Survey coverage:	Cruise TN037, R/V *Thomas Thompson* • Seismic Line 8 (time: 1537Z, 14 Aug 1994) (Fig. **AF5**) • Track map (Fig. **AF3**)
Objective: (see text for details)	• Core igneous basement from the lower flank of Central High for petrographic, geochemical, isotopic, radiometric dating, and paleolatitude investigation. • Determine the origin and emplacement history of Shatsky Rise basement rocks.
Drilling, coring, and downhole measurement program:	Hole A • RCB wash to ~50 m above basement, coring to TD (possible need for second bit and FFF deployment?) • Wireline log (triple combo, FMS-Sonic)
Anticipated lithology:	• 0–21 mbsf: pelagic ooze • 21–177 mbsf: chalk with chert • >177 mbsf: basalt

Site summaries (continued)

Proposed Site SRCH-5

Priority:	Primary site
Position:	36°06.944′N, 158°27.526′E
Water depth (m):	3148
Target drilling depth (mbsf):	384 (184 m sediment, 200 m basement)
Requested maximum penetration (mbsf):	~484 (300 m basement)
Survey coverage:	Cruise TN037, R/V *Thomas Thompson* • Seismic Line 8 (time: 0005Z, 15 Aug 1994) (Fig. **AF6**) • Track map (Figs. **AF3, AF4**)
Objective: (see text for details)	• Core igneous basement from Central High summit for petrographic, geochemical, isotopic, radiometric dating, and paleolatitude investigation. • Determine the origin and emplacement history of Shatsky Rise basement rocks.
Drilling, coring, and downhole measurement program:	Hole A • RCB wash to ~50 m above basement, core to TD (possibly two bits needed and FFF deployment?) • Wireline log (triple combo, FMS-Sonic)
Anticipated lithology:	• 0-54 mbsf: pelagic ooze • 54–184 mbsf: chalk with chert • >184 mbsf: basalt

Site summaries (continued)

Proposed Site SRNH-1

Priority:	Alternate site
Position:	37°49.266′N, 162°59.220′E
Water depth (m):	3339
Target drilling depth (mbsf):	385 (285 m sediment, 100 m basement)
Requested maximum penetration (mbsf):	~585 (300 m basement)
Survey coverage:	Cruise TN037, R/V *Thomas Thompson* • Seismic Line 5C (time: 0030Z, 11 Aug 1994) (Fig. **AF7**) • Seismic Line 6 (time: 2320Z 11 Aug 1994) (Fig. **AF8**) • Track map (Figs. **AF9, AF10**)
Objective: (see text for details)	• Core igneous basement from Northern High for petrographic, geochemical, isotopic, radiometric dating, and paleolatitude investigation. • Determine the origin and emplacement history of late Shatsky Rise basement rocks.
Drilling, coring, and downhole measurement program:	Hole A • RCB wash to ~50 m above basement, core to TD or bit failure • Wireline log (triple combo, FMS-Sonic)
Anticipated lithology:	• 0–83 mbsf: pelagic ooze • 83–196 mbsf: chalk with chert • 196–285 mbsf: shaley chalk • >285 mbsf: basalt

Site summaries (continued)

Proposed Site SRNH-2

Priority:	Primary site
Position:	38°04.400′N, 162°38.710′E
Water depth (m):	3654
Target drilling depth (mbsf):	294 (194 m sediment, 100 m basement)
Requested maximum penetration (mbsf):	~494 (300 m basement)
Survey coverage:	Cruise TN037, R/V *Thomas Thompson* • Seismic Line 5A (time: 2130, 09 Aug 1994) (Fig. **AF11**) • Track map (Fig. **AF9**)
Objective: (see text for details)	• Core igneous basement from Northern High for petrographic, geochemical, isotopic, radiometric dating, and paleolatitude investigation. • Determine the origin and emplacement history of late Shatsky Rise basement rocks.
Drilling, coring, and downhole measurement program:	Hole A • RCB wash to ~50 m above basement, core to TD or bit failure. • Wireline log (triple combo, FMS-Sonic)
Anticipated lithology:	• 0–54 mbsf: pelagic ooze • 54–194 mbsf: chalk and chert • >194 mbsf: basalt

Site summaries (continued)

Proposed Site SRNH-2A

Priority:	Alternate site
Position:	37°59.333′N, 162°39.275′E
Water depth (m):	3586
Target drilling depth (mbsf):	428 (328 m sediment, 100 m basement)
Requested maximum penetration (mbsf):	~628 (300 m basement)
Survey coverage:	Cruise TN037, R/V *Thomas Thompson* • Seismic Line 5A (time: 2144, 09 Aug 1994) (Fig. **AF11**) • Track map (Fig. **AF9**)
Objective: (see text for details)	• Core igneous basement from Northern High for petrographic, geochemical, isotopic, radiometric dating, and paleolatitude investigation. • Determine the origin and emplacement history of late Shatsky Rise basement rocks.
Drilling, coring, and downhole measurement program:	Hole A • RCB wash to ~50 m above basement, core to TD or bit failure • Wireline log (triple combo, FMS-Sonic)
Anticipated lithology:	• 0–41 mbsf: pelagic ooze • 41–104 mbsf: chalk and chert • 104–328 mbsf: shaley chalk, limestone, and chert • >328 mbsf: basalt

Site summaries (continued)

Proposed Site SRSH-2A

Priority:	Alternate site
Position:	30°49.176′N, 156°21.883′E
Water depth (m):	4743
Target drilling depth (mbsf):	397 (297 m sediment, 100 m basement)
Requested maximum penetration (mbsf):	~600 (300 m basement)
Survey coverage:	Cruise TN037, R/V *Thomas Thompson* • Seismic Line 17D (time: 0115Z, 29 Aug 1994) (Fig. **AF12**) • Track map (Figs. **AF13, AF14**)
Objective: (see text for details)	• Core igneous basement rocks from the deep flank of Southern High for petrographic, geochemical, isotopic, radiometric dating, and paleolatitude investigation. • Determine the origin and emplacement history of early Shatsky Rise basement rocks.
Drilling, coring, and downhole measurement program:	Hole A • RCB wash to ~50 m above basement, core to TD or bit failure • Wireline log (triple combo, FMS-Sonic)
Anticipated lithology:	• 0–41 mbsf: pelagic ooze • 41–200 mbsf: chert/chalk • 200–297 mbsf: shaley chalk, limestone, and chert • >297 mbsf: basalt

Site summaries (continued)

Proposed Site SRSH-2B

Priority:	Alternate site
Position:	30°54.357′N, 156°32.473′E
Water depth (m):	4783
Target drilling depth (mbsf):	611 (511 m sediment, 100 m basement)
Requested maximum penetration (mbsf):	~811 (300 m basement)
Survey coverage:	Cruise TN037, R/V *Thomas Thompson* • Seismic Line 17C (time: 2301Z, 28 Aug 1994) (Fig. **AF15**) • Track map (Figs. **AF13, AF14**)
Objective: (see text for details)	• Core possible late stage sills and igneous basement rocks from the deep flank of Southern High for petrographic, geochemical, isotopic, radiometric dating, and paleolatitude investigation. • Determine the origin and emplacement history of early Shatsky Rise basement rocks.
Drilling, coring, and downhole measurement program:	Hole A • RCB wash to ~50 m above sediment reflectors (sill or postshield lava flow?), core to TD or bit failure • Wireline log (triple combo, FMS-Sonic)
Anticipated lithology:	• 0–74 mbsf: pelagic ooze • 74–511 mbsf: chert/chalk/limestone and possible sill? • >511 mbsf: basalt

Site summaries (continued)

Proposed Site SRSH-3

Priority:	Alternate site
Position:	32°18.570′N, 158°59.880′E
Water depth (m):	2987
Target drilling depth (mbsf):	611 (311 m sediment, 300 m basement)
Requested maximum penetration (mbsf):	~611 (300 m basement)
Survey coverage:	Cruise TN037, R/V *Thomas Thompson* • Seismic Line 14B (time: 1207Z, 23 Aug 1994) (Fig. **AF16**) • Seismic Line 14D (time: 2107Z, 24 Aug 1994) (Fig. **AF17**) • Track map (Figs. **AF13, AF18**)
Objective: (see text for details)	• Deep core igneous basement from summit area of Southern High for petrographic, geochemical, isotopic, radiometric dating, and paleolatitude investigation. • Determine the origin and emplacement history of Shatsky Rise basement rocks.
Drilling, coring, and downhole measurement program:	Hole A • RCB wash to ~50 m above basement, core to TD (two bits needed and FFF deployment) • Wireline log (triple combo, FMS-Sonic, and UBI)
Anticipated lithology:	• 0–50 mbsf: pelagic ooze • 50–200 mbsf: chalk with chert • 200–311 mbsf: shaley chalk and limestone • >311 mbsf: basalt

Site summaries (continued)

Proposed Site SRSH-3B

Priority:	Primary site
Position:	32°30.474′N, 159°14.082′E
Water depth (m):	3477
Target drilling depth (mbsf):	469 (169 m sediment, 300 m basement)
Requested maximum penetration (mbsf):	~469 (300 m basement)
Survey coverage:	Cruise TN037, R/V *Thomas Thompson* • Seismic Line 14C (time: 1625Z, 23 Aug 1994) (Fig. **AF19**) • Track map (Fig. **AF13**)
Objective: (see text for details)	• Deep core igneous basement from summit area of Southern High for petrographic, geochemical, isotopic, radiometric dating, and paleolatitude investigation. • Determine the origin and emplacement history of Shatsky Rise basement rocks.
Drilling, coring, and downhole measurement program:	Hole A • RCB wash to ~50 m above basement, core to TD (two bits needed and FFF deployment) • Wireline log (triple combo, FMS-Sonic, and UBI)
Anticipated lithology:	• 0–78 mbsf: pelagic ooze • 78–169 mbsf: chalk with chert • >169 mbsf: basalt

Site summaries (continued)

Proposed Site SRSH-5

Priority:	Alternate site
Position:	32°50.982′N, 157°52.920′E
Water depth (m):	3499
Target drilling depth (mbsf):	310 (210 m sediment, 100 m basement)
Requested maximum penetration (mbsf):	~510 (300 m basement)
Survey coverage:	Cruise TN037, R/V *Thomas Thompson* • Seismic Line 15 (time: 2246Z, 25 Aug 1994) (Fig. **AF20**) • Seismic Line 16 (time: 1114Z, 27 Aug 1994) (Fig. **AF21**) • Track map (Fig. **AF13, AF22**)
Objective: (see text for details)	• Core igneous basement near the summit of the Southern High for petrographic, geochemical, isotopic, radiometric dating, and paleolatitude investigation. • Determine the origin and emplacement history of Shatsky Rise basement rocks.
Drilling, coring, and downhole measurement program:	Hole A • RCB wash to ~50 m above basement, core to TD or bit failure • Wireline log (triple combo, FMS-Sonic)
Anticipated lithology:	• 0–210 mbsf: cherty chalks and limestone • >210 mbsf: basalt

Site summaries (continued)

Proposed Site SRSH-6

Priority:	Primary site
Position:	34°25.320′N, 159°22.932′E
Water depth (m):	3285
Target drilling depth (mbsf):	277 (177 m sediment, 100 m basement)
Requested maximum penetration (mbsf):	~477 (300 m basement)
Survey coverage:	Cruise TN037, R/V *Thomas Thompson* • Seismic Line 13 (time: 0225Z, 22 Aug 1994) (Figs. **AF23, AF24**) • Track map (Fig. **AF25, AF26**)
Objective: (see text for details)	• Core igneous basement from the late stage of Southern High for petrographic, geochemical, isotopic, radiometric dating, and paleolatitude investigation. • Determine the origin and emplacement history of Shatsky Rise basement rocks.
Drilling, coring, and downhole measurement program:	Hole A • RCB wash to ~50 m above basement, core to TD or bit failure • Wireline log (triple combo, FMS-Sonic)
Anticipated lithology:	• 0–58 mbsf: pelagic ooze • 58–177 mbsf: chalk with chert and limestone • >177 mbsf: basalt

Site summaries (continued)

Proposed Site SRSH-7

Priority:	Alternate site
Position:	34°44.269′N, 159°22.620′E
Water depth (m):	4196
Target drilling depth (mbsf):	330 (230 m sediment, 100 m basement)
Requested maximum penetration (mbsf):	~530 (300 m basement)
Survey coverage:	Cruise TN037, R/V *Thomas Thompson* • Seismic Line 13 (time: 2350Z, 21 Aug 1994) (Fig. **AF27**) • Track map (Figs. **AF25**)
Objective: (see text for details)	• Core igneous basement from the late stage of Southern High for petrographic, geochemical, isotopic, radiometric dating, and paleolatitude investigation. • Determine the origin and emplacement history of Shatsky Rise basement rocks.
Drilling, coring, and downhole measurement program:	Hole A • RCB wash to ~50 m above basement, core to TD or bit failure • Wireline log (triple combo, FMS-Sonic)
Anticipated lithology:	• 0–41 mbsf: pelagic ooze • 41–230 mbsf: chalk with chert and limestone • >230 mbsf: basalt

Site summaries (continued)

Proposed Site SRSH-8

Priority:	Primary site
Position:	31°05.752′N, 156°55.981′E
Water depth (m):	4670
Target drilling depth (mbsf):	255 (155 m sediment, 100 m basement)
Requested maximum penetration (mbsf):	~455 (300 m basement)
Survey coverage:	Cruise TN037, R/V *Thomas Thompson* • Seismic Line 17C (time: 1814Z, 28 Aug 1994) (Fig. **AF28**) • Track map (Fig. **AF13**)
Objective: (see text for details)	• Core igneous basement from the oldest part of Shatsky Rise (southwest flank of Southern High) for petrographic, geochemical, isotopic, radiometric dating, and paleolatitude investigation. • Determine the origin and emplacement history of Shatsky Rise basement rocks.
Drilling, coring, and downhole measurement program:	Hole A • RCB wash to ~50 m above basement, core to TD or bit failure • Wireline log (triple combo, FMS-Sonic)
Anticipated lithology:	• 0–116 mbsf: pelagic ooze • 116–155 mbsf: chalk with chert • >155 mbsf: basalt

Figure AF1. Seismic Line 11C at proposed Site SRCH-3.

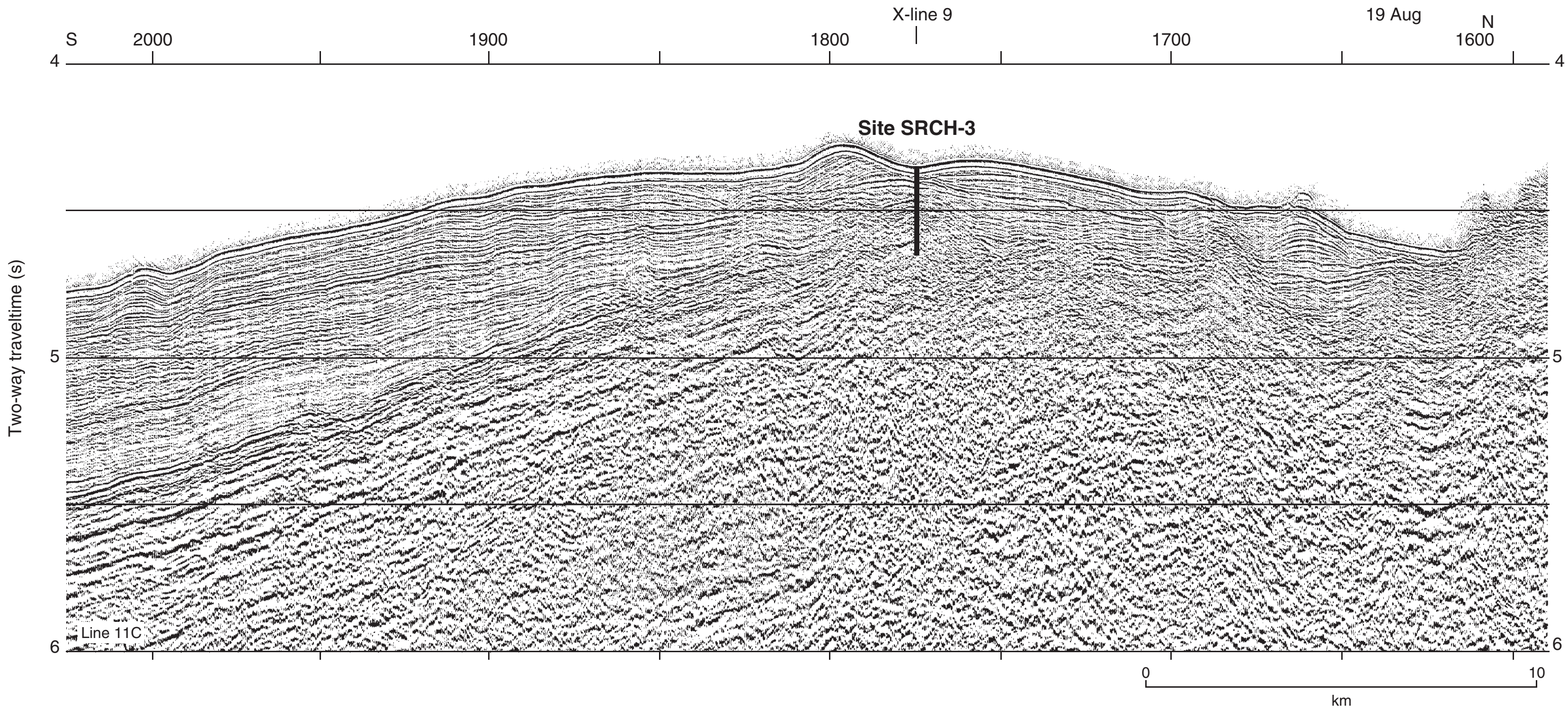


Figure AF2. Seismic Line 9 at proposed Site SRCH-3.

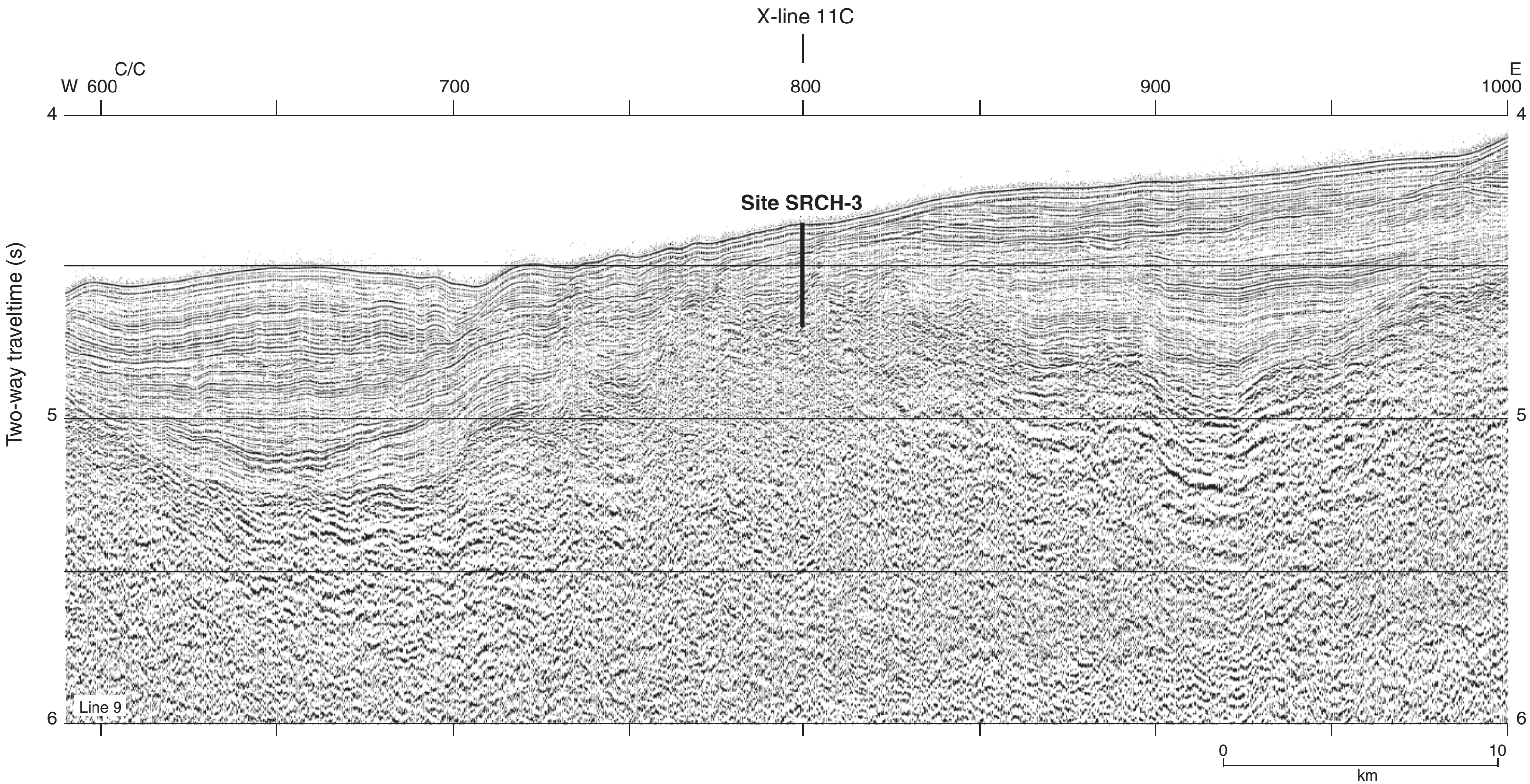


Figure AF3. Track map for proposed Sites SRCH-3, SRCH-4, and SRCH-5. White box shown in Figure **AF4.**

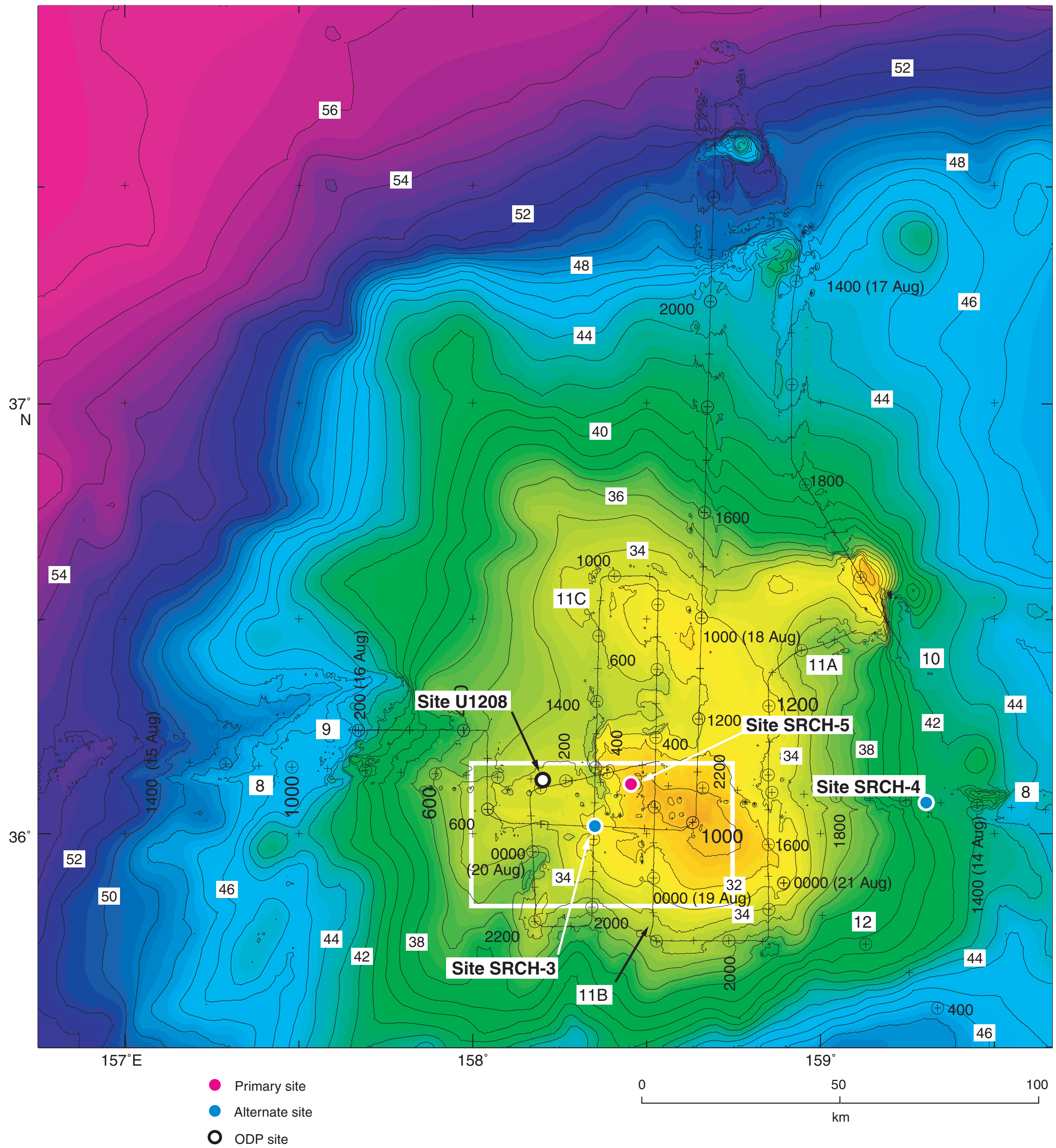


Figure AF4. Close-up track map for proposed Sites SRCH-3 and SRCH-5.

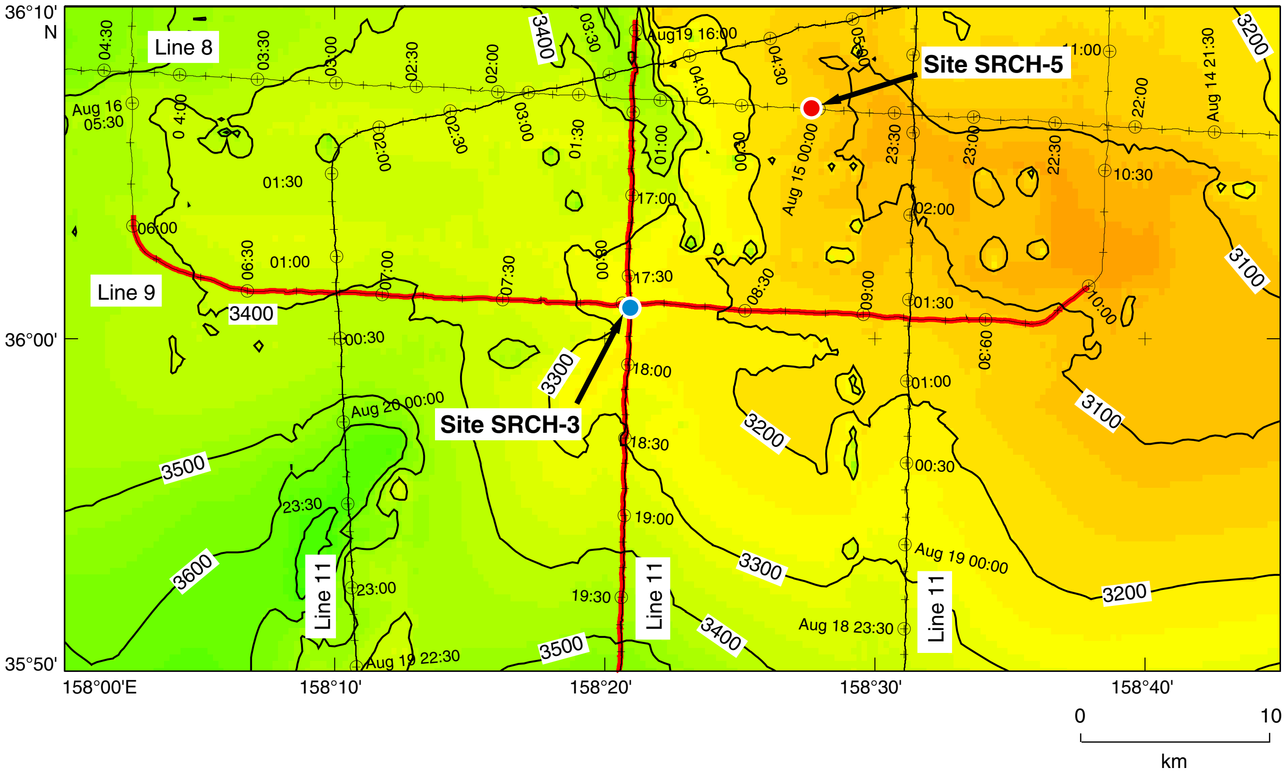


Figure AF5. Seismic Line 8 at proposed Site SRCH-4.

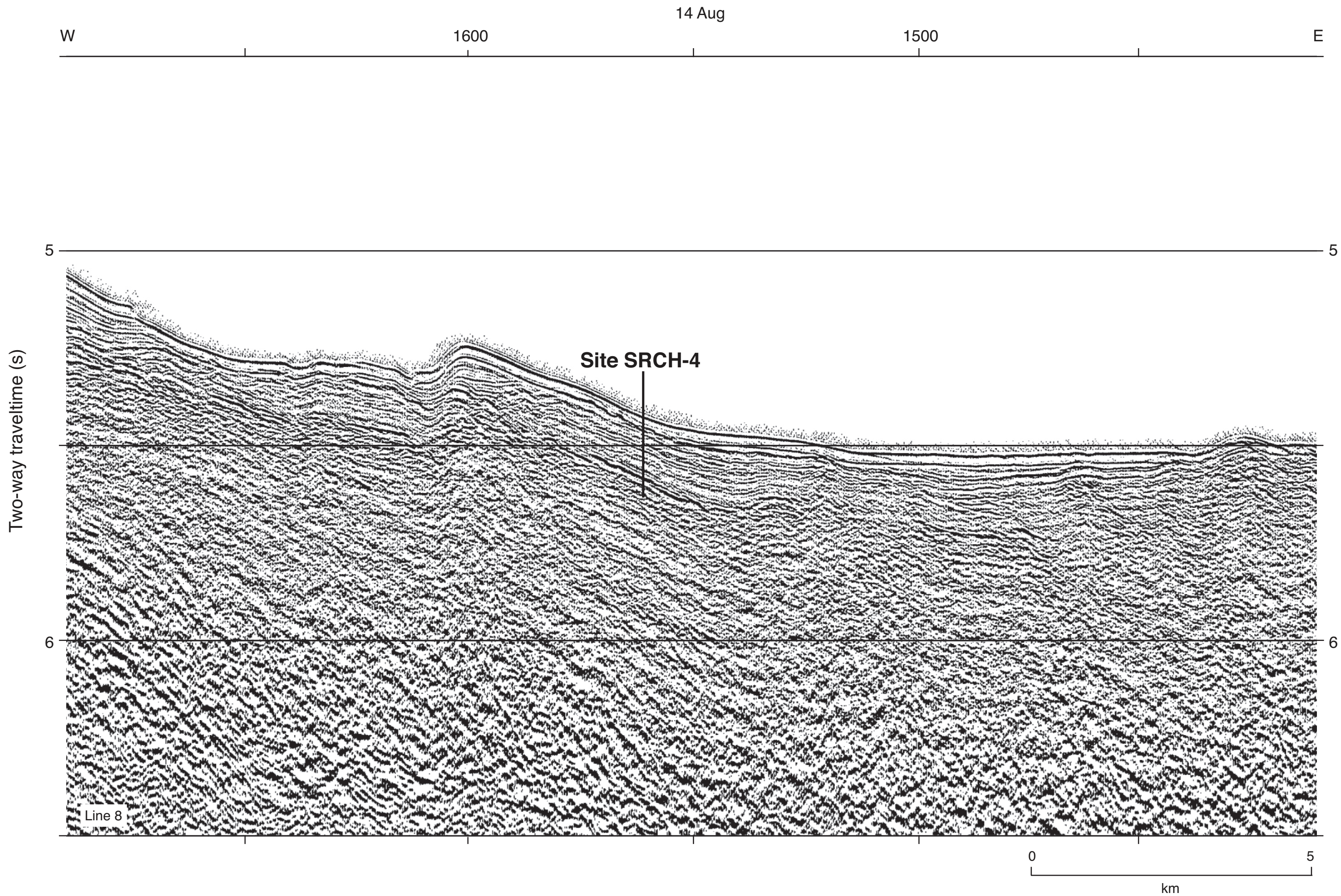


Figure AF6. Seismic Line 8 at proposed Site SRCH-5.

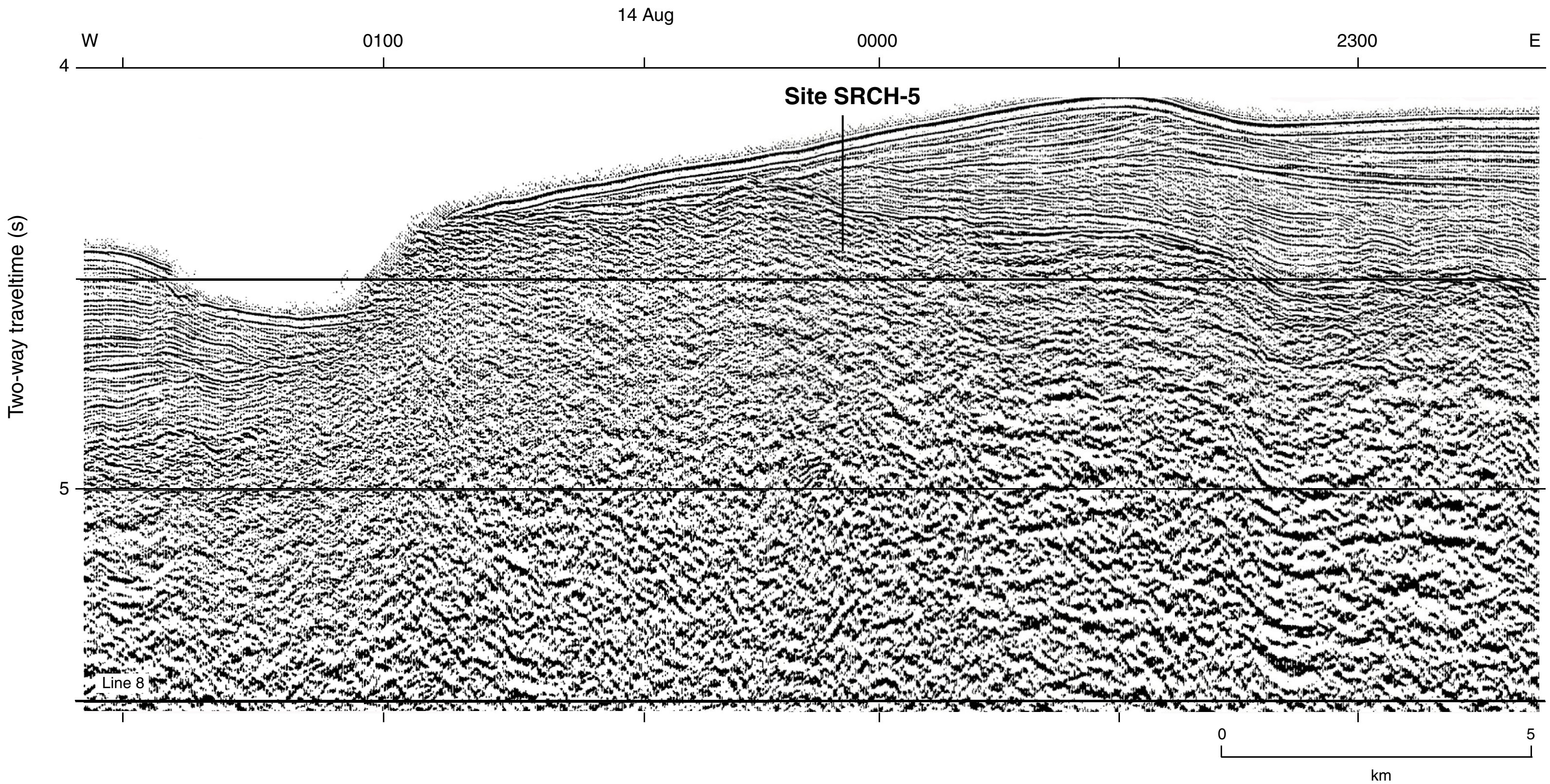


Figure AF7. Seismic Line 5c at proposed Site SRNH-1.

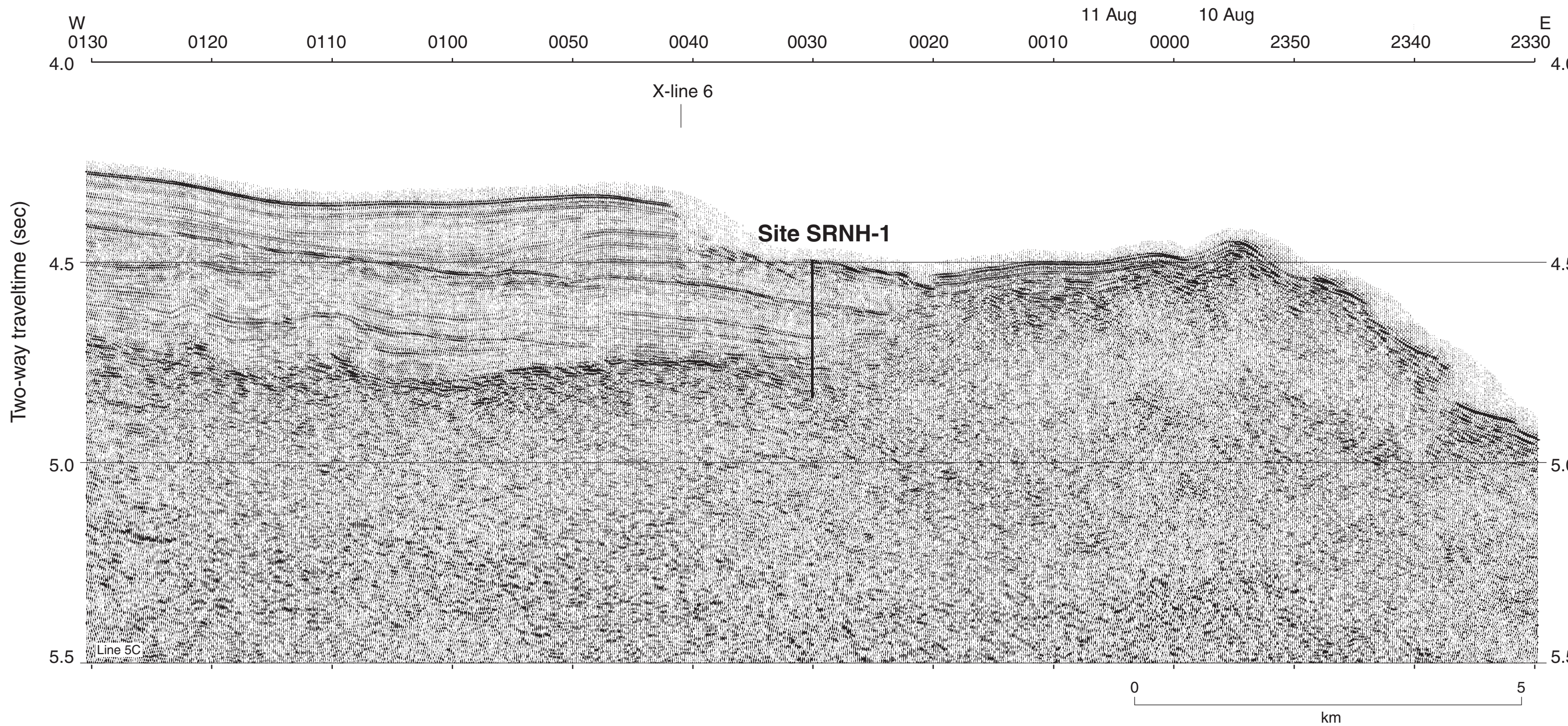


Figure AF8. Seismic Line 6 near proposed Site SRNH-1.

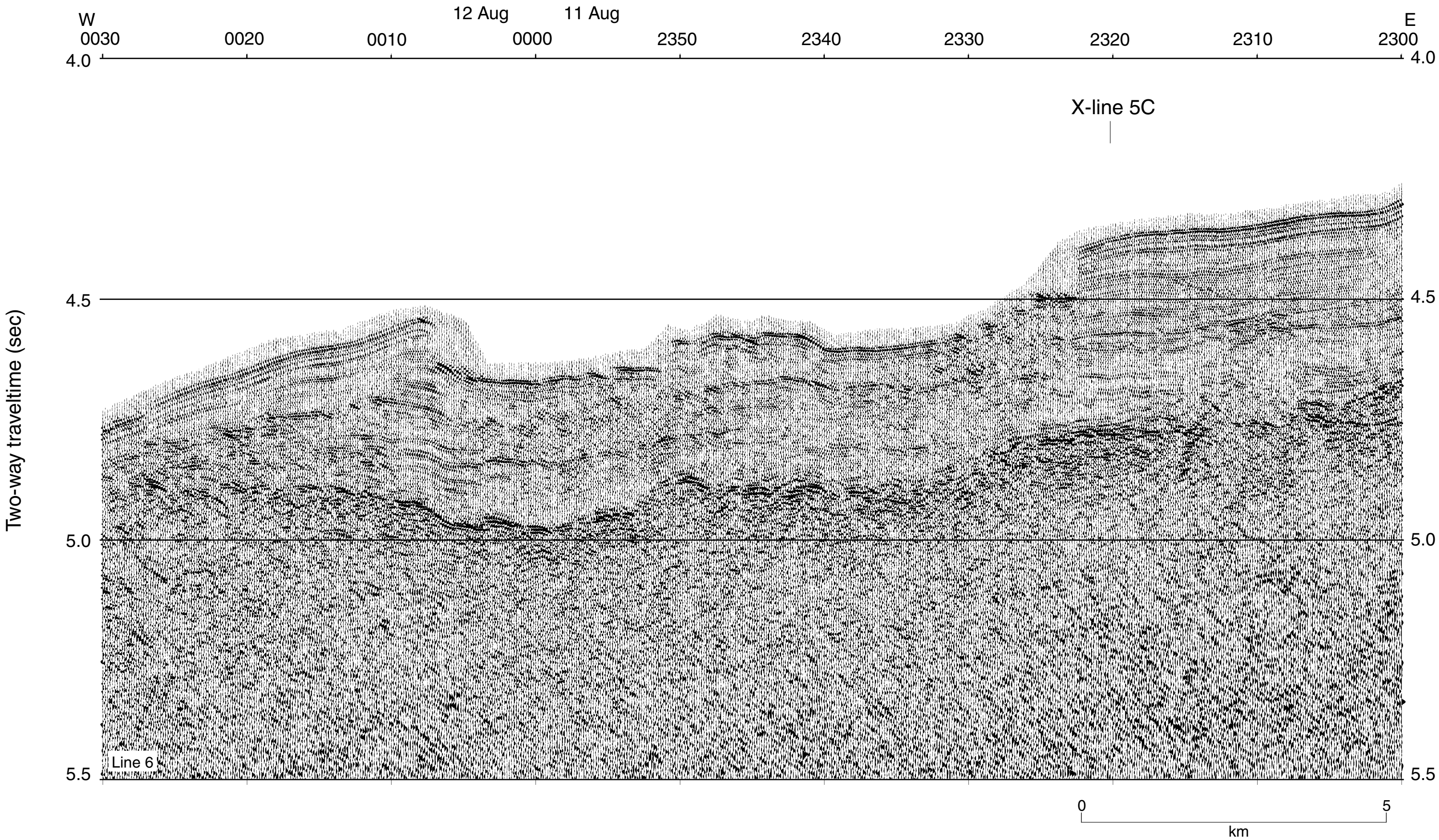


Figure AF9. Track map for proposed Sites SRNH-1, SRNH-2, and SRNH-2A. White box shown in Figure AF10.

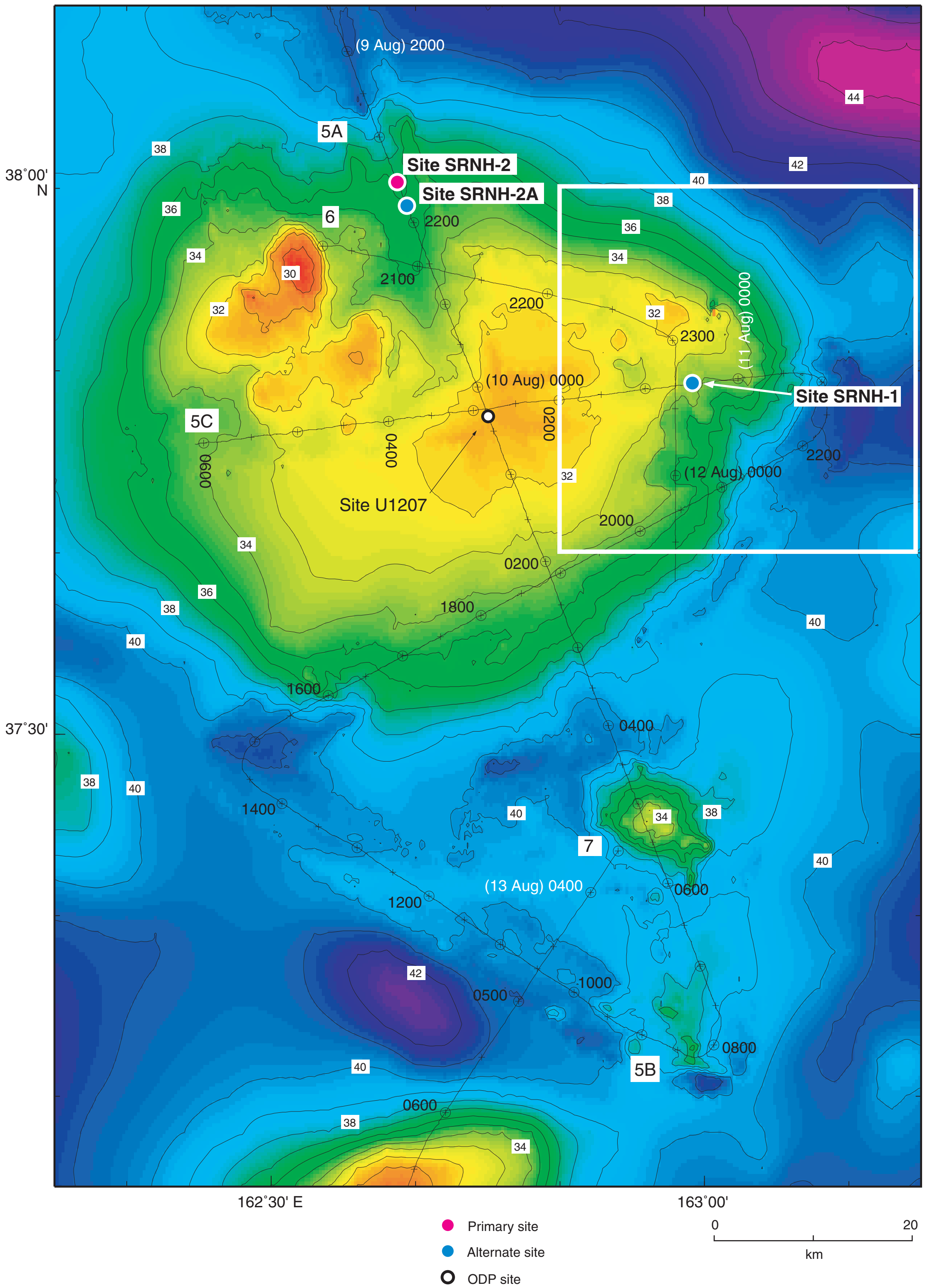


Figure AF10. Close-up track map for proposed Site SRNH-1.

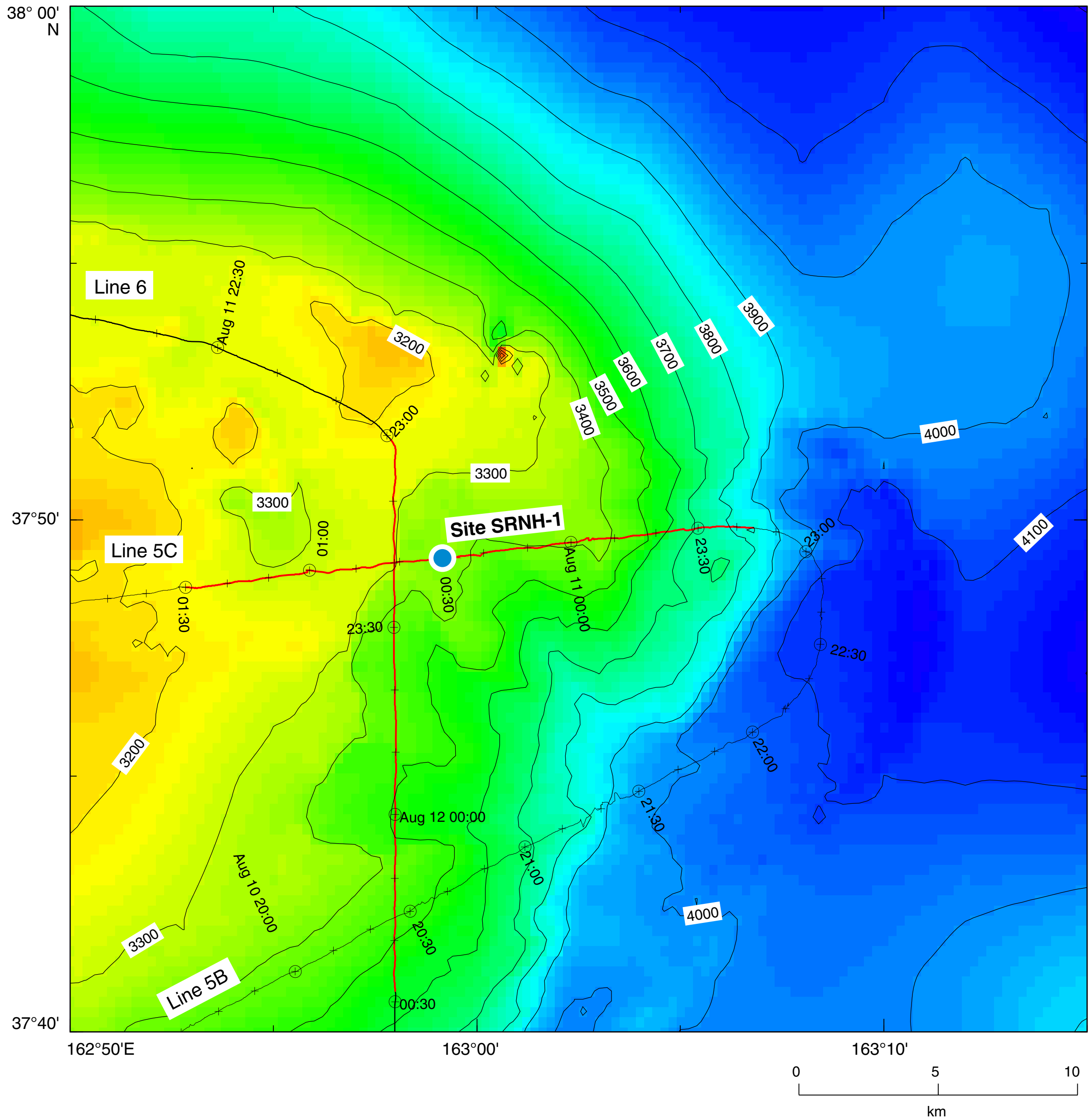


Figure AF11. Seismic Line 5A at proposed Sites SRNH-2 and SRNH-2A.

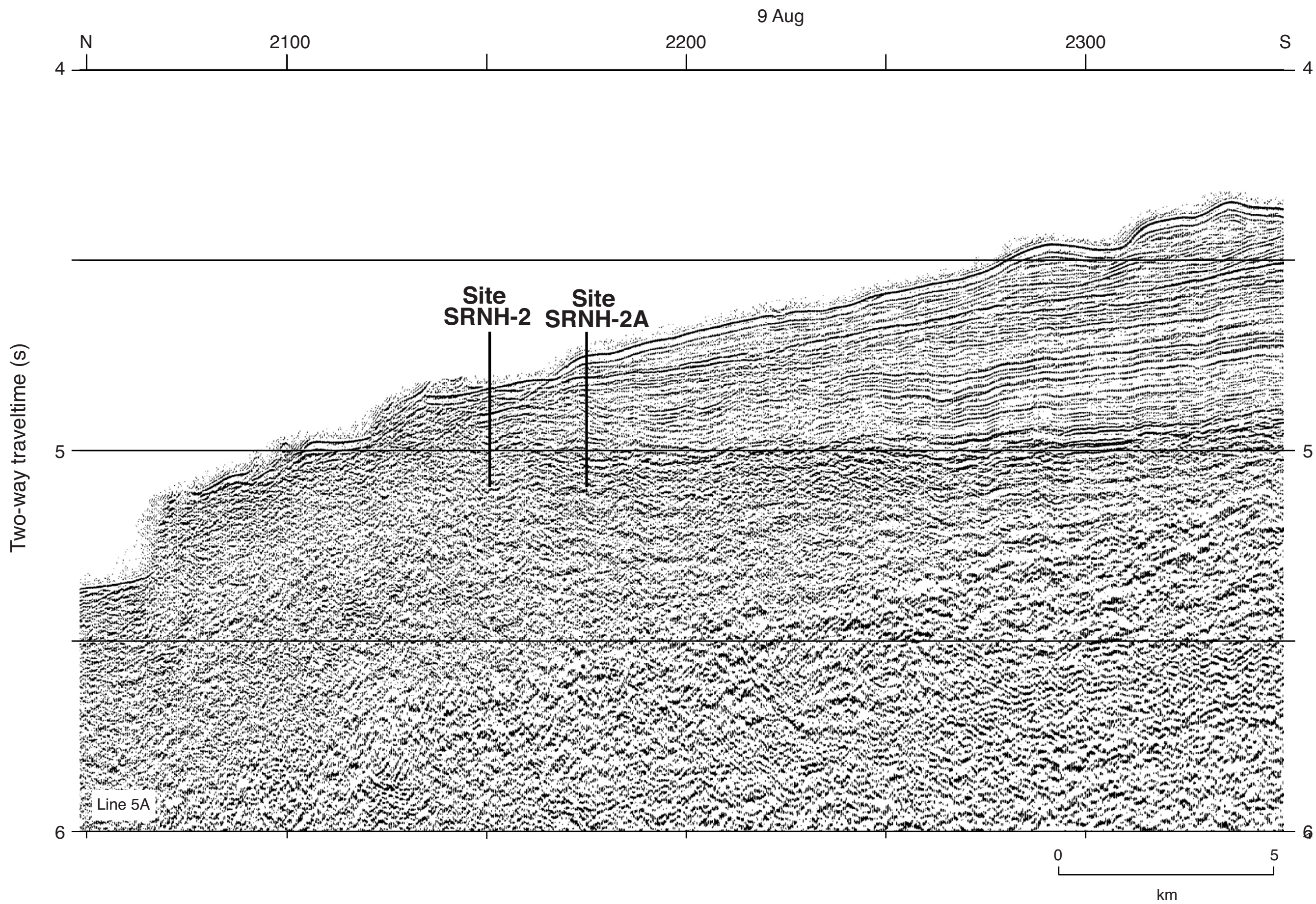


Figure AF12. Seismic Line L17 at proposed Site SRSH-2A.

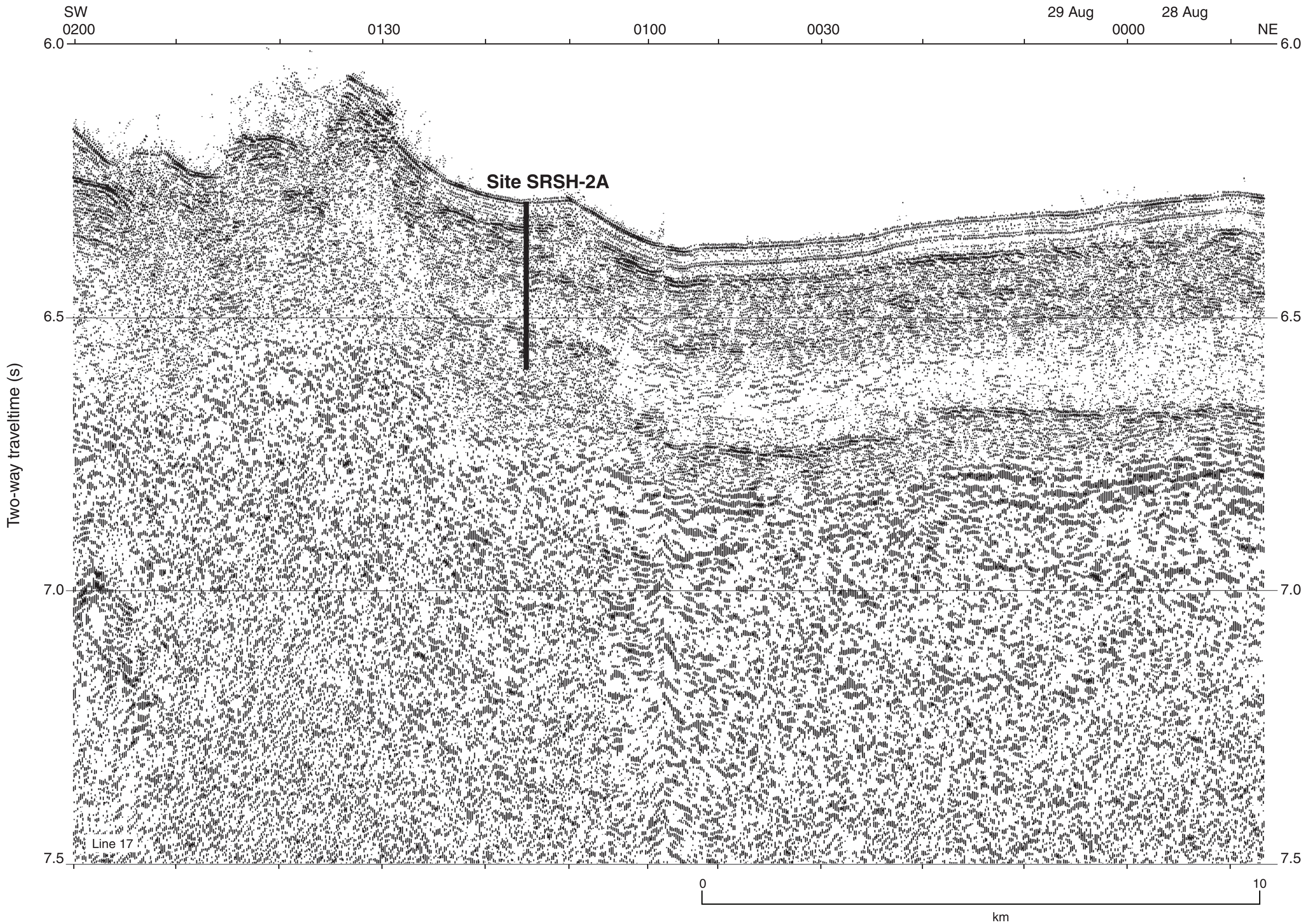


Figure AF13. Track map for proposed Sites SRSH-2A, SRSH-2B, SRSH-3, SRSH-3B, SRSH-5, and SRSH-8. Red box shown in Figure AF14, blue box shown in Figure AF18, yellow box shown in Figure AF22.

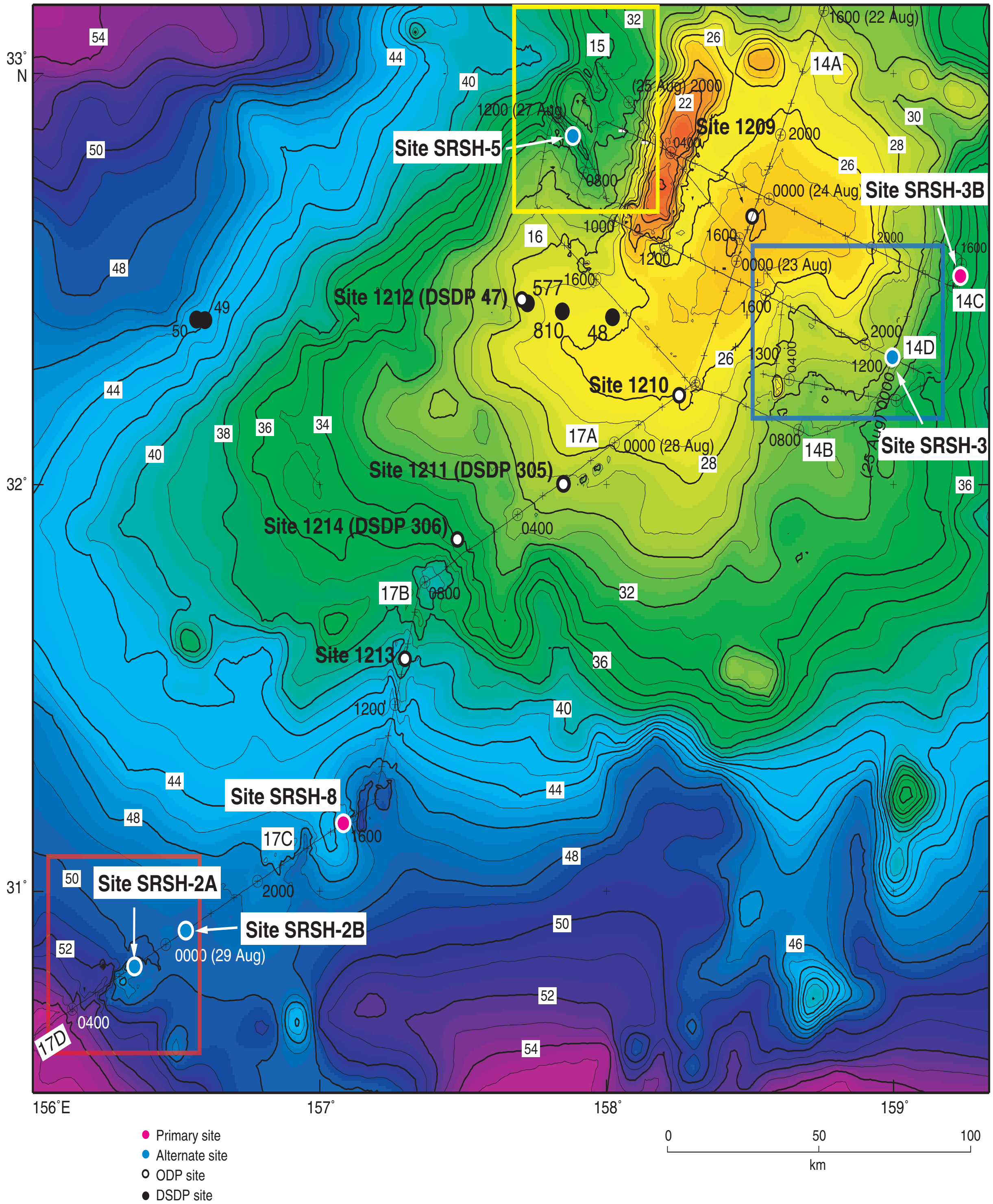


Figure AF14. Close-up track map for proposed Sites SRSH-2A and SRSH-2B.

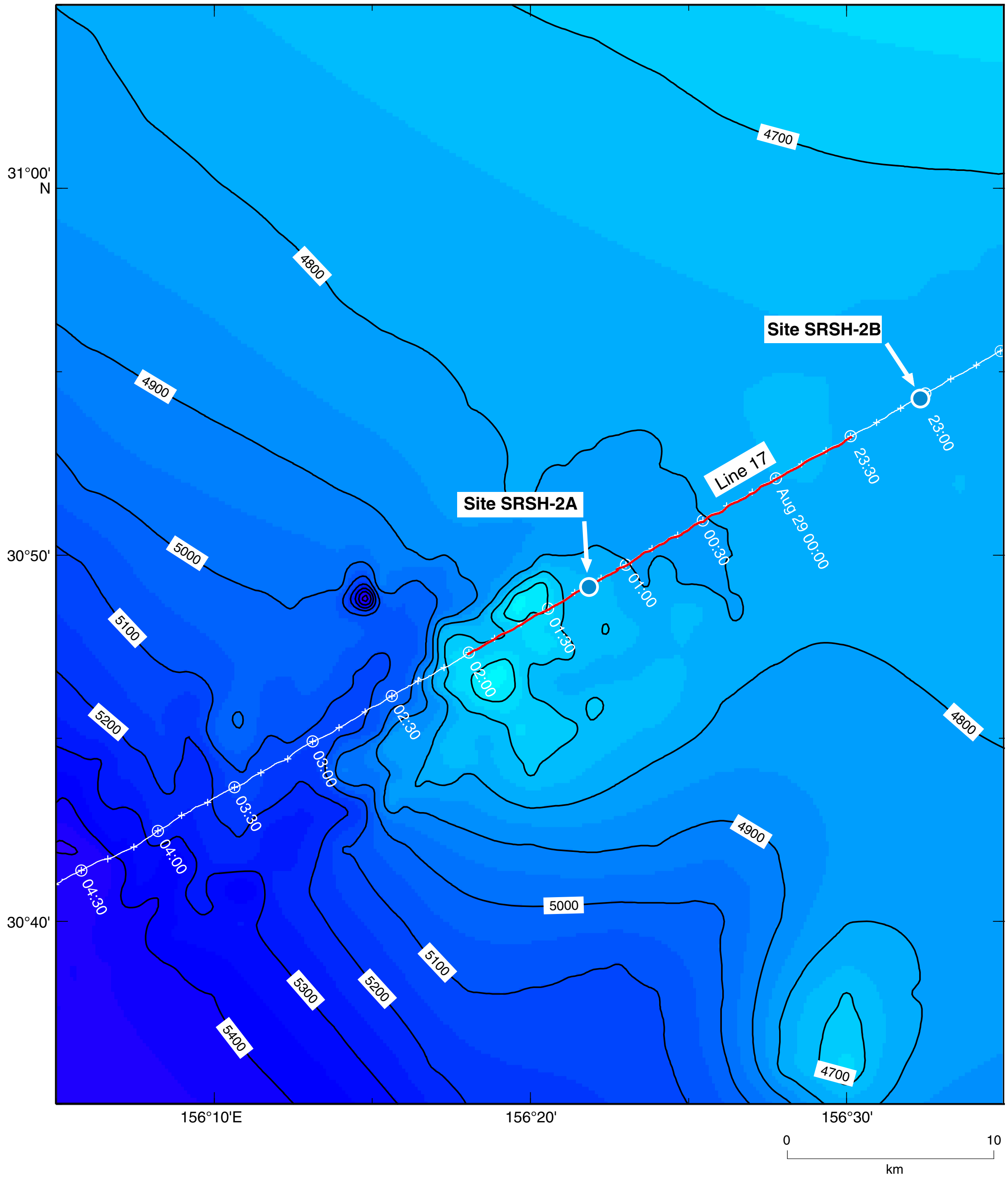


Figure AF15. Seismic Line 17C at proposed Site SRSH-2B.

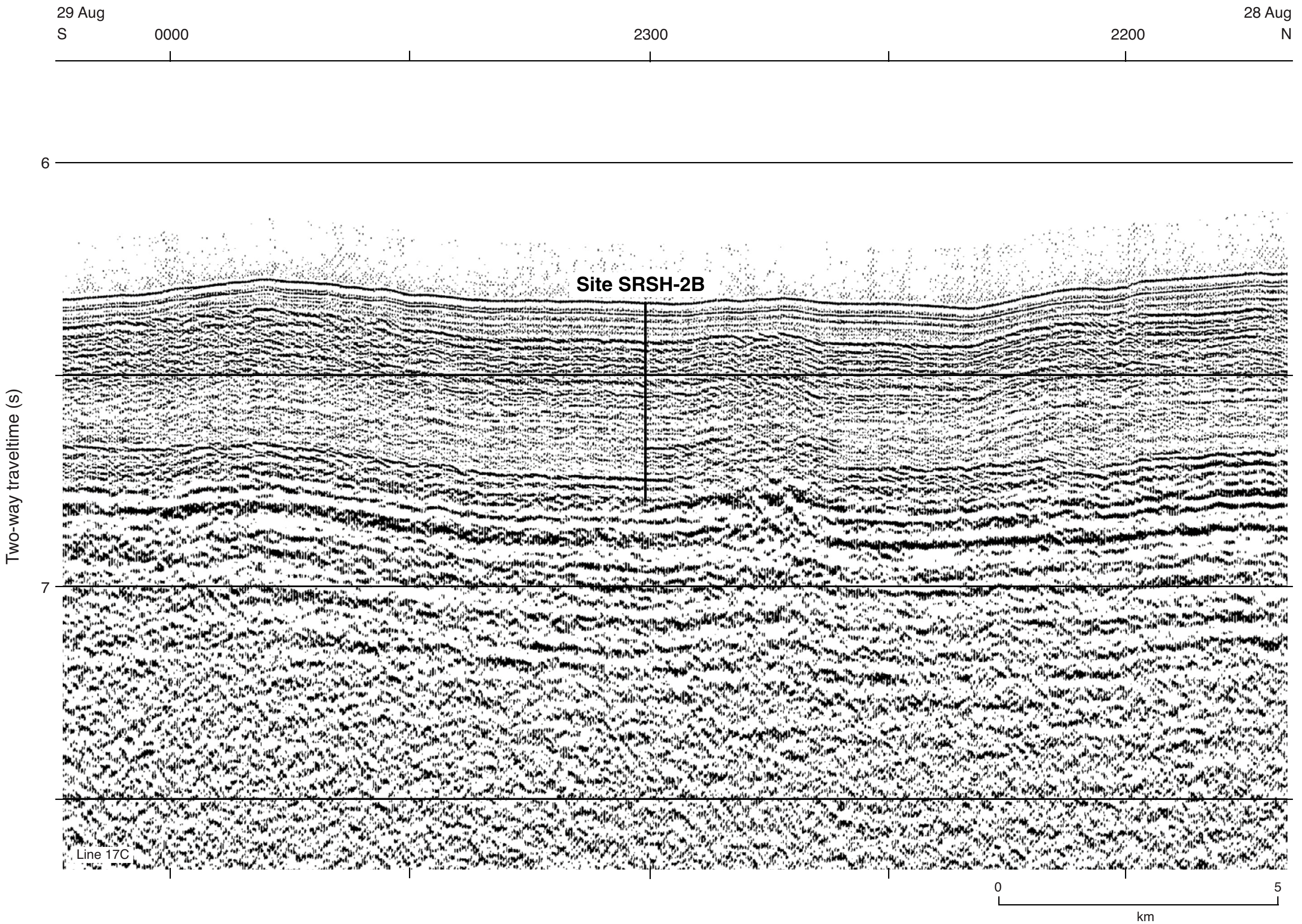


Figure AF16. Seismic Line 14B at proposed Site SRSH-3.

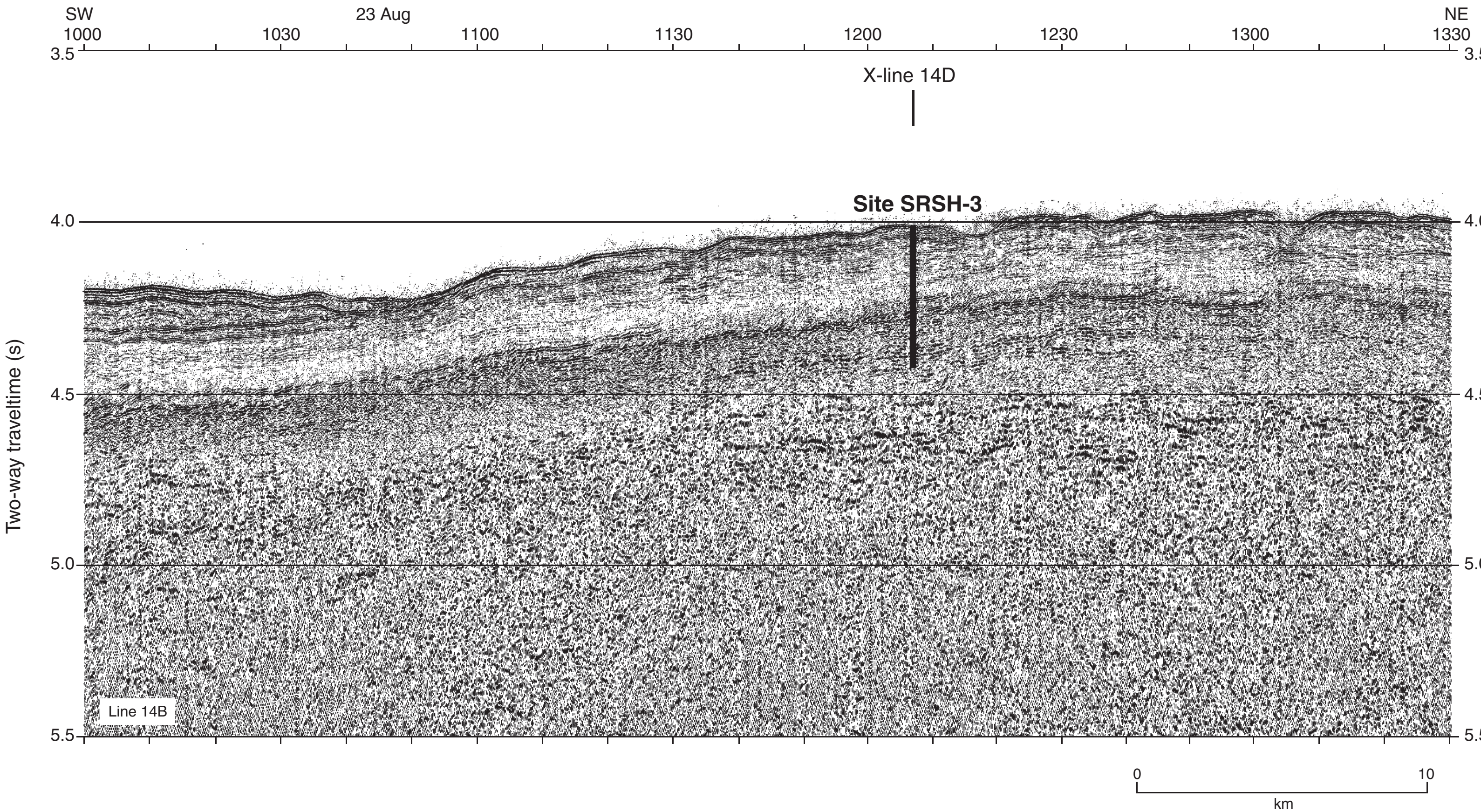


Figure AF17. Seismic Line 14D at proposed Site SRSH-3.

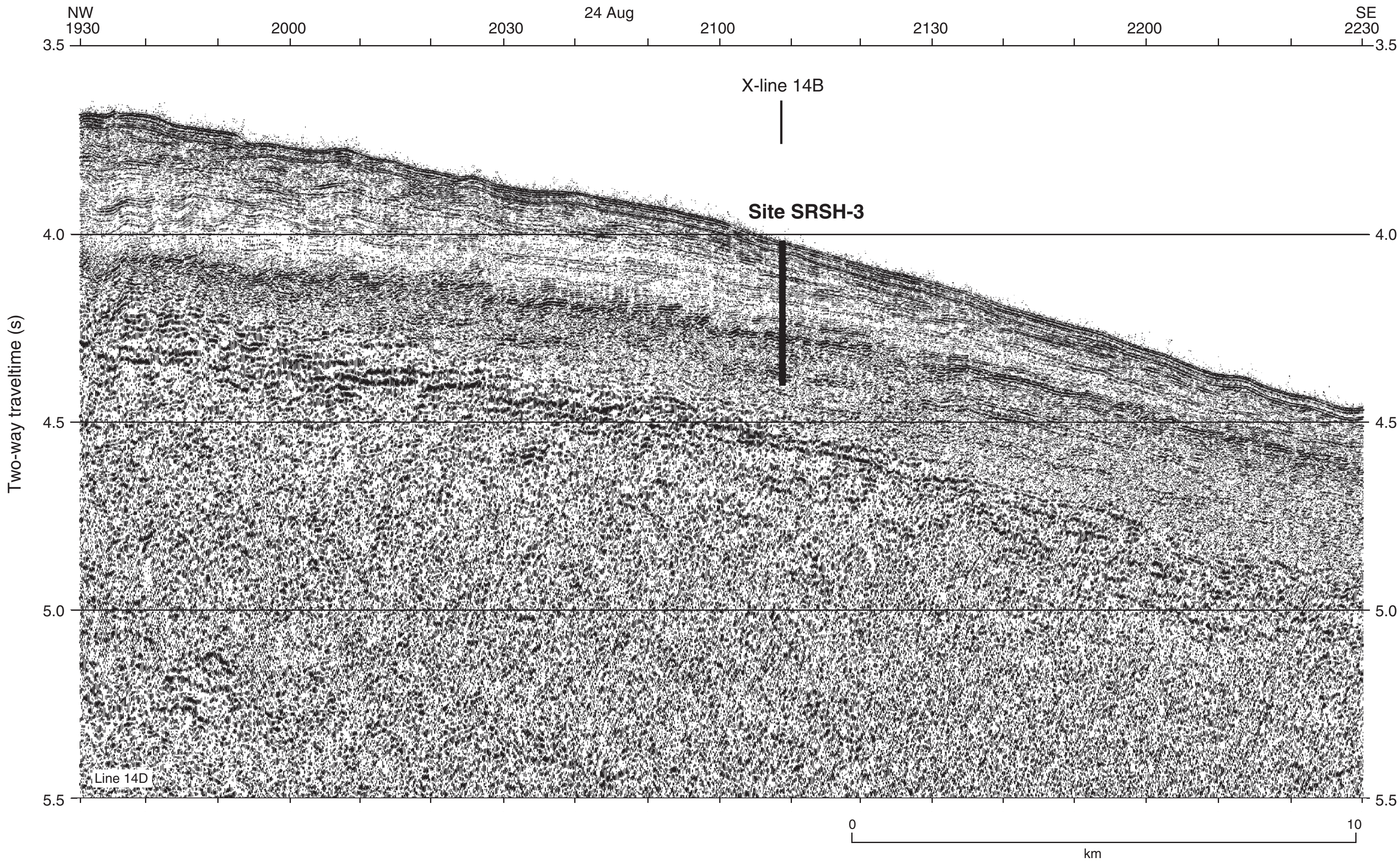


Figure AF18. Track map for proposed Site SRSH-3.

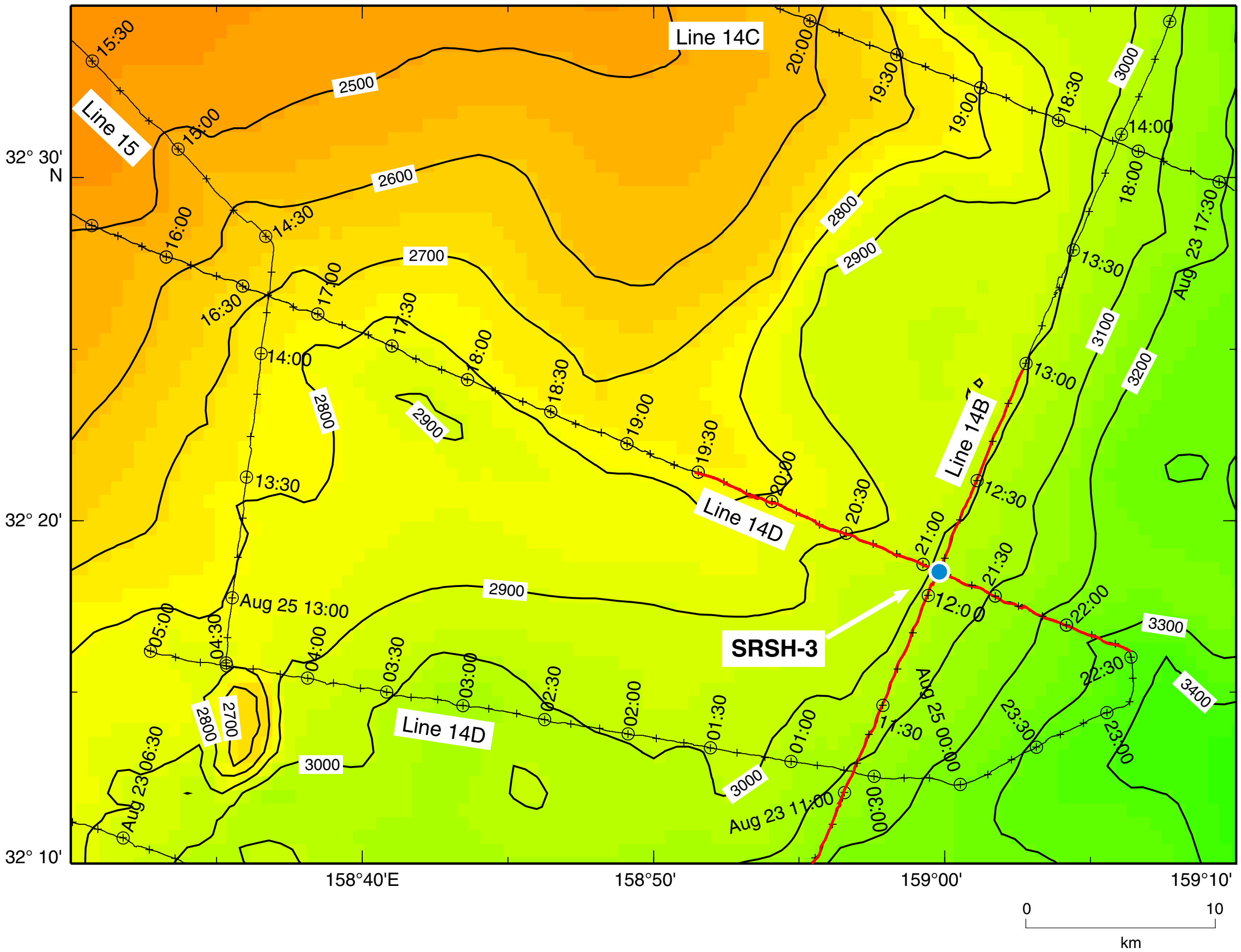


Figure AF19. Seismic Line 14C at proposed Site SRSH-3B.

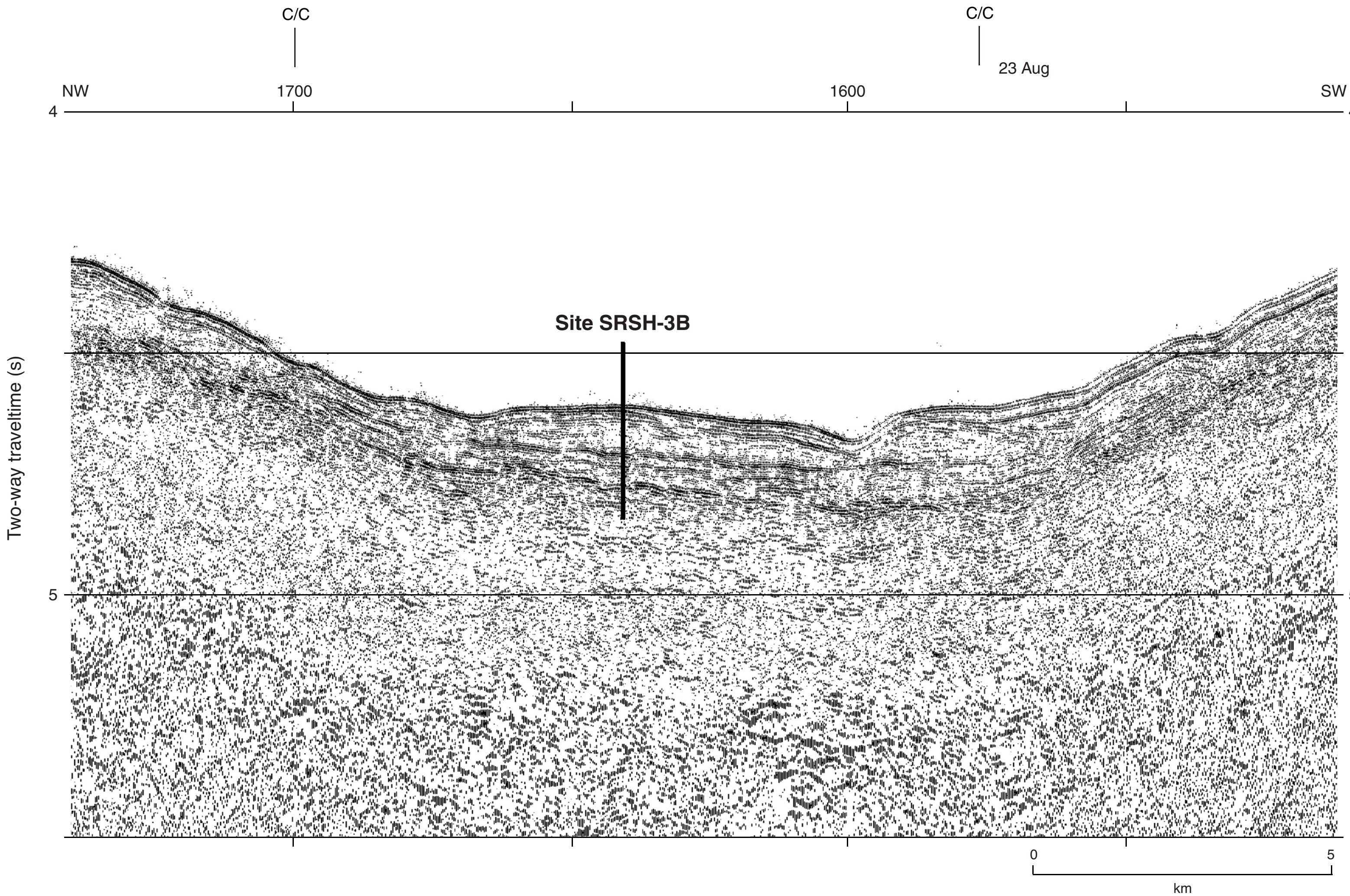


Figure AF20. Seismic Line 15 at proposed Site SRSH-5.

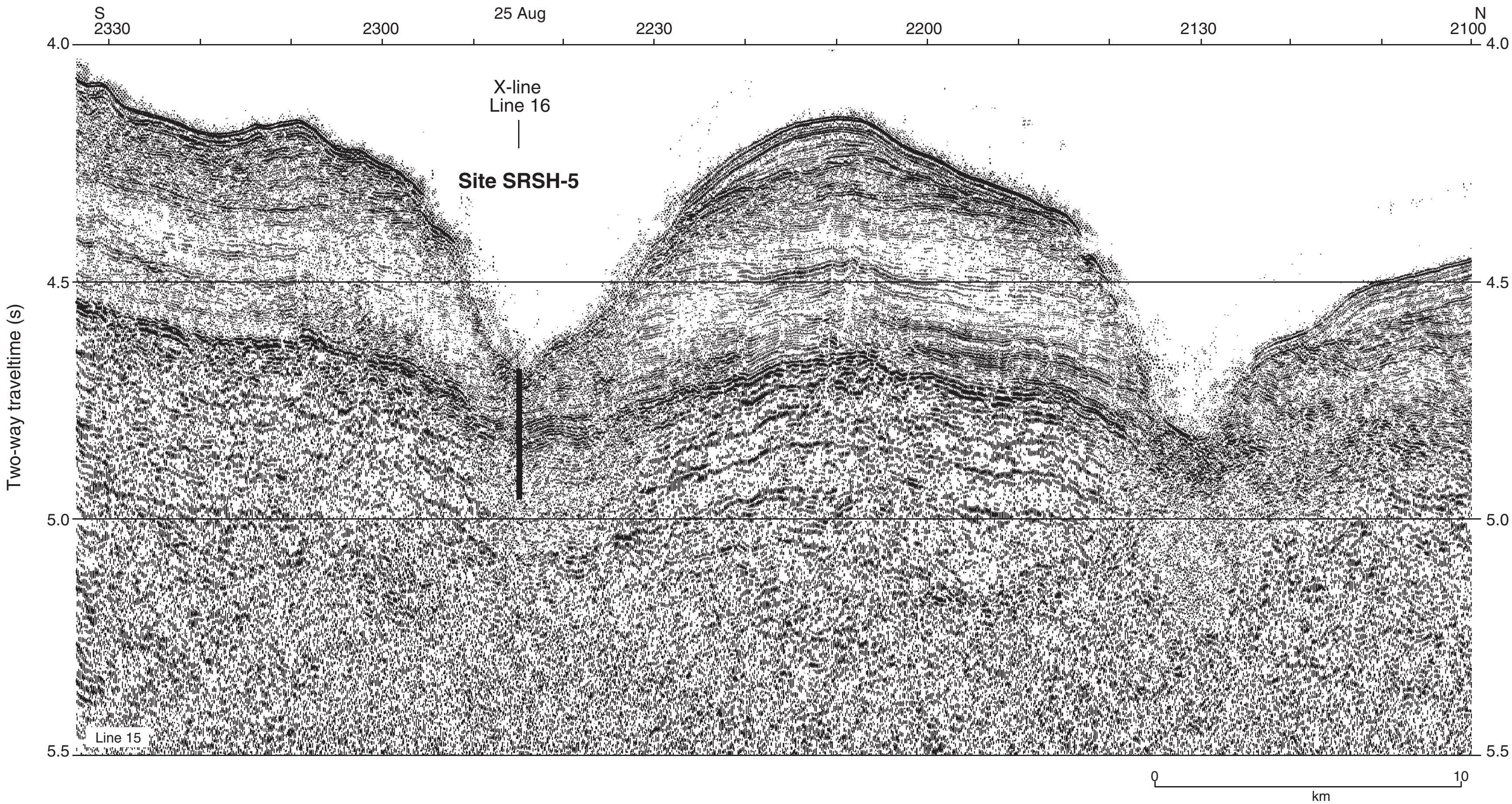


Figure AF21. Seismic Line 16 at proposed Site SRSH-5

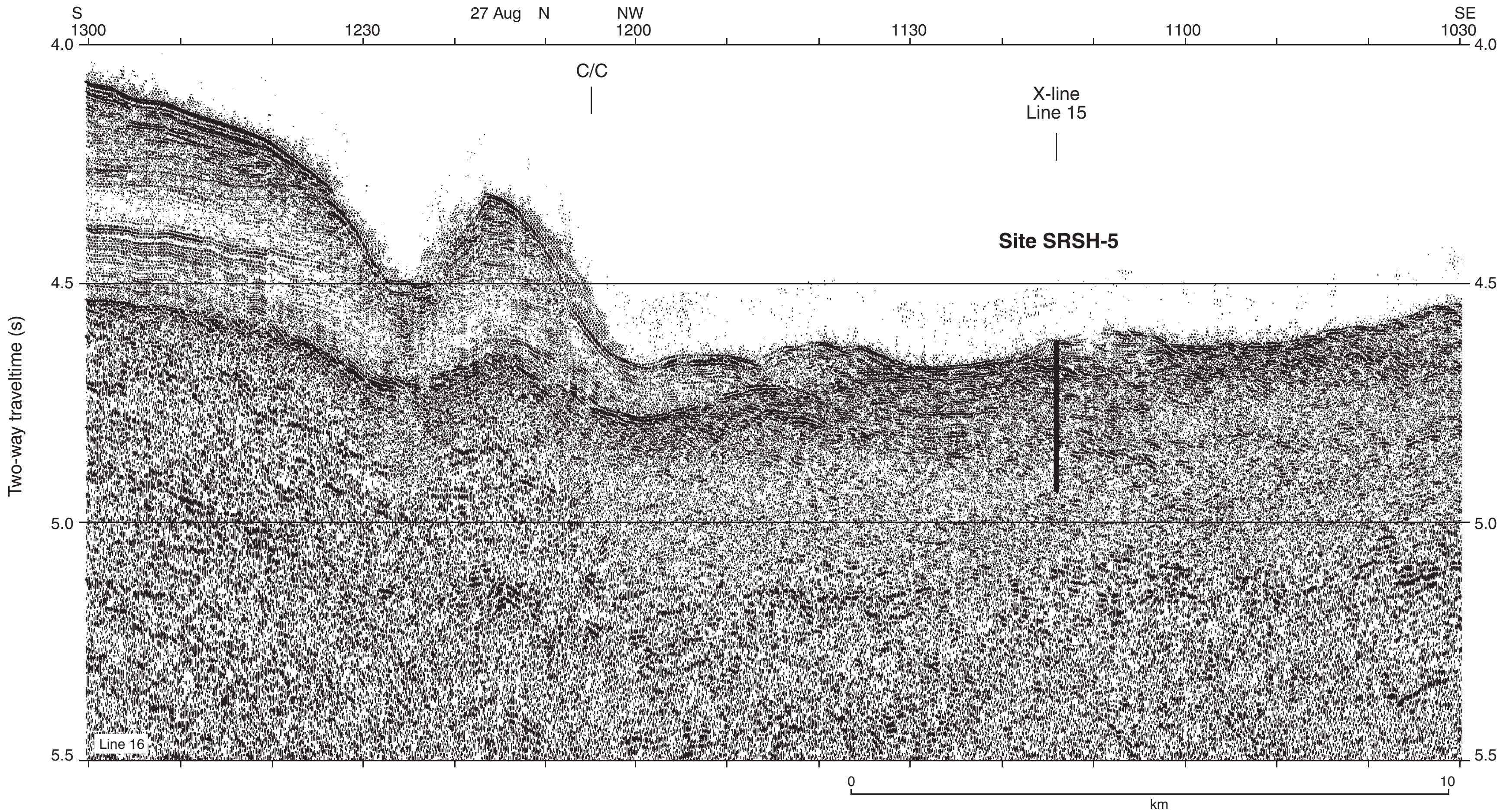


Figure AF22. Track map for proposed Sight SRSH-5.

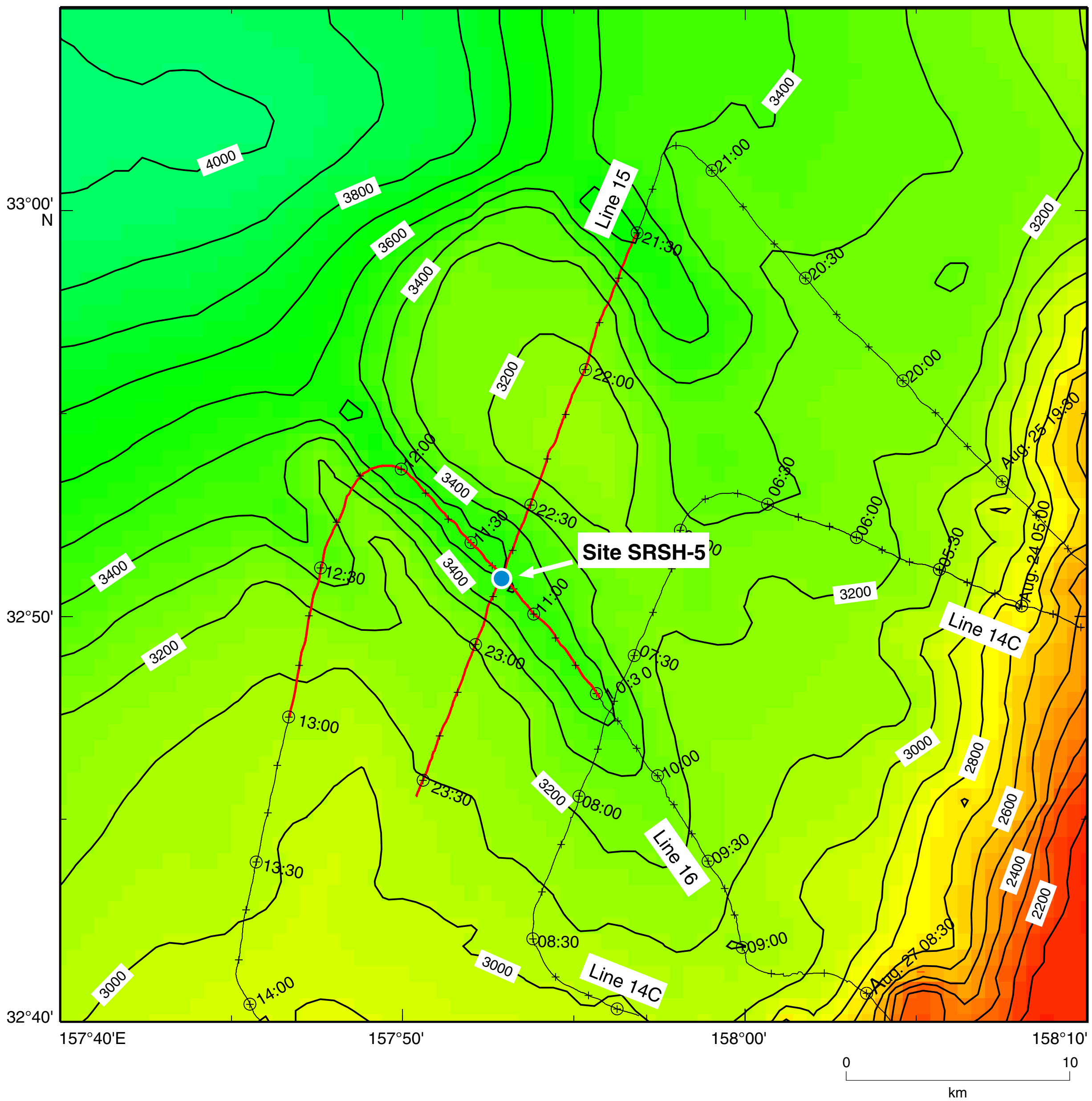


Figure AF23. Seismic Line 13 at proposed Site SRSH-6.

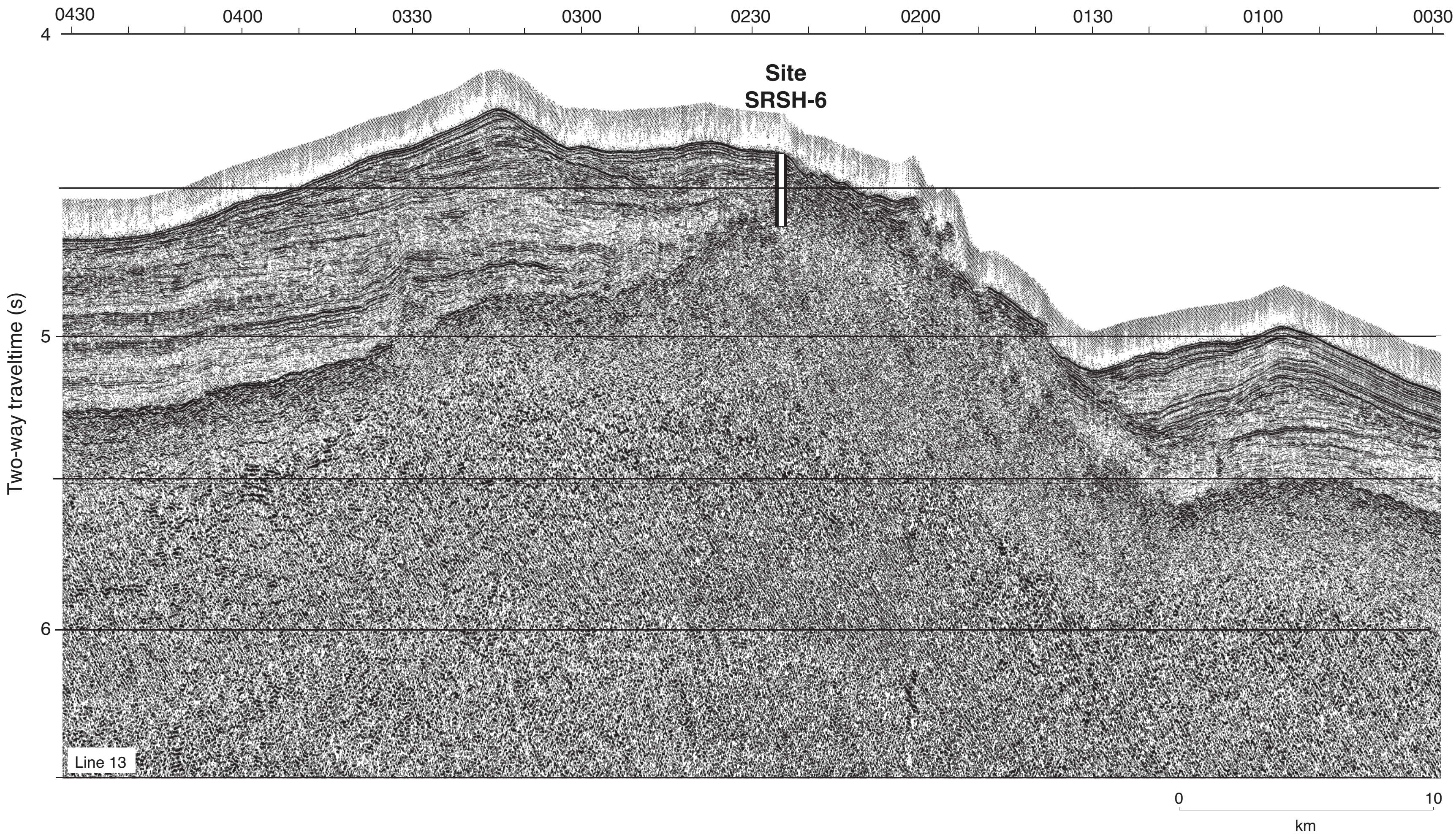


Figure AF24. Close-up of seismic Line 13 at proposed Site SRSH-6.

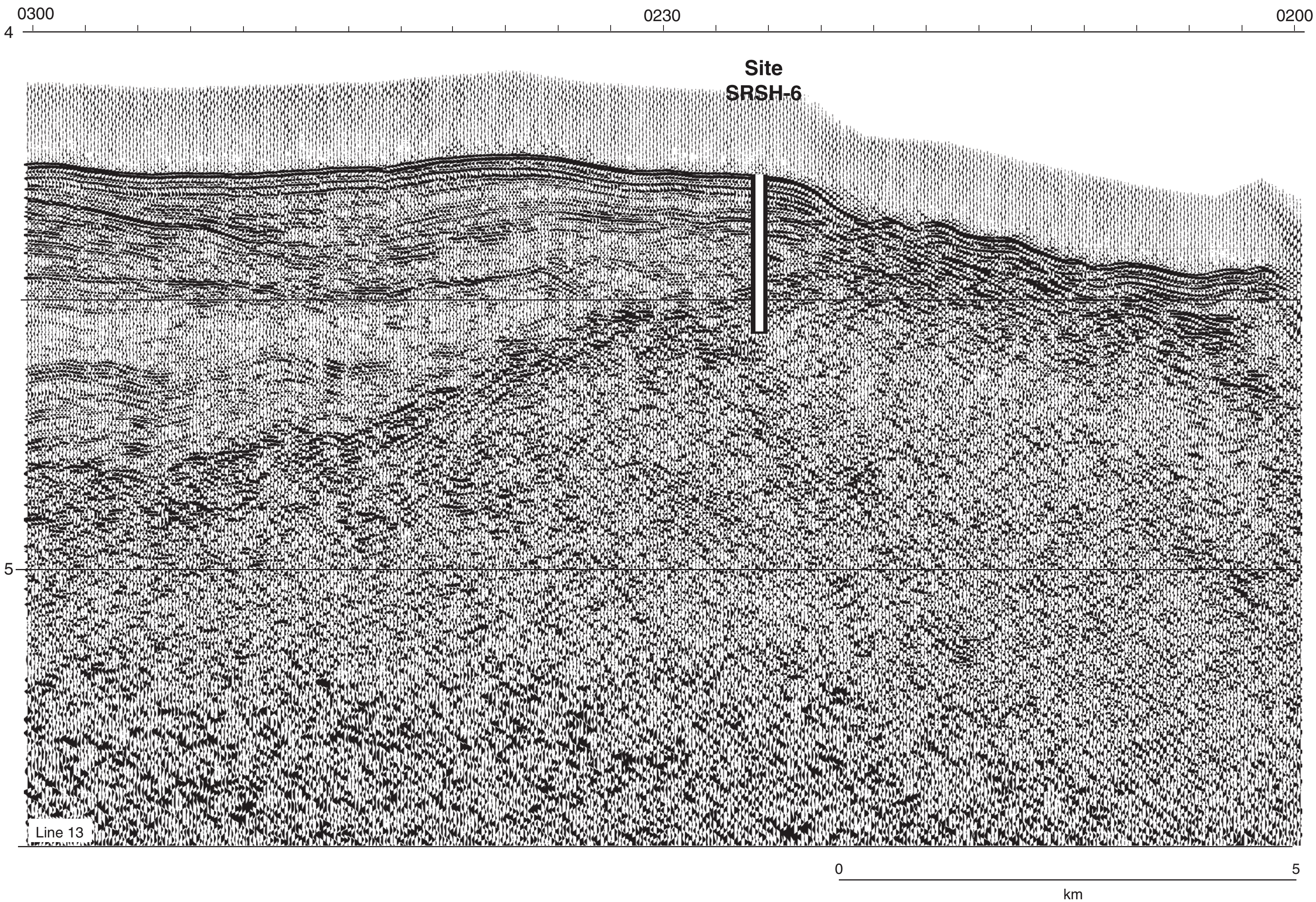


Figure AF25. Track map of proposed Sites SRSH-6 and SRSH-7. White box shown in Figure AF26.

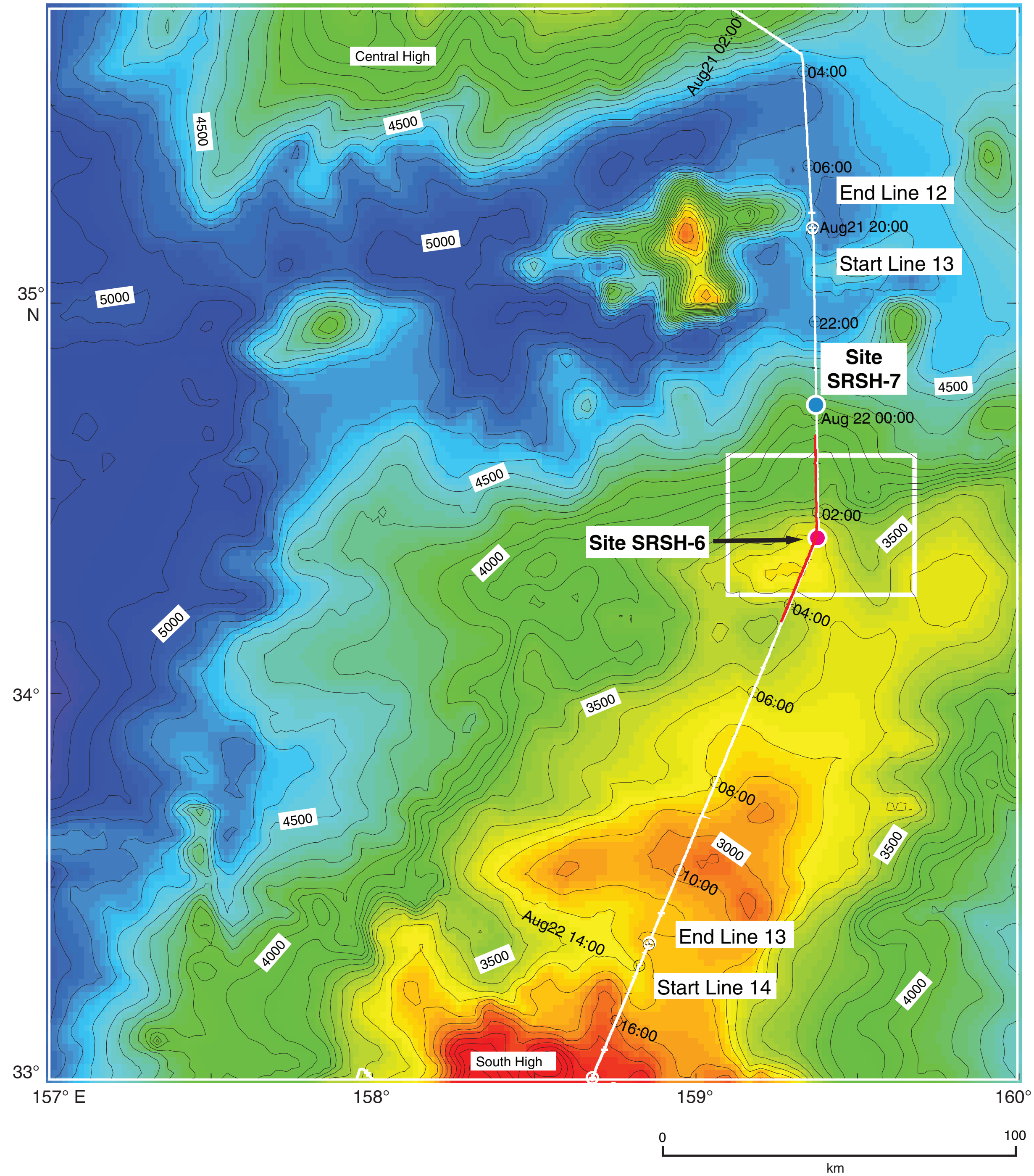


Figure AF26. Close-up track map for proposed Site SRSH-6.

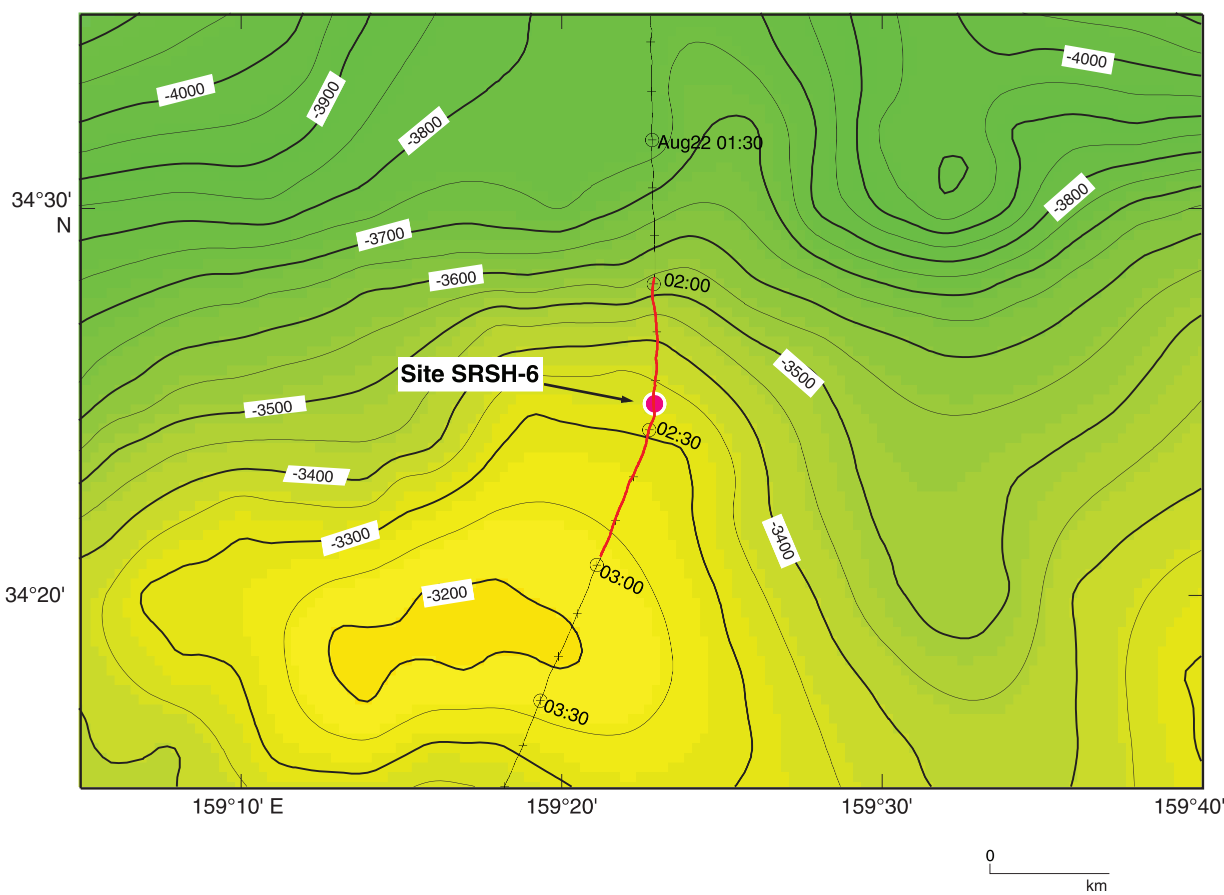


Figure AF27. Seismic Line 13 at proposed Sites SRSH-6 and SRSH-7.

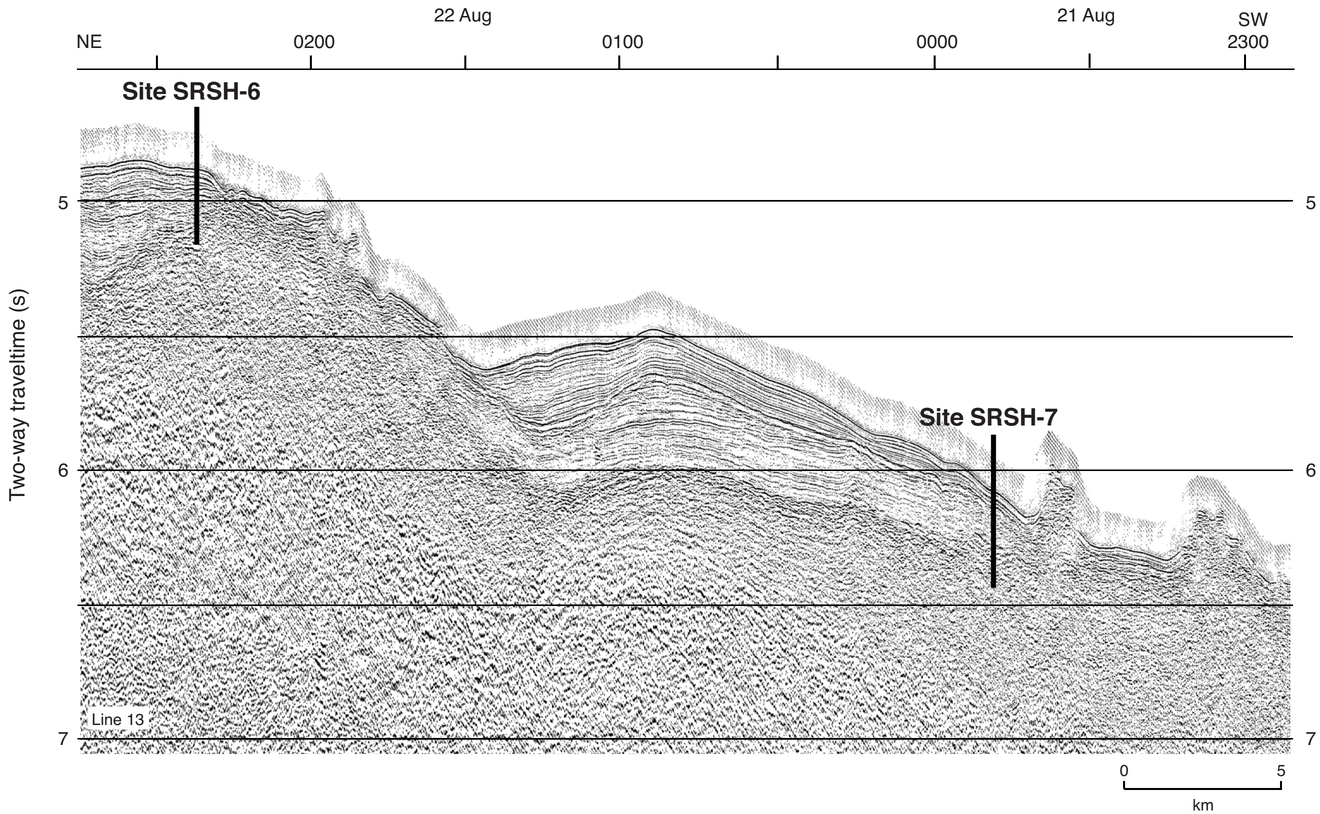
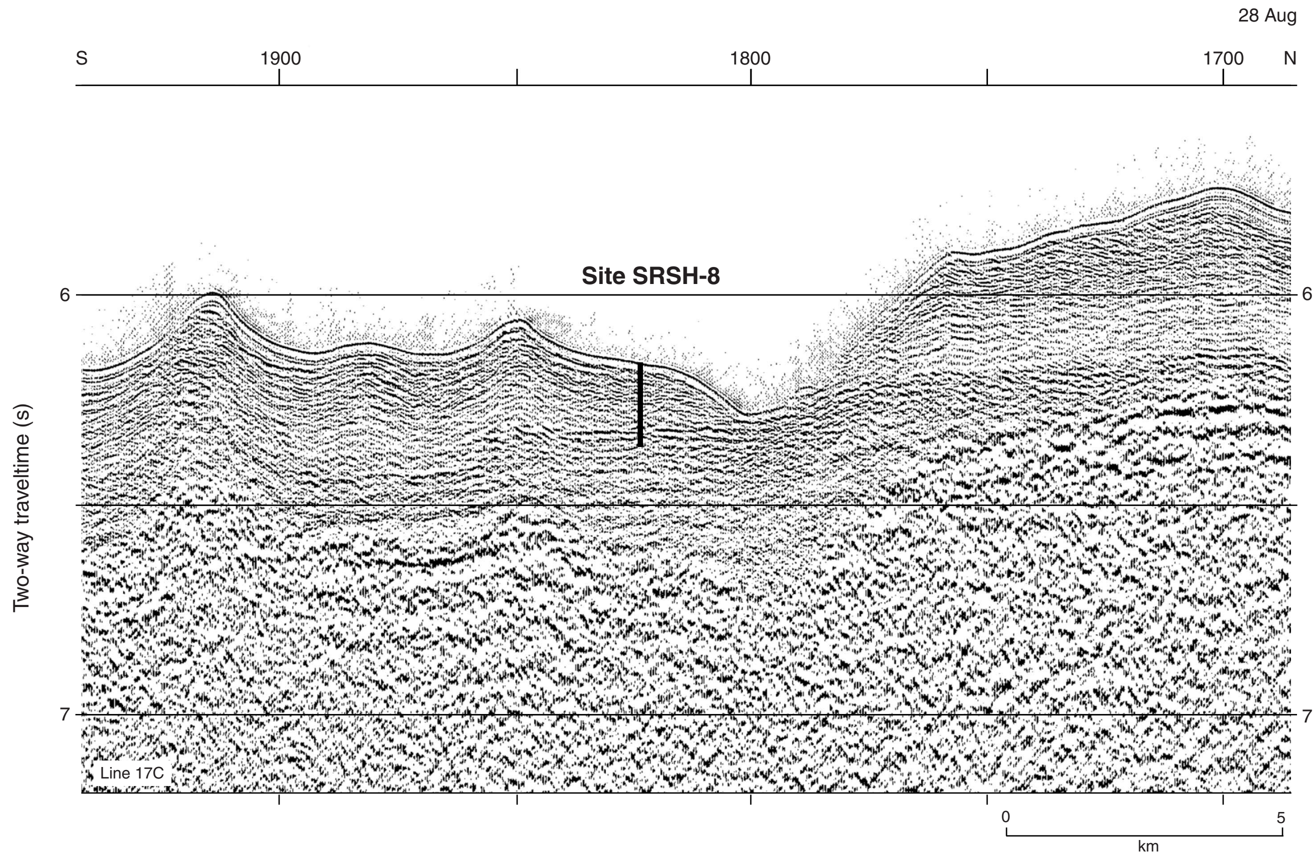


Figure AF28. Seismic Line 17C at proposed Site SRSH-8.



Expedition scientists and scientific participants

The current list of participants for Expedition 324 can be found at **iodp.tamu.edu/scienceops/precruise/shatskyrise/participants.html.**