International Ocean Discovery Program
Expedition 355 Scientific Prospectus

Arabian Sea Monsoon

Deep sea drilling in the Arabian Sea: constraining tectonic-monsoon interactions in South Asia

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Abstract

Interactions between the solid Earth and climate system represent a frontier area for geoscientific research that is strongly emphasized in the International Ocean Discovery Program (IODP) Science Plan. The continental margin of India adjoining the Arabian Sea offers a unique opportunity to understand tectonic-climatic interactions and the net impact of these on weathering and erosion of the Himalaya. Scientific drilling in the Arabian Sea is designed to understand the coevolution of mountain building, weathering, erosion, and climate over a range of timescales. The southwest monsoon is one of the most intense climatic phenomena on Earth. Its long-term development has been linked to the growth of high topography in South and Central Asia. Conversely, the tectonic evolution of the Himalaya, especially the exhumation of the Greater Himalaya, has been linked to intensification of the summer monsoon rains, as well as to plate tectonic forces. Weathering of the Himalaya has also been linked to long-term drawdown of atmospheric CO_2 during the Cenozoic, culminating in the onset of Northern Hemisphere glaciation. No other part of the world has such intense links between tectonic and climatic processes. Unfortunately, these hypotheses remain largely untested because of limited information on the history of erosion and weathering recorded in the resultant sedimentary prisms. This type of data cannot be found on shore because the proximal foreland basin records are disrupted by major unconformities, and depositional ages are difficult to determine with high precision. We therefore propose to recover longer records of erosion and weathering from the Indus Fan that will allow us to understand links between paleoceanographic processes and the climatic history of the region. The latter was partially addressed by Ocean Drilling Program (ODP) Leg 117 on the Oman margin, and further studies are proposed during IODP Expedition 353 (Indian Monsoon Rainfall) that will core several sites in the Bay of Bengal. Such records can be correlated to structural geological and thermochronology data in the Himalaya and Tibetan Plateau to estimate how sediment fluxes and exhumation rates change through time. The drilling will be accomplished within a regional seismic stratigraphic framework and will for the first time permit an estimation of sediment budgets together with quantitative estimates of weathering fluxes and their variation through time. Specific goals of this expedition include

1. Testing whether the timing of the exhumation of Greater Himalaya correlates with an enhanced erosional flux and stronger chemical weathering after ~23 Ma,
2. Determining the amplitude and direction of the environmental change at 8 Ma, and

3. Dating the age of the base of the fan and the underlying basement to constrain the timing of India-Asia collision.

Drilling through the fan base and into the underlying basement in the proposed area will permit additional constraints to be placed on the nature of the crust in the Laxmi Basin (Eastern Arabian Sea), which has a significant bearing on paleogeographic reconstructions along conjugate margins in the Arabian Sea and models of continental breakup on rifted volcanic margins.

Schedule for Expedition 355

International Ocean Discovery Program (IODP) Expedition 355 is based partly on IODP drilling Proposal 793-CPP2 (**iodp.tamu.edu/scienceops/expeditions/arabian_sea.html**). Following ranking by the IODP Scientific Advisory Structure and a commitment from India to contribute to the cost of the expedition, the expedition was scheduled for the research vessel R/V *JOIDES Resolution,* operating under contract with Texas A&M University. At the time of publication of this *Scientific Prospectus,* the expedition is scheduled to start in Colombo, Sri Lanka, on 31 March 2015 and end in Mumbai, India, on 31 May. A total of 61 days will be available for the transit, drilling, coring, and downhole measurements described in this report (for the current detailed schedule, see **iodp.tamu.edu/scienceops/**). As Expedition 355 is a Complimentary Project Proposal (CPP) with the government of India contributing to the expedition costs, there will be substantially increased shipboard participation by Indian scientists. Further details about the facilities aboard the *JOIDES Resolution* can be found at **www.iodp-usio.org/.**

Introduction

The theory of plate tectonics has established that the solid Earth's lithosphere interacts intimately with the asthenosphere, but more recently it has been revealed that the lithosphere also has significant interactions with the atmosphere and oceans, where it can influence circulation and thereby control Earth's climate. These interactions between the solid Earth and the climate system can occur in at least two different ways. The opening and closure of deep-ocean gateways is believed to have caused large-scale climate change by affecting heat transport between ocean basins or between polar and tropical regions (Haug and Tiedemann, 1998; Cane and Molnar, 2001; von der Heydt and Dijkstra, 2006). In addition, mountain building is proposed to have perturbed planetary scale atmospheric circulation, influencing continental environments and even the oceanography of the surrounding basins. The suggestion that mountain building in Asia has intensified the Asian monsoon is the most dramatic proposed example of such interactions (Prell and Kutzbach, 1992; Molnar et al., 1993; An et al., 2001). Asia is the only continent that experiences such an intense monsoon, partly a reflection of the size of the landmass but also linked to its tectonic history and anomalous altitude. Therefore, understanding what controls the monsoon intensity is of great scientific interest and has substantive societal importance considering the large number of people whose livelihood depends on the summer rains and the increasing global economic importance of the region. If we can identify the various processes that control monsoon intensity over geologic timescales, we can establish an improved context for shorter term modeling of how future climate change may affect the densely populated environments of Asia. Specifically, we aim to answer the question of what are the links between the monsoon and the building of high topography in Asia and whether there are feedbacks?

The Arabian Sea in the northern Indian Ocean (Fig. **F1**) preserves regional sedimentary records of rifting and paleoceanographic history, as well as providing sedimentary archives of long term erosion of the Himalaya since the start of collision between India and Asia, which probably began in the Eocene (Rowley, 1996; Najman et al., 2010). Scientific drilling in the Eastern Arabian Sea is designed to reconstruct the evolution of the Indian monsoon system and define its role in controlling weathering and erosion in the Himalaya under the IODP Science Plan theme, “Climate and Ocean Change.”

As well as being a repository of information about climate and mountain building, the Arabian Sea also holds potentially illuminating records of continental rifting and break-up tectonics dating from the time of Gondwana fragmentation (Heine et al., 2004). Paleogeographic reconstructions, as well as similarities in the structural/tectonic elements, suggest a conjugate relationship between the western continental margin of India and the eastern continental margin of Madagascar and the Seychelles margin (Storey et al., 1995; Collier et al., 2008). In-depth studies on the conjugate margins in this region offer new data to complement our knowledge from other well-studied conjugate margins such as the Iberia-Newfoundland and Greenland-Norway margins of the Atlantic Ocean (Minshull et al., 2008). This secondary objective of the proposal addresses the “Earth Connections” theme of the IODP Science Plan.

Background

Link between India-Eurasia collision and southwest monsoon

The southwest monsoon is one of the strongest climatic systems on Earth; it provides a lifeline for more than half the global population. Some have suggested that the southwest monsoon is strongly influenced by the topography of the Tibetan Plateau (Molnar et al., 1993, 2010; An et al., 2001) (Fig. F2). However, the situation is likely more complex, as the importance of the Himalayan barrier rather than the wide Tibetan Plateau in modulating the Asian monsoon has also been invoked as a key control (Boos and Kuang, 2010). Still other workers have highlighted processes such as the retreat of shallow seas in central Asia (Ramstein et al., 1997) and the closure of the Indonesian gateways (Potter and Szatmari, 2009) as crucial constraints. Nonetheless, numerical modeling confirms that introduction of a higher plateau to Asian topography intensifies rainfall over southwest Asia (Huber and Goldner, 2012). Presently, the plateau redistributes the regional mid-latitude circulation and affects the annual precipitation in this region (Molnar et al., 1993; An et al., 2001; Wang et al., 2005; Clift and Plumb, 2008;). The erosion of the Himalaya, largely driven by the southwest monsoon, has resulted in the accumulation of the world's two largest submarine sedimentary deposits: the Indus Fan in the Arabian Sea and the Bengal Fan in the Bay of Bengal (Curray and Moore, 1982; Kolla and Coumes, 1987; Clift et al., 2001; Curray et al., 2003). The two basins jointly preserve records of past erosion and weathering that are controlled, at least in part, by monsoonal variability that in turn may be linked to the progressive uplift of the Tibetan Plateau (France-Lanord et al., 2000; Wang et al., 2005; Lunt et al., 2010).

The relationship between tectonic uplift and variability in strength of the southwest and East Asian monsoons is highly complex and their phase relationship is not yet understood. A rising Tibetan Plateau could have altered climate in a number of ways, including

1. A rising plateau would have deflected and blocked regional air systems, affecting global atmospheric circulation (Held, 1983).
2. The elevated region would have enhanced pressure-driven atmospheric flows as higher and lower atmospheric pressure systems developed over the plateau during the winter and summer. This would have intensified the southwest monsoon, leading to heavier rainfall along the frontal ranges of the Himalaya (Hahn and Manabe, 1975; Wang et al., 2003, 2005).

3. Higher elevations in eastern Tibet would have increased orographic precipitation in that region, which diabatically heated the atmosphere there. This heating would then force subsidence of air masses to the west, potentially suppressing rainfall in southwest Asia (Molnar and Rajagopalan, 2012).

Interactions between the solid Earth and atmosphere are not limited to the impact of mountains on the monsoon, but also vice versa. It has variously been suggested that the onset of Greater Himalayan exhumation was triggered by monsoon intensification (Clift et al., 2008) or by the relocation of the Intertropical Convergence Zone above the Himalaya as a result of India's northward motion (Armstrong and Allen, 2011). Further, the enhanced availability of fresh rock surfaces exposed by denudation processes and the increased moisture availability might be predicted to enhance chemical weathering (Raymo and Ruddiman, 1992; Derry and France-Lanord, 1997). During chemical weathering, atmospheric carbon dioxide (CO_2) reacts with rock-forming silicates to produce bicarbonates, which may then be transported to the oceans where they eventually form carbonate rocks (Raymo and Ruddiman, 1992). Because CO_2 is an important greenhouse gas helping to warm the atmosphere, a decrease in the amount of atmospheric CO_2 would lead to global cooling. Raymo and Ruddiman (1992) argued that increased chemical weathering of the Himalaya resulted in decreased global CO_2, which culminated in Northern Hemisphere glaciation after 2.7 Ma.

The erosional records needed to reconstruct past environmental conditions can come from foreland basins as well as from the offshore deltas and fans where most of the sedimentation has occurred. Unfortunately, terrestrial records in this region tend to be poorly dated and incomplete, with a particularly large unconformity that spans the Eocene to early Miocene across the whole of the basin (Burbank et al., 1996; DeCelles et al., 1998). On the other hand, >70% of the total eroded mass from the Himalaya resides in the Indian Ocean (Clift, 2002), making any mass balancing that neglects the fans largely meaningless. As a result, testing competing hypotheses is possible only through analyzing long term quantitative records of erosion obtained from the Indian Ocean submarine fans.

The timing of uplift of the Himalaya-Tibetan Plateau is one of the major uncertainties in the linkage between mountain building and climate change in this region. Different views on the style and extent of surface uplift exist. Some advocate rapid late Pliocene–Pleistocene uplift based on mammalian fauna, paleokarst, and geomorphology (Ding et al., 1999; Qiang et al., 2001), whereas others suggest that uplift occurred gradually since the early Eocene, with substantial elevations reached by late Eocene, at least in southern Tibet (Dewey et al., 1988; Tapponnier et al., 2001). This latter view has been supported by oxygen isotopic compositions of paleosols and lacustrine sediment in central and southern Tibet (Garzione et al., 2000; Rowley and Currie, 2006), although these do not discriminate between the stepwise plateau growth favored by Tapponnier et al. (2001) and the more progressive growth modeled by Royden et al. (2008). Others think that major rapid uplift occurred after ~25 Ma and that the plateau attained its present elevation by ~14–15 Ma (Garzione et al., 2000; Harris, 2006), subsequently growing in area principally by expansion to the northeast and southeast (Clark et al., 2005; Schoenbohm et al., 2006; Royden et al., 2008). An alternative view suggests that the present elevation and extensional deformation of the plateau probably resulted from uplift caused by convective thinning of the underlying lithospheric mantle (England and Houseman, 1989), although this model does not make any firm predictions about when the uplift occurred.

Understanding passive rifted margins and continental breakup

The eastern Arabian Sea evolved after the break-up of Madagascar and India in the mid-Cretaceous and between India and the Seychelles during the Late Cretaceous (Norton and Sclater, 1979; Courtillot et al., 1988; White and McKenzie, 1989). The Deccan Traps, one of the best known examples of rapidly emplaced flood basalt, are considered to be imprints of the Réunion hotspot, which was located below the Indian continental lithosphere at ~66 Ma (Courtillot et al., 1988). Subsequently, hotspot activity emplaced magmatic intrusions within the crust of the western continental margin of India (Pandey et al., 1996; Singh, 2002). The interaction between the hotspot and the moving Indian plate also caused formation of a new seafloor spreading center, the Carlsberg Ridge (Storey et al., 1995), which resulted in conjugate rifted margins forming along the western margin of India and the eastern Seychelles (Chaubey et al., 2002a; Royer et al., 2002). The nature of these conjugate margins is poorly constrained, and knowledge about the entire break-up history and its relationship to the impact of the Réunion mantle plume is still elusive in the absence of direct observations.

The western continental margin of India consists of northeast–southwest trending structural highs, namely the Laccadive and Laxmi Ridges (Fig. F1) (Naini and Talwani, 1982; Biswas, 1987; Kolla and Coumes, 1990; Gopala Rao et al., 1992; Krishna et al., 1994; Subrahmanyam et al., 1995). Laxmi Ridge is largely considered to be a continental sliver that separated from India prior to the Seychelles-India break-up. The ridge differs from other oceanic features, aseismic ridges, and continental plateaus by being associated with a prominent negative free-air gravity anomaly (Naini and Talwani, 1982; Krishna et al., 1992; 1994; 2006). In contrast, Laxmi Basin, which is located between Laxmi Ridge and the Indian continental shelf, occupies an area of ~2.4 × 10^5 km^2 and is marked by positive gravity anomalies, implying oceanic or strongly extended continental crust. Seismic investigations suggest that Laxmi Ridge has a crustal thickness of >21 km and has continental velocity characteristics similar to those found beneath the Indian Shield (Naini and Talwani, 1982). However, the nature of the crust under Laxmi Basin, with a thickness of ~11 km, is ambiguous because it neither matches a typical continental crust nor a typical oceanic crust seismic velocity model. If the crust in Laxmi Basin is oceanic and similar in age and emplacement mechanism to the Deccan Traps, this would strongly suggest a first-order tie between plume impact and break-up. However, if continental, Laxmi Basin crust should fit in the reassembled Gondwana and could challenge the hypothesis that the eastern Arabian Sea was generated as a volcanic rifted margin linked to the Deccan Traps. Consequently, drilling into Laxmi Basin to sample and date the basement rocks is a secondary objective of this proposal, but one that has the potential to resolve both the precise timing of the break-up as well as the nature of crust across the continent/ocean boundary.

Recently, the Ministry of Earth Sciences (MoES) in India has initiated deep continental drilling (8 km deep hole) onshore in the Deccan Traps region (central western India). This project is conducted in collaboration with the International Continental Scientific Drilling Program (ICDP), and the sites lie geographically opposite to the offshore sites proposed here. The onshore sites in central India are planned to core through the Deccan Traps and the Mesozoic sedimentary rocks underneath to reach metamorphic basement. This development provides an opportunity for the scientists involved in both Expedition 355 and the ICDP drilling project to build collaborations and to create an onshore-offshore lithologic/structural correlation for improved geodynamic understanding of this region.

Geological setting

The eastern Arabian Sea presents an intriguing case for the study of continental breakup, differing in important ways from both the classic nonvolcanic Iberia-Newfoundland conjugate (e.g., Boillot et al., 1995) and the volcanic Norway-Greenland sets (e.g., Skogseid et al., 2000). Similar to the North Atlantic, the northern Arabian Sea is characterized by the presence of a large continental block located between the western continental shelf of India and deep seafloor in the Arabian Basin. This block is known as Laxmi Ridge, which is separated from the western Indian margin proper by Laxmi Basin. The oldest seafloor spreading–related magnetic anomalies are Anomaly 27n (62.2–62.5 Ma) and 28n (63.5–64.7 Ma) located south of Laxmi Ridge in the Arabian Basin and north of the Seychelles, respectively (Chaubey et al., 2002a; Royer et al., 2002). Previous studies using magnetic anomalies describe the juxtaposition of India and the Seychelles immediately before the onset of extensional tectonics; however, most plate models for this region predict a wide, deep-water offshore region (Laxmi Basin and Offshore Indus Basin) of ~300 km width between the Seychelles and the Indian subcontinent before the onset of seafloor spreading between Laxmi Ridge and the Seychelles in the Paleocene. Numerous geophysical studies carried out to investigate the nature of crust in the deep Laxmi Basin remain inconclusive, with some authors favoring the presence of rifted continental crust (Naini, 1980; Naini and Talwani, 1982; Kolla and Coumes, 1990; Miles and Roest, 1993; Miles et al., 1998; Radha Krishna et al., 2002; Krishna et al., 2006; Minshull et al., 2008), whereas others favor oceanic crust (Biswas and Singh, 1988; Bhattacharya et al., 1994; Malod et al., 1997; Talwani and Reif, 1998; Singh, 1999; Bernard and Munschy, 2000). Testing of these competing models requires direct sampling of rocks from the basement of Laxmi Ridge and Laxmi Basin.

Significant sediment cover overlies the basement of Laxmi Basin, with the oldest parts representing a postrift passive margin sequence. Since the onset of India-Eurasia collision, the Indus and its associated tributaries have been the primary drainage system for sedimentation in the Arabian Sea (Clift, 2002) and this Indus-derived sediment accounts for most of the sedimentary section we target here. Far lesser amounts are discharged from small rivers on the steep western margin of India and from the Narmada River. Much of the present Indus discharge represents run-off during the summer monsoon rains, enhanced with the seasonal melting of Karakoram and Himalayan glaciers. The Indus Fan covers more than one million square kilometers, stretching 1500 km into the Arabian Sea from the present delta front. It is the second largest submarine fan in the world and is >10 km thick at the northernmost part (Clift et al., 2001). As the proto-Indus Fan prograded southward in the late Oligocene, characteristic sediment eroded from the Indus drainage began to accumulate on the distal parts, as observed at Deep Sea Drilling Project (DSDP) Site 221 (Kolla and Coumes, 1987). The Indus appears to have experienced major drainage capture during the Miocene (Clift and Blusztajn, 2005) but has otherwise been stable within the Indus Suture and western syntaxis of the Himalaya since the Eocene. Drilling can provide erosion records through analyses of the sediment cores, as well as by providing age control for regional seismic stratigraphy. It is only by quantifying the volume of sediment deposited in the fan that we will be able to mass balance the volume eroded from the mountains as constrained by thermochronology with the volume deposited in the offshore.

Stratigraphic framework

The stratigraphic framework around the proposed sites has been developed using regional seismic lines in conjunction with industrial wells on the adjacent shelf (Fig. **F3**). The seismic stratigraphy of the Indus Fan has received attention in its upper and proximal levels (McHargue, 1991), where multiple fan channels have been identified (Deptuck et al., 2003). Droz and Bellaiche (1991) used a regional, single-channel survey to interpret the uppermost part of the sequence characterized by clear channeling and levee formation (Indus Fan Megasequence) and two lower sedimentary sequences, a “basement cover” and a simple parallel-stratified, topography-filling series, not marked by the channel levee complex of the youngest unit. The latter sequence is separated by a major unconformity from the “basement cover.” Clift et al. (2001) dated the Indus Fan Megasequence as mid-Miocene to Recent. Previous studies have imaged a mid-Miocene unconformity as a key horizon in the shelf region (Chaubey et al., 2002b; Ramaswamy and Rao, 1980; Biswas and Singh, 1988). Further, Krishna et al. (2006) confirmed the regional nature of this unconformity, showing that it runs from the shelf to the outer margin of the fan. Fan sediment is relatively thin in the area selected for drilling, with thicker deposits found locally in Laxmi Basin.

The sedimentary sequence can be divided into different units spanning the Paleocene through Pleistocene (Fig. **F4**). Thick post-Miocene strata (~1 s two-way traveltime) are observed on the profiles except over volcanic highs. The presence of channel-levee complexes in the upper fan and channels under the slope regions shows that the fan is built up by a series of overlapping lobes sourced from at least three generations of submarine canyons that predate the present bathymetric canyon (Deptuck et al., 2003). The location of the modern shelf has been a clastic delta since at least the early Miocene (Daley and Alam, 2002), although the presence of deep-marine clastic sediments on Owen Ridge and in the Makran suggests that the paleo-Indus River was connected to the deep sea well before that time but that the sediment flux greatly increased shortly after the Oligocene/Miocene boundary when the first major channel-levee complexes developed in the northern Arabian Sea (Clift et al., 2001). The proximal fan has experienced rapid sedimentation, and the stratigraphy is locally disrupted by mud volcanoes below the upper slope (Calvès et al., 2011). Carbonate ooze with a smaller component of siliceous microfossils cover the seafloor around the proposed sites because of postglacial sea level rise allowing sediment sequestration on the Indus Shelf (Clift et al., 2014). Data from nearby cores indicate that sediment in this region contains well-preserved, abundant foraminifers and diatoms (Gupta et al. 2011) giving confidence for good biostratigraphic age control in the recovered sections.

Site surveys

Sites proposed for Expedition 355 were selected based on an extensive seismic survey covering much of the eastern Arabian Sea (Fig. F5). The existing seismic grid will be further enhanced by seismic tie-lines around the proposed sites to be collected in 2014. This seismic grid will permit us to estimate the overall sediment budget and thus sediment accumulation rates after coring through the reflectors during the expedition. In addition, industrial wells on the shelf adjacent to the proposed sites, as well as previous DSDP holes, have been used to infer the lithologies we expect to encounter and to provide estimated depositional ages to the sediment packages prior to the expedition. Furthermore, we have utilized available seismic refraction, reflection, gravity, and magnetic data from this region to establish the geodynamic setting of the drill sites. High-resolution multibeam bathymetric data have also been acquired around the proposed sites (Fig. F6). Supporting site survey data for Expedition 355 are archived at the **IODP Site Survey Data Bank.**

Scientific objectives

Expedition 355 is designed to drill deep into the Indus submarine fan at three locations and to sample the underlying volcanic basement at two of these sites. The primary objective is to better understand the erosional and weathering response of the western Himalaya, Karakoram, and Hindu Kush to the changing intensity of the southwest Asian monsoon since the onset of the India-Eurasia collision in the early Paleogene (e.g., Najman et al., 2010). In doing so we aim to understand what feedbacks exist between climatic evolution, mountain building, and surface processes in the global type area for such studies. In addition, coring the basement of Laxmi Basin will allow us to date and characterize the tectonics of continental break-up and the role that mantle thermal anomalies, most notably the proposed Réunion Plume, have played in the break-up and subsequent formation of the Indian Ocean and the emplacement of the Deccan Traps. This particular event has implications for biotic mass extinction events, as well as for continental margin tectonics. Specifically, our objectives are

1. *Reconstruct long-term changes in erosion and weathering rates at submillennial to millennial timescales in order to compare with existing records of high frequency climatic variability.*

Neogene sedimentary sections from the Indus Fan record the erosional and weathering response of the Indus drainage basin to changing climate, which have already been reconstructed using speleothem (Fleitmann et al., 2003), aeolian dust (deMenocal et al., 1991; Clemens and Prell, 2003), and upwelling/productivity records (Kroon et al., 1991; Prell et al., 1992), largely from the Oman margin on the opposite side of the Arabian Sea. Attempts to understand the response of landscape to climate change in southwest Asia have largely been limited to the last glacial cycle (Bookhagen et al., 2005; Giosan et al., 2012; Alizai et al., 2012); however, our proposed deep coring will permit us to examine the changes spanning many such cycles. Weathering intensity will be reconstructed using bulk sediment geochemical analysis, selected isotope systems (such as Sr), and clay mineralogy. These measurements must be performed in concert with provenance work to establish whether any of the chemical changes could be driven by changes in source composition or drainage capture (cf., Clift and Blusztajn, 2005). Bulk sediment and single grain provenance methods, including heavy mineral studies, U-Pb dating of detrital zircons, Ar-Ar dating of detrital mica grains, and apatite fission track, represent some of the methods known to be effective in this drainage system (Clift et al., 2004, 2012; Garzanti et al., 2005) that will allow changing patterns of erosion caused by waxing and waning of the monsoon to be tracked.

Age control will be central to the success of this objective, especially if we are to estimate the lag times between climate change and the sediment record of the deep basin. This will be achieved using a combination of biostratigraphy and magnetostratigraphy. The current water depths of our proposed sites suggest that calcareous microfossils should be present through much of the section, but we also plan siliceous microfossil studies in case carbonate microfossils are missing or poorly preserved over any part of the section. Palynology, carbon isotopes, and leaf wax organic geochemical studies will provide further information on the evolving onshore landscape, as they are known to be effective in this region (Budziak et al., 2000; Ponton et al., 2012). The data from our expedition can then be correlated with existing climate records to determine links between erosion and climate on shorter timescales.

2. *Reconstruct changes in erosion and weathering intensity over tectonic timescales and assess whether any changes occurred at ~23, 15, and 10–8 Ma to test earlier hypotheses that invoke changes in monsoon intensity at those times.*

Competing hypotheses exist for the timing of initial monsoon intensification based on a variety of proxies from across Asia, with some invoking the growth of the Tibetan Plateau (Molnar et al., 1993), the rising of the Greater Himalaya (Boos and Kuang, 2010), or the retreat of shallow seas from Central Asia (Ramstein et al., 1997). Unfortunately, most of the existing climate reconstructions do not span tectonic timescales, especially the critical initiation of the Greater Himalaya along the Main Central Thrust at ~23 Ma (Catlos et al., 2001; Godin et al., 2006; Tobgay et al., 2012). Without a long-term reconstruction of monsoon intensity, it is impossible to judge what tectonic processes are responsible for the intensification. Our improved understanding of how the monsoon and erosion/weathering interact on short timescales (Objective 1) will allow us to better use the long-term record to reconstruct environmental conditions through the Cenozoic. Many tectonic models for the Himalaya link intensified erosion, driven by stronger summer monsoon rains, to the start of Greater Himalayan exhumation (Hodges, 2006; Harris, 2007; Clift et al., 2008). However, currently no well-dated erosion record spans this critical interval, so these models remain untested. Correlating changes in Himalayan-Tibetan tectonics with the marine record of erosion and weathering is the key test for these mechanisms. Changes in sediment provenance tracked by a variety of bulk and single grain proxies are needed to show the intensified erosion that is predicted during Greater Himalayan exhumation. The timing of the final unroofing of the Greater Himalaya is also poorly defined (Najman, 2006) and should be indicated by influxes of high-grade metamorphic minerals into the fan. Comparison of detrital mineral cooling ages with depositional ages will allow us to assess changing rates of exhumation in Himalayan source regions in order to see how these are linked to climate change. Combined biostratigraphic and magnetostratigraphic studies will allow the age of these changes to be fixed.

Determining the age of the base of the fan is a key objective, as this is only known in distal (and therefore young) locations at the present time (e.g., Site 221 [Shipboard Scientific Party, 1974]). Provenance methods and mass accumulation rates are expected to show when the first detritus sourced from the northern side of the Indus-Yarlung Suture Zone arrived in the Arabian Sea. This age would provide an important constraint on the much-debated timing of India-Eurasia collision (Aitchison et al., 2007; Najman et al., 2010; Wu et al., 2014). This age is of much more than simple local paleogeographic interest because it constrains how much Indian continental crust has been underthrust into the collision zone. Simple comparison of that volume with the size of the Tibetan Plateau will allow us to assess whether horizontal compression can explain all of the strain accommodation since the onset of collision (England and Houseman, 1986; Dewey et al., 1989), or if major "extrusion" of crust as rigid blocks along major strike-slip faults is needed to accommodate the impact of Greater India (Molnar and Tapponnier, 1975; Replumaz and Tapponnier, 2003).

3. *Decipher the nature of basement rocks in Laxmi Basin and constrain the timing of early seafloor spreading and the relationship to the emplacement of Deccan Flood Basalts. Does mantle plume initiation predate or postdate rifting and early spreading?*

We plan penetration of 50–100 m of basement at two sites in order to determine the nature of basement rocks and the age of their eruption. Although biostratigraphic and magnetostratigraphic analyses conducted during the expedition will provide an age for the oldest sediment overlying the basement, postcruise radiometric dating, using methods such as ^{40}Ar-^{39}Ar, will be employed to constrain the age of eruption. Because the Deccan Traps have been very precisely dated onshore (Baksi, 1994; Courtillot et al., 2000; Chenet et al., 2008), the relationship between opening of Laxmi Basin and emplacement of the Deccan Traps will be revealed. Considering that the precise timing of the rifting in Laxmi Basin is unknown (Minshull et al., 2008), the indistinct nature of the magnetic anomalies in the basin leave open the possibility that it is floored by hyperextended continental crust (Bhattacharya et al., 1994; Krishna et al., 2006). Shipboard geochemical analyses will allow the composition of the volcanic rocks to be compared with Deccan Flood Basalts or mid-ocean-ridge basalts (MORBs), which would have no linkage to a deep-seated mantle plume or other mantle compositional anomalies. Sediment overlying the basement may potentially show the subsidence of the margin, which can further be used to look at the thermal state of the mantle under Laxmi Basin during its rifting. Many rifted volcanic margins are characterized by subaerial eruption and rapid subsidence (Calvès et al., 2008). If the volcanic sequences of Laxmi Basin are linked to the Deccan Traps, then this would add significantly to their volume and thus to their potential environmental impact and role in the biotic mass extinctions at the Cretaceous/Paleogene boundary (Courtillot et al., 1988; Self et al., 2008). The timing of rifting and bathymetric evolution of Laxmi Basin also have strong implications for precise paleogeographic reconstructions of the Arabian Sea during the Paleogene (Royer et al., 2002).

Drilling and coring strategy

Proposed drill sites

Proposed Site IND-01A (alternate proposed Site IND-02B) targets the recovery of sediment that will be used to investigate the role of orbital processes in monsoon and environmental development. This site is intended to provide high-resolution weathering and erosion records on millennial timescales. Based on experience at nearby shallow core sites (Gupta et al., 2011; Singh et al., 2011), this proposed site will also provide paleoceanographic data from foraminifers hosted within the sediment. In contrast, a short transect designed to sample a continuous long-term record (proposed Sites IND-03C and IND-04A) by sampling as deep as the acoustic basement will provide information for the entire Cenozoic history of weathering and erosion within the Indus basin. These deeper sites will also elucidate the syn- and postrift history of the region. Special attention will be paid to the 25–8 Ma period, during which crucial environmental and geodynamic changes are known to have occurred. We particularly focus on the time around the initial exhumation of the Greater Himalaya (~23 Ma) in order to test the model that this was climatically triggered, as well as also reconstructing the interval at ~15 Ma during the mid-Miocene Climatic Optimum to assess the nature of the monsoon under those forcing conditions.

Drilling and coring operations

The overall operations plan and time estimates for Expedition 355 are summarized in Tables **T1** and **T2.** An alternate site has also been established and could be cored if time is available (Tables **T1, T3**). Time estimates are based on formation lithologies and depths inferred from seismic and regional interpretation. After departing Colombo, we will transit for ~3.6 days to the first site and prepare for drilling operations.

Our coring strategy will consist of advanced piston corer (APC) coring using nonmagnetic core barrels in two holes at each site to ~250 meters below seafloor (mbsf) or APC refusal. In addition, the FlexIT core orientation tool will be deployed above the core barrel during APC operations in at least the first hole (A) at each site so that the cores can be oriented. For planning purposes, APC refusal depth is estimated at 250 mbsf, although this could be exceeded at some sites. APC refusal is conventionally defined in two ways: (1) the piston fails to achieve a complete stroke (as determined from the pump pressure reading) because the formation is too hard or (2) excessive force (>60,000 lb; ~267 kN) is required to pull the core barrel out of the formation because the sediment is too cohesive or “sticky.” In cases where a significant stroke can be achieved, but excessive force cannot retrieve the barrel, the core barrel can be “drilled over” (i.e., after the inner core barrel is successfully shot into the formation, the bit is advanced to some depth to free the APC core barrel). Time permitting, the half-length APC (HLAPC) with a 4.8 m advance may be used to advance the APC total depth, although the FlexIT orientation tool cannot be used with the HLAPC. When APC refusal occurs in a hole before the target depth is reached, the extended core barrel (XCB) may be used to advance the hole.

The target depth at all primary sites is greater than the anticipated APC refusal depth. The second APC hole at each site will be advanced by XCB coring to either the total depth planned for the site (690 mbsf for proposed Site IND-01A) or to a predetermined depth of ~500–600 mbsf for the two sites with basement targets (proposed Sites IND-03C and IND-04A) (Table T2). XCB coring could be terminated before reaching the planned total depth because of XCB refusal or if the consensus is that rotary core barrel (RCB) coring will improve core recovery, core quality, and/or penetration rates. In this event, we would begin a new hole and drill down to a short distance above the total depth of the XCB hole (~10–20 m) and then begin RCB coring. This procedure is planned for proposed Site IND-04A, where a third hole will be drilled without coring to ~500 mbsf (with the upper part of the section already recovered by APC/XCB coring in the first two holes) and then RCB cored using nonmagnetic core barrels to the target depth of ~950 mbsf, which includes 50 m of basement (Table T2). The total amount of basement cored at this site may be reduced, depending on time available during the expedition and if enough basement material has been recovered to meet the scientific objectives of the expedition.

The total depth proposed for proposed Site IND-03C is ~1570 mbsf, which includes 100 m of basement. We have included a reentry system consisting of three strings of casing in our operations plan for this site to improve our chances of achieving the basement objective. Estimated depths for the three casing strings are 20 inch casing to ~60 mbsf, 16 inch casing to ~250 mbsf, and 10¾ inch casing to ~600 mbsf; however, these depths may be modified to accommodate hole conditions and lithologies encountered in previous holes at the site. In addition to the two holes that will be cored using the APC and/or XCB, an additional hole will consist of a jet-in test for the 20 inch casing string. The reentry system will be installed in the final hole at the site, which will then be RCB cored below the reentry system through the sedimentary section and into basement, with a minimum target depth of 50 m into basement (Table T2). If time is available, we plan to core ~100 m into basement.

After coring is completed at each site, holes will be conditioned, displaced with logging mud, and logged as per the logging program (see **"Downhole measurements strategy"**). At proposed Site IND-03C, two holes will be logged. The shallow section will be logged in the XCB hole (planned penetration to ~600 mbsf), with logging of the deep section (~600–1500 mbsf) below the reentry system completed in the final hole (Table T2).

Risks and contingency

There are a number of challenges associated with drilling operations in deep water that could impact the drilling and coring operations strategy of this expedition. Weather is always a potential issue, as sea state and the resulting heave can have adverse effects on drilling and coring. Although we are sailing during a reasonable weather window, the end of the expedition will overlap with the initiation of the summer monsoon season. Although this should not seriously hamper operations, the expedition could experience some weather delays depending on conditions during critical operations, such as casing and reentry system deployment and RCB basement coring.

In order to fit into the time available for operations, one of the original primary sites has been designated an alternate site (proposed Site IND-02B). Based on our operations plan, this should allow the depth objectives to be reached at the three remaining primary sites; however, installation of a reentry system with three strings of casing, followed by deep coring, could take longer than anticipated. Should this be the case, the remaining operations plan will be modified to maximize achievement of expedition objectives at the remaining sites. This could be accomplished through shallower penetration, coring at an alternate site with a shallower target, reducing the number of holes cored at the remaining sites, or a combination of these possibilities.

The significant depth of coring at proposed Site IND-03C and the basement objective at the bottom of the hole present several challenges for successful drilling. Hole stability is always a risk during coring operations and the longer the open-hole sections, the higher the risk. Casing has been planned to ~600 mbsf to mitigate the risk of hole collapse and to provide a smaller annulus for improved annular velocity for hole cleaning. Hole cleaning also becomes a problem in the deeper sections of the hole, particularly when dense basement material is cored. Additional mud sweeps with larger volumes of mud will be planned for this section. The same problems apply to proposed Site IND-04A, but no casing has been planned to achieve the depth objective at that site, as it requires penetration to only ~950 mbsf. Lower annular velocities will make hole cleaning more difficult in the deeper sections of these holes. Increasing flow rates to ensure hole cleaning could result in washed-out sections of sediment in the upper part of the hole. This can also cause hole stability problems toward the end of the drilling and logging process.

Although we do not anticipate using a free-fall funnel (FFF) for any of the expedition sites, we have the ability to deploy one to reduce the amount of time required to reach the planned objective if we are short on operational time. There are several risks associated with FFF deployment. The FFF can be dislodged while pulling out of the hole. The FFF can become buried or impossible to use for reentry. The use of the FFF leaves the open-hole section open longer, which can contribute to hole instability.

A stuck drill string is always a risk during coring operations and can consume expedition time while attempting to free the stuck drill string or, in the worst case, severing the stuck drill string. This can result in the complete loss of the hole, lost equipment, and lost time while starting a new hole. The *JOIDES Resolution* carries sufficient spare drilling equipment to enable the continuation of coring, but the time lost to the expedition can be significant.

Downhole measurements strategy

Wireline logging

The downhole measurements plan for Expedition 355 aims to provide continuous stratigraphic coverage of in situ formation properties at all three primary drilling sites over both the sedimentary and basement sections. Downhole logging data will provide the only stratigraphic data where core recovery is incomplete, which is likely when sites are single-cored with XCB and RCB coring. The logging thus represents an essential data set for the fulfillment of the scientific objectives.

The two standard IODP tool strings will be deployed at each logged site, with an additional tool string deployed at proposed Site IND-03C if conditions and time permit (Table T2). The first run will be the triple combination (triple combo) tool string, which logs formation resistivity, density, porosity, natural gamma radiation (NGR), and borehole diameter. The General Purpose Inclinometry Tool (GPIT) will be added to the triple combo tool string because it includes a fluxgate magnetometer that can provide information on the magnetization of the basement rocks, which may be significant for constraining the age of formation. If available, the Lamont-Doherty magnetic susceptibility sonde will also be added to the triple combo tool string to provide magnetic field and susceptibility information for both the sedimentary and basement sections. The borehole diameter log provided by the caliper on the density tool will allow assessment of hole conditions (e.g., wash-outs of sandy beds), log quality, and the potential for success of the following runs.

The second logging run will be the Formation MicroScanner (FMS)-sonic tool string, which provides an oriented resistivity image of the borehole wall and logs of formation acoustic velocity, NGR, GPIT magnetometry, and borehole diameter. To provide a link between borehole stratigraphy and the seismic section, sonic velocity and density data will be combined to generate synthetic seismograms for detailed well-seismic correlations. If hole conditions allow, a third run at proposed Site IND-03C will consist of a check shot survey using the Versatile Seismic Imager (VSI), with a station spacing of ~100 m where the borehole diameter is narrow enough to give good coupling of the tool's geophone with the borehole wall. The objective would be to directly establish the link between lithostratigraphic depths in the borehole and reflectors in the seismic profiles. The seismic source for the check shots will be a generator-injector air gun, and its deployment is subject to the IODP marine mammal policy; the check shot survey would have to be postponed or canceled if policy conditions are not met. Details of the logging tools are available at **iodp.ldeo.columbia.edu/TOOLS_LABS/tools.html.**

Downhole temperature measurements

Temperature measurements are planned for all sites with APC coring to reconstruct the thermal gradient at each location. Typically, ~3–5 measurements are made at one hole per site using the advanced piston corer temperature tool, potentially supplemented by the sediment temperature tool if necessary where sediments are more consolidated.

Risk and contingency

Any logging operations involve a number of potential risks. First, the upper parts of the holes will have been open longer before logging, and high levels of fluid circulation will have been used to raise the cuttings and clear the hole, particularly in the sites that penetrate to dense basement material. Therefore, the hole could be washed out (wide) over intervals through unlithified sediment, and log quality will be reduced for those tools that need good contact with the borehole wall (density, porosity, FMS resistivity images, and VSI check shots). Secondly, there is a risk of bridging where the hole closes up. This would mean either not reaching the total depth of the hole or, in the worst case scenario, getting a tool string stuck in the hole. A good guide for this will be the conditions encountered during drilling and a wiper trip before logging. If the risk is considered to be significant, the radioactive source will be left out of the density tool.

Sampling and data sharing strategy

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 to research scientists, curators, and educators. The document also defines the obligations that sample and data recipients incur. The Sample Allocation Committee (SAC) must approve all requests for core samples and data. The SAC is composed of the Co-Chief Scientists, Expedition Project Manager, and the IODP Curator onshore or curatorial representative on board the ship. The SAC will work with the entire scientific party to formulate a formal expedition-specific sampling plan for shipboard and postexpedition sampling.

Every member of the science party is obligated to carry out scientific research for the expedition and publish the results. For this purpose, shipboard and shore-based scientists are expected to submit both a research plan and sample and/or data request using the Sample and Data Request system (**iodp.tamu.edu/sdrm/**) at least three months before the beginning of the expedition. Based on shipboard and shore-based research plans submitted by this deadline, the SAC will prepare a tentative sampling plan, which will be revised on the ship as dictated by recovery and cruise objectives. The sampling plan will be subject to modification depending upon the actual material recovered and collaborations that may evolve between scientists during the expedition. Great care will be taken to maximize shared sampling to promote integration of data sets and enhance scientific collaboration among members of the scientific party so that our scientific objectives are met and each scientist has the opportunity to contribute.

All sample frequencies and sizes must be justified on a scientific basis and will depend on core recovery, the full spectrum of other requests, and the expedition objectives. 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. Substantial collaboration and cooperation are highly encouraged.

Shipboard sampling will be restricted to acquiring ephemeral data types and shipboard measurements, as well as limited low-resolution sampling for personal research at the discretion of the SAC. The data collected will be used to produce an age model that is critical to the overall objectives of the expedition and for planning for higher resolution sampling postcruise. Whole-round samples may be taken for interstitial water measurements, microbiology, and physical property measurements. High-resolution sampling for personal research will be postponed until a shore-based sampling party that will be implemented approximately four months after the end of the expedition at the Kochi Core Center in Kochi, Japan.

If some critical intervals are recovered, there may be considerable demand for samples from a limited amount of cored material. These intervals may require special handling, a higher sampling density, reduced sample size, or continuous core sampling for the highest priority research objectives. The SAC may require an additional formal sampling plan before critical intervals are sampled and a special sampling plan will be developed to maximize scientific participation and to preserve some material for future studies. The SAC can decide at any stage during the expedition or during the moratorium period which recovered intervals should be considered critical.

Following Expedition 355, cores will be delivered to the IODP Kochi Core Center in Kochi, Japan. All collected data and samples will be protected by a one year moratorium period following the completion of the postcruise sampling meeting, during which time data and samples will be available only to the Expedition 355 science party and approved shore-based participants. The SAC must approve modifications to the sampling strategy during the expedition and the one-year postexpedition moratorium period.

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Table T1. Primary and alternate proposed sites, Expedition 355.

Site	Latitude	Longitude	Water depth (m)	Sediment penetration (m)	Basement penetration (m)	Total penetration depth (mbsf)	EPSP approval	Estimated basal sediment age
Primary:								
IND-01A	17°47.6100′N	67°59.7480′E	3461	690	0	690	750 mbsf	Miocene
IND-03C	16°37.2858′N	68°50.3376′E	3630	1470	100*	1570	Basement + 200 m	Eocene
IND-04A	16°36.8820′N	69°21.5100′E	3622	900	50	950	Basement + 200 m	Eocene
Alternate:								
IND-02B	17°53.8656′N	68°43.1328′E	3431	580	0	580	5.4 s TWT (629 mbsf)	Miocene

* = 50 m basement penetration currently in operations plan, but 100 m penetration desired. TWT = two-way traveltime.

Table T2. Operations plan for primary proposed sites, Expedition 355.

Expedition 355 (P793-CPP) Arabian Sea Monsoon

Operations Plan Summary & Schedule

Site No.	Location (Latitude Longitude)	Seafloor Depth (mbrf)	Operations Description	Transit (days)	Drilling Coring (days)	WL Log (days)
Colombo, Sri Lanka			**Begin Expedition** 5.0 Port Call Days			
			Transit ~904 nmi to IND-03C @ 10.5	**3.6**		
IND-03C	**16° 37.2858' N**	**3641**	**Hole A - APC to 250 mbsf with orientation and APCT-3 Measurements**		**1.9**	
EPSP to	**68° 50.3376' E**		**Hole B - Jet-in Test**		**0.6**	
basement			**Hole C - APC/XCB to 600 mbsf - Log with Triple Combo and FMS Sonic**		**4.4**	**1.3**
+ 200 m			**Hole D - Reentry system, RCB core from 600 mbsf to 1520 mbsf**		**19.0**	**1.8**
			(incl 50 m* of basement & WL logging with Triple Combo, FMS-sonic, & VSI)			
			***Note: 100 m of basement penetration is desired**			
			Sub-Total Days On-Site: 29.0			
			Transit ~30 nmi to IND-04A @ 10.5	**0.1**		
IND-04A	**16° 36.8820' N**	**3633**	**Hole A - APC to 250 mbsf with orientation and APCT-3 Measurements**		**2.1**	
EPSP to	**69° 21.5100' E**		**Hole B - APC/XCB to 500 mbsf**		**3.5**	
basement			**Hole C - Drill down to 490 mbsf, RCB to 950 mbsf**		**6.1**	**1.8**
+ 200 m			**(incl 50 m of basement & WL logging with Triple Combo & FMS-sonic)**			
			Sub-Total Days On-Site: 13.6			
			Transit ~82 nmi to IND-01A @ 10.5	**0.4**		
IND-01A	**17° 47.6100' N**	**3472**	**Hole A - APC to 250 mbsf with orientation and APCT-3 Measurements**		**1.9**	
EPSP to	**67° 59.7480' E**		**Hole B - APC/XCB to 690 mbsf**		**4.9**	**1.4**
750 mbsf			**(incl WL logging with Triple Combo & FMS-sonic)**			
			Sub-Total Days On-Site: 8.2			
			Transit ~284 nmi to Mumbai @ 10.5	**1.1**		
Mumbai, India			**End Expedition**	**5.3**	**44.4**	**6.3**

Port Call:	**5.0**	**Total Operating Days:**	**56.0**
Sub-Total On-Site:	**50.8**	**Total Expedition:**	**61.0**

EPSP = Environmental Protection and Safety Panel. APC = advanced piston corer, XCB = extended core barrel, RCB = rotary core barrel, APCT-3 = advanced piston corer temperature tool, triple combo = triple combination, FMS = Formation MicroScanner, WL = wireline, VSI = Versatile Seismic Imager.

Table T3. Operations plan for alternate proposed site, Expedition 355.

Site No.	Location (Latitude Longitude)	Seafloor Depth (mbrf)	Operations Description	Transit (days)	Drilling Coring (days)	WL Log (days)
IND-02B	17° 53.8656' N	3442	Hole A - APC to 250 mbsf with orientation and APCT-3 Measurements		1.9	0.0
EPSP to	68° 43.1328' E		Hole B - APC/XCB to 580 mbsf		4.3	1.3
629 mbsf			(incl WL logging with Triple Combo & FMS-sonic)			
			Sub-Total Days On-Site: 7.5			

EPSP = Environmental Protection and Safety Panel. APC = advanced piston corer, XCB = extended core barrel, RCB = rotary core barrel, APCT-3 = advanced piston corer temperature tool, triple combo = triple combination, FMS = Formation MicroScanner, WL = wireline, VSI = Versatile Seismic Imager.

Figure F1. Major physiographic features in the Arabian Sea and adjoining areas. The existing Deep Sea Drilling Project and Ocean Drilling Program locations are marked with red stars. Expedition 355 proposed drill sites lie in the Laxmi Basin area. Yellow circles = primary sites, white circle = alternate site.

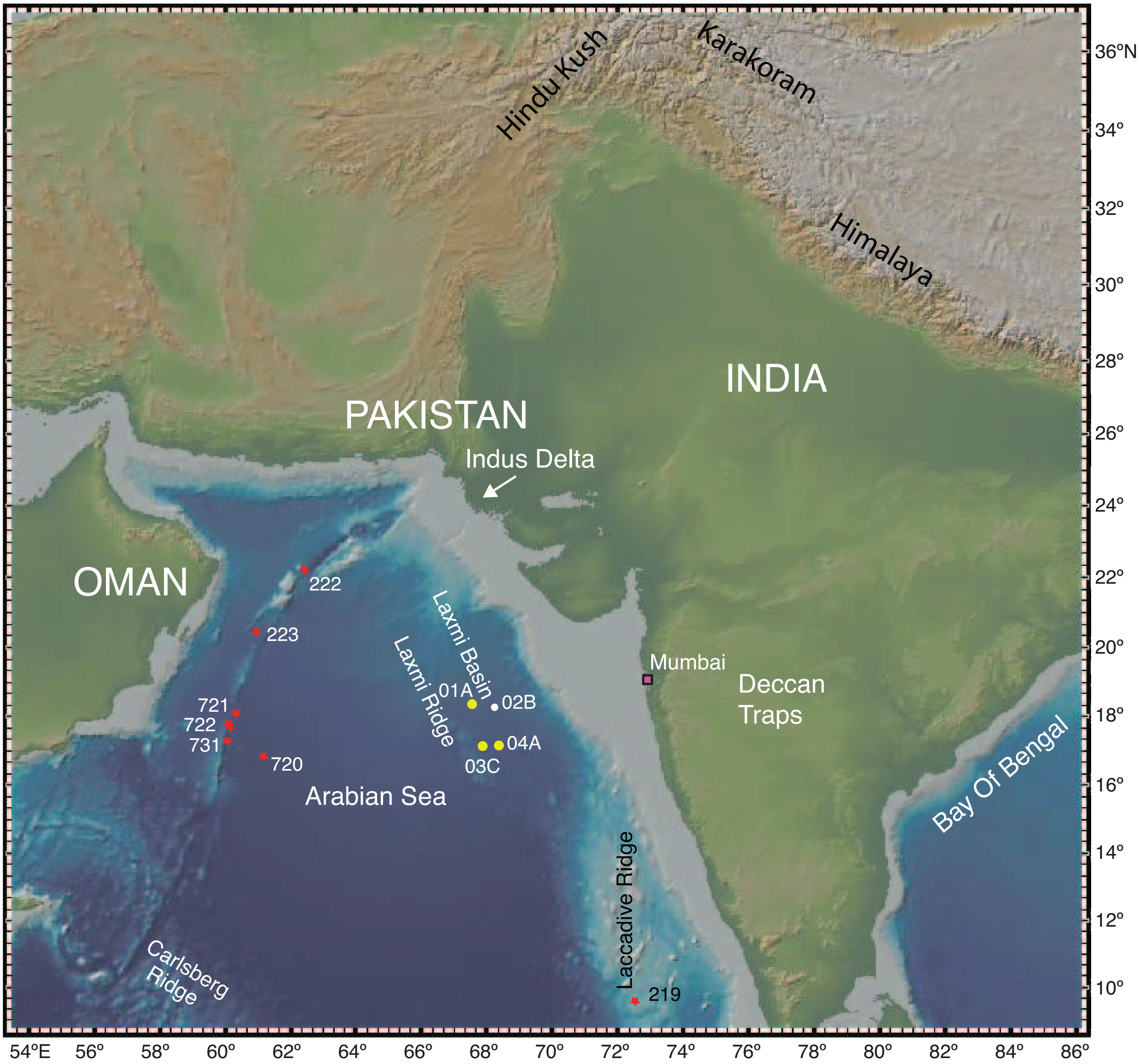


Figure F2. Schematic model showing the influence of plateau uplift on monsoons. Monsoon rains cause focused erosion in the Himalaya and this in turn drives exhumation patterns and controls the orogenic structure. Sediment eroded from the mountain front forms the submarine fans of the Indian Ocean. STD = South Tibetan Detachment, MCT = Main Central Thrust, MBT = Main Boundary Thrust.

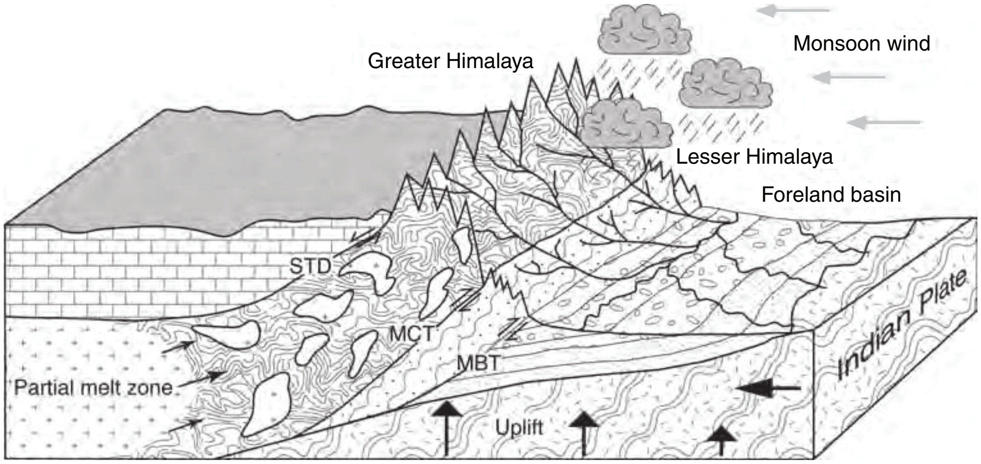


Figure F3. Multichannel seismic grid map in the eastern Arabian Sea. Solid blue circles represent industry wells. Green stars represent locations of shallow cores from published studies (ABP-25: Gupta et al., 2011; 2491, J7, 2506, 3268G5: Bhushan et al., 2001; SK17/MD76-131: Singh et al., 2011). Red stars represent Expedition 355 proposed primary sites. Yellow star represents proposed alternate site. Blue shaded area indicates high-resolution multibeam bathymetry shown in Figure F6. RS = Raman Seamount, PS = Panikkar Seamount, WG = Wadia Guyot.

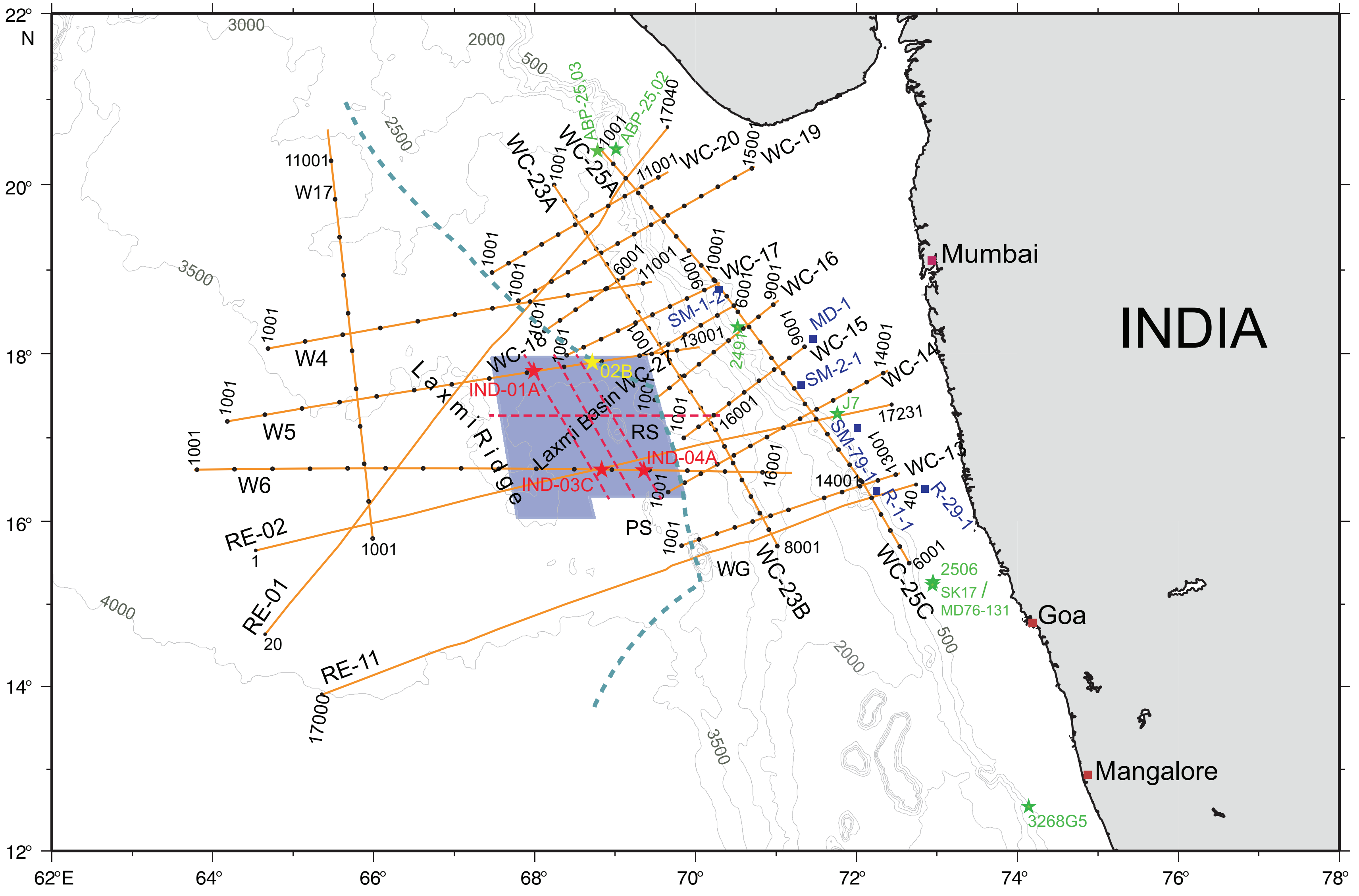


Figure F4. Uninterpreted (top) and interpreted (bottom) seismic sections with Expedition 355 proposed drill sites (see Fig. **F3** for seismic line locations). Solid orange line = primary site, dashed orange line = alternate site. TWT = two-way traveltime. **A.** Line W-05. (Continued on next page.)

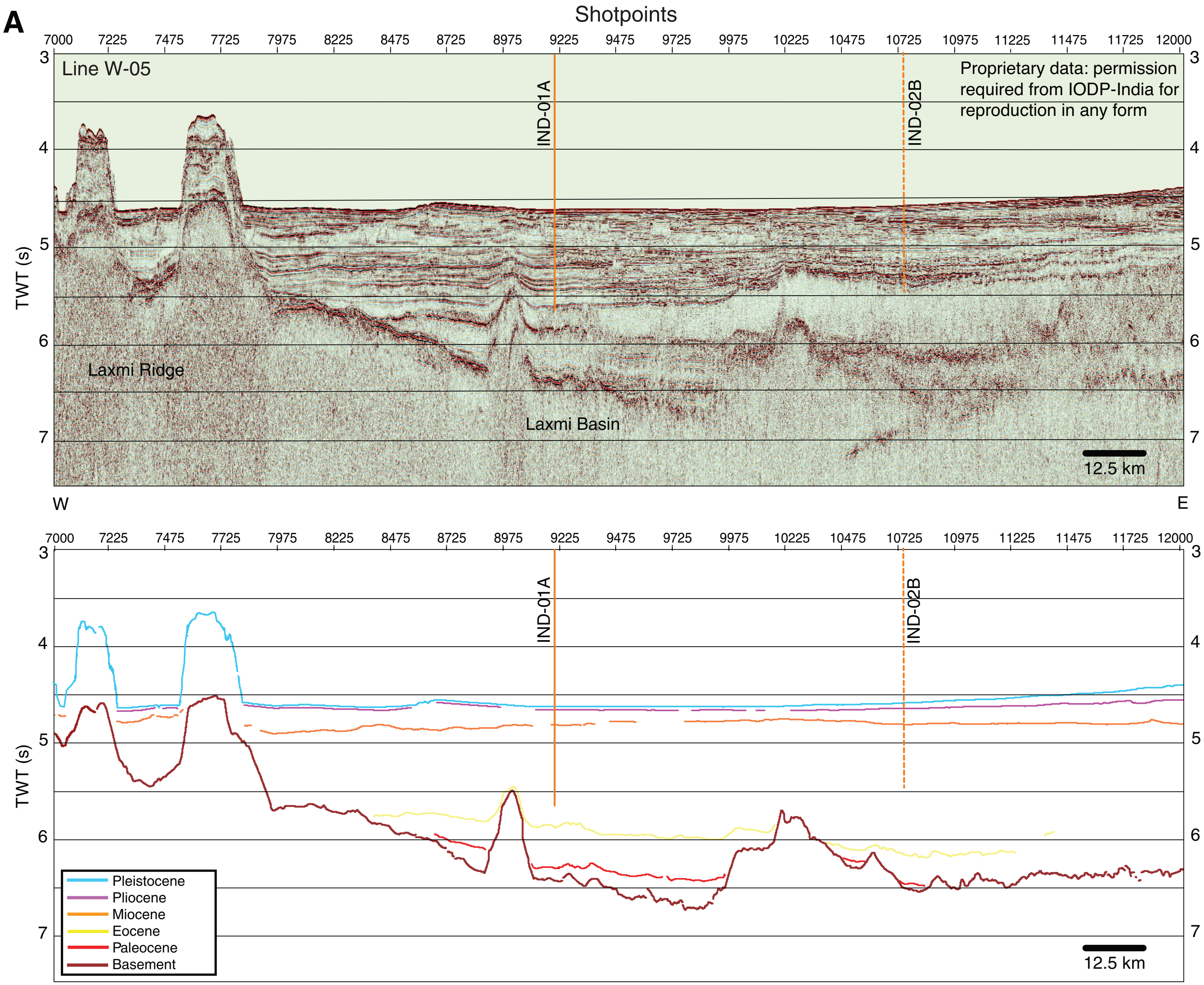


Figure F4 (continued). B. Line W-06.

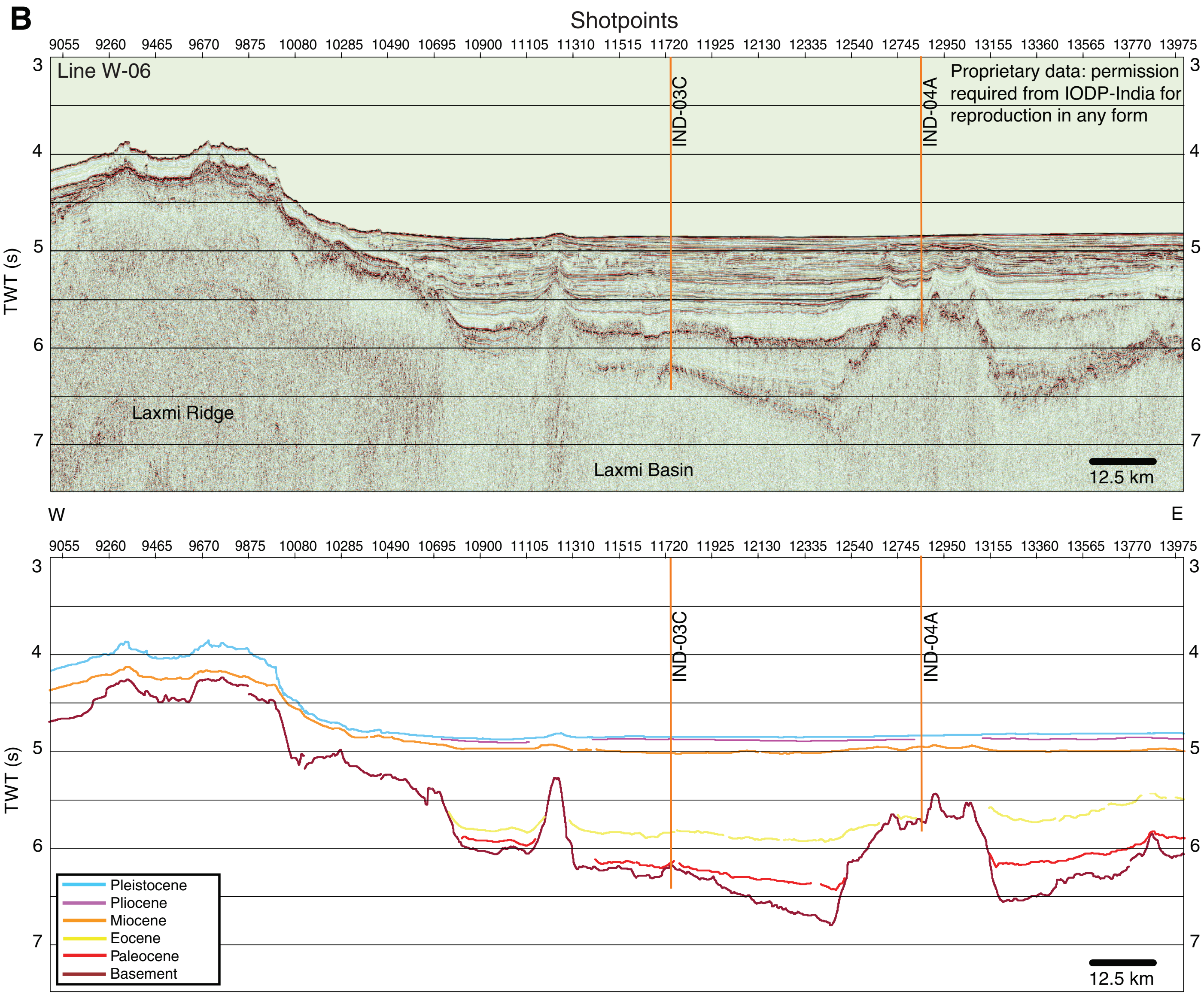


Figure F5. Locations of all seismic profiles acquired by the Ministry of Earth Sciences in the Arabian Sea. The proposed locations for Expedition 355 drilling are on Lines W-05 and W-06.

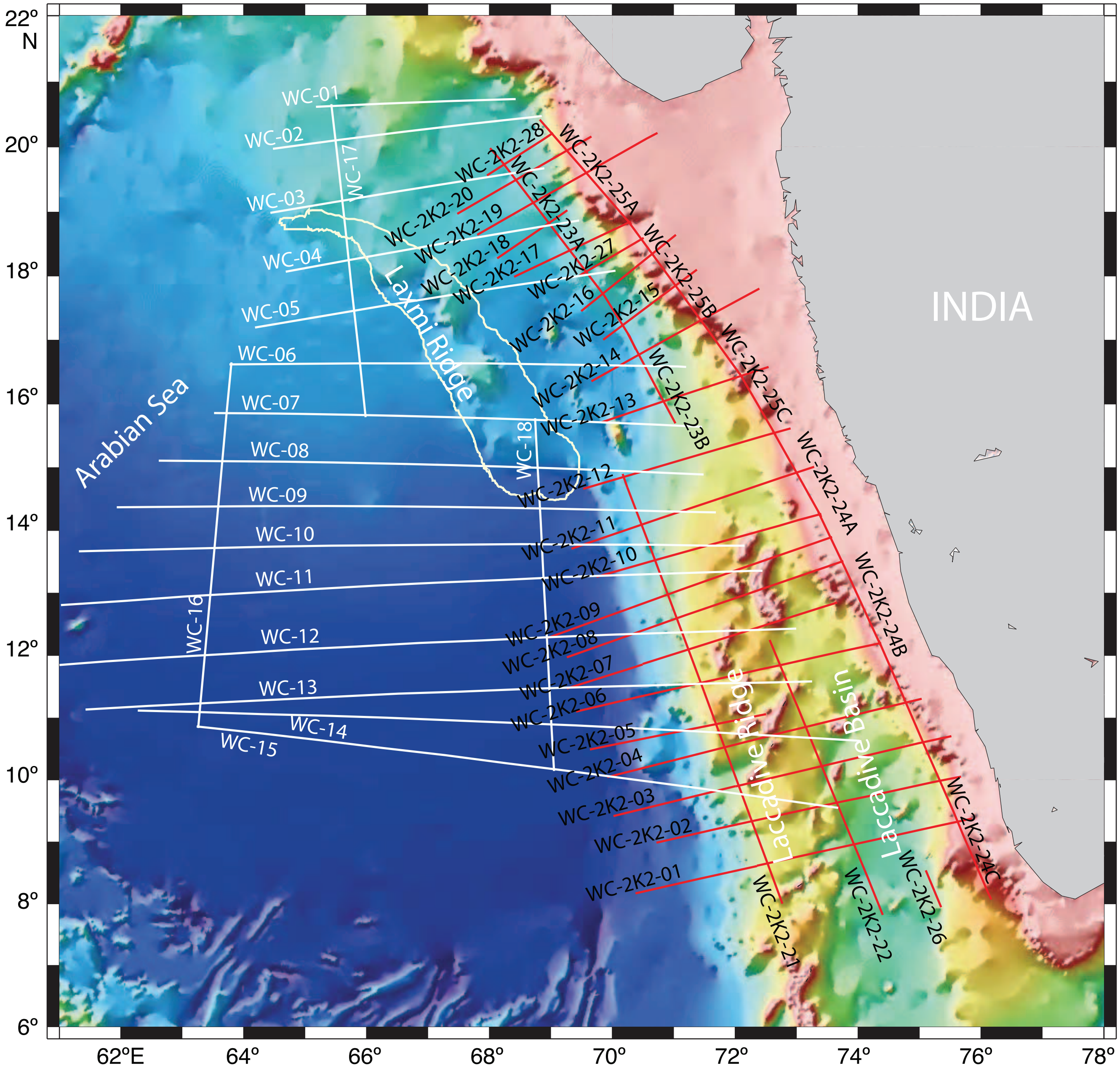
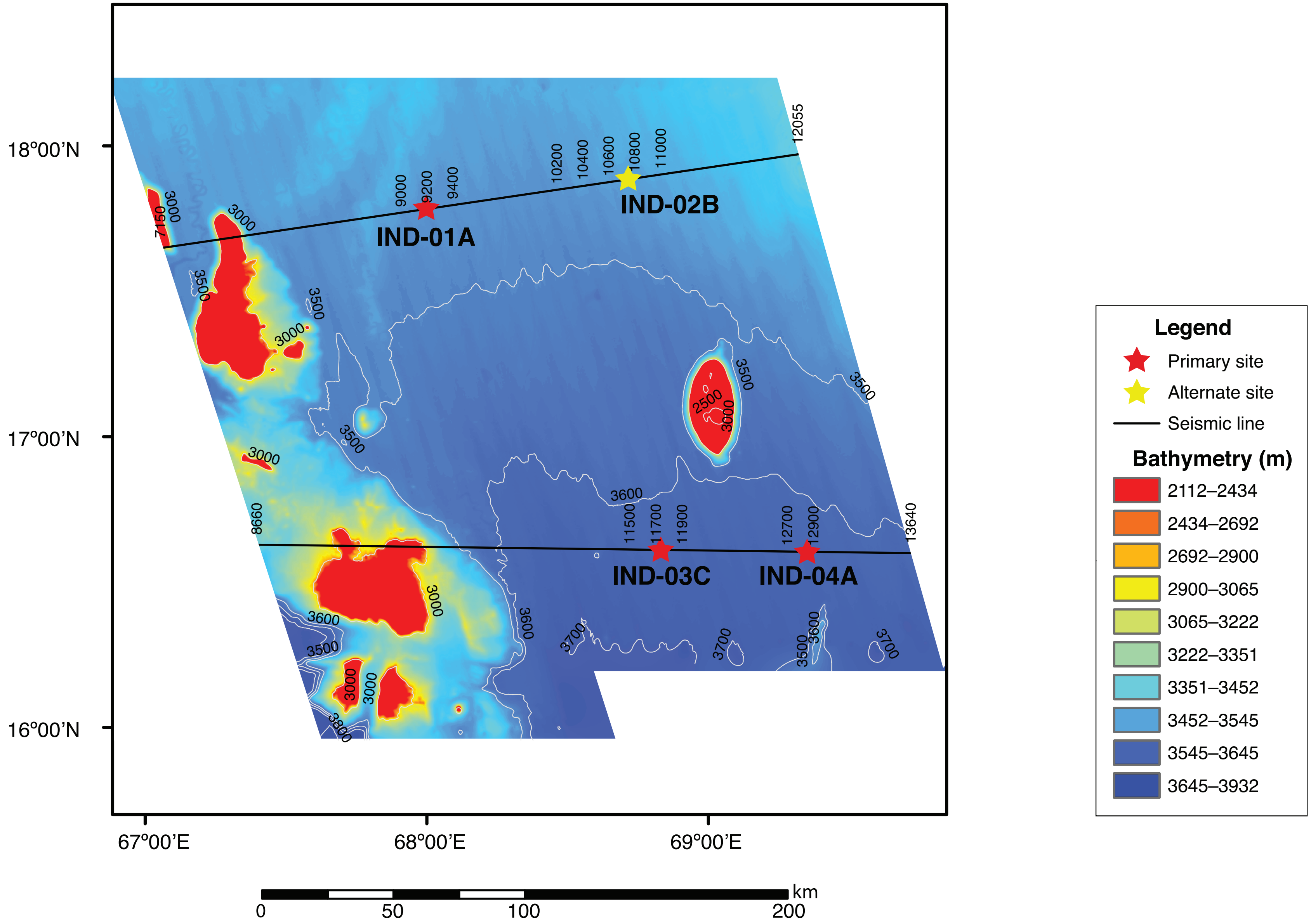


Figure F6. Map showing high-resolution multibeam bathymetry data acquired around the Expedition 355 proposed drill sites.



Site summaries

Site IND-01A

Priority:	Primary
Position:	17°47.6100′N, 67°59.7480′E
Water depth (m):	3461
Target drilling depth (mbsf):	690
Approved maximum penetration (mbsf):	750
Survey coverage (track map; seismic profile):	Bathymetric sketch and site track map (Fig. **AF1**) Deep-penetration seismic reflection: • Primary line: W-05 (SP 9200) (Fig. **AF2**)
Objectives:	• Reconstruct changes in erosion and weathering rates at millennial to sub-millennial timescales
Drilling program:	Hole A: • APC to refusal with nonmagnetic core barrels, core orientation (FlexIT tool), and APCT-3 Hole B: • APC to refusal with nonmagnetic core barrels • XCB to 690 mbsf
Downhole logging program:	Hole B: • Triple combo • FMS-sonic
Nature of rock anticipated:	Siltstone, sandstone, shale

Site summaries (continued)

Site IND-02B

Priority:	Alternate
Position:	17°53.8656′N, 68°43.1328′E
Water depth (m):	3431
Target drilling depth (mbsf):	580
Approved maximum penetration:	5.4 s TWT (629 mbsf)
Survey coverage (track map; seismic profile):	Bathymetric sketch and site track map (Fig. **AF3**) Deep-penetration seismic reflection: • Primary line: W-05 (SP 10750) (Fig. **AF4**)
Objectives:	Alternate for IND-01A • Reconstruct changes in erosion and weathering rates at millennial to sub-millennial timescales
Drilling program:	Hole A: • APC to refusal with nonmagnetic core barrels, core orientation (FlexIT tool), and APCT-3 Hole B: • APC to refusal with nonmagnetic core barrels • XCB to 580 mbsf
Downhole logging program:	Hole B: • Triple combo • FMS-sonic
Nature of rock anticipated:	Siltstone, sandstone, shale

Site summaries (continued)

Site IND-03C

Priority:	Primary
Position:	16°37.2858′N, 68°50.3376′E
Water depth (m):	3630
Target drilling depth (mbsf):	1570
Approved maximum penetration:	Basement + 200 m
Survey coverage (track map; seismic profile):	Bathymetric sketch and site track map (Fig. **AF5**) Deep-penetration seismic reflection: • Primary line: W-06 (SP 11741) (Fig. **AF6**)
Objectives:	• Reconstruct changes in weathering and erosion rates over tectonic timescales • Ascertain the nature of basement rocks in the Laxmi Basin • Constrain velocity variations with depth within sedimentary and basement layers
Drilling program:	Hole A: • APC to refusal with nonmagnetic core barrels, core orientation (FlexIT tool), and APCT-3 Hole B: • Jet-in test Hole C: • APC to refusal with nonmagnetic core barrels • XCB to 600 mbsf Hole D: • Reentry system (20, 16, and 10¾ inch casing to ~600 mbsf) • RCB core with nonmagnetic core barrels to 1570 mbsf (includes 100 m of basement)
Downhole logging program:	Hole C: • Triple combo • FMS-sonic Hole D: • Triple combo • FMS-sonic • VSI
Nature of rock anticipated:	• Siltstone, sandstone, shale, basalt

Site summaries (continued)

Site IND-04A

Priority:	Primary
Position:	16°36.8820′N, 69°21.5100′E
Water depth (m):	3622
Target drilling depth (mbsf):	950
Approved maximum penetration:	Basement + 200 m
Survey coverage (track map; seismic profile):	Bathymetric sketch and site track map (Fig. **AF7**) Deep-penetration seismic reflection: • Primary line: W-06 (SP 12875) (Fig. **AF8**)
Objectives:	• Reconstruct changes in weathering and erosion rates over tectonic timescales • Examine linkage between basement samples and Deccan Traps volcanism • Constrain paleogeographic reconstructions and continental break-up
Drilling program:	Hole A: • APC to refusal with nonmagnetic core barrels, core orientation (FlexIT tool), and APCT-3 Hole B: • APC to refusal with nonmagnetic core barrels • XCB to 500 mbsf Hole C: • Drill down to 490 mbsf • RCB with nonmagnetic core barrels to 950 mbsf (includes 50 m of basement)
Downhole logging program:	Hole C: • Triple combo • FMS-sonic
Nature of rock anticipated:	Siltstone, sandstone, shale, basalt, granite

Figure AF1. Contoured bathymetric map showing seismic reflection profile Line W-05 (Fig. AF2) and the location of proposed primary Site IND-01A.

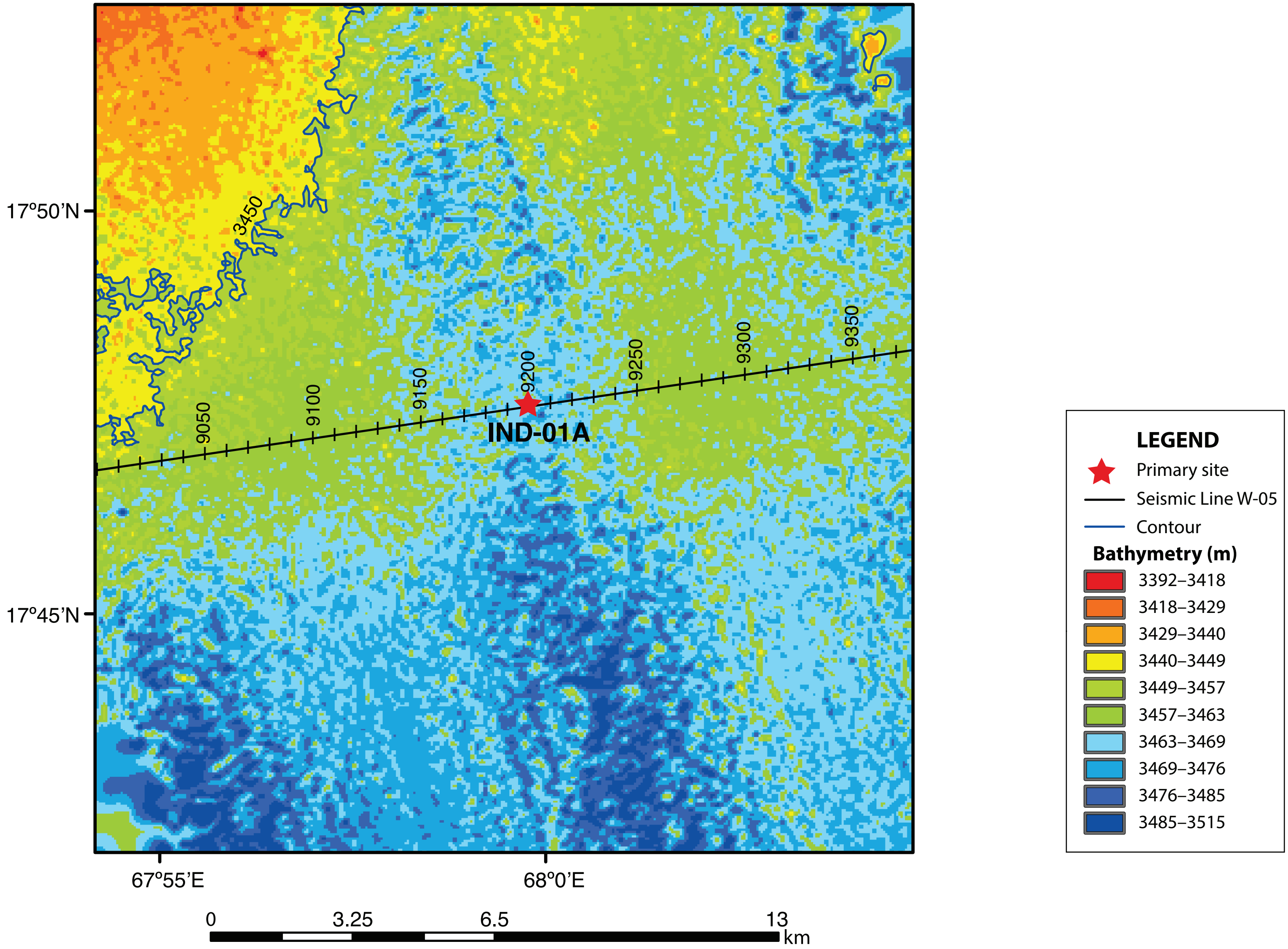


Figure AF2. Seismic profile Line W-05 (west–east) with location of proposed primary Site IND-01A (17°47.6100′N, 67°59.7480′E; shotpoint [SP] 9200; water depth = 3461 m; target depth = 690 mbsf). CDP = common depth point. IODP = International Ocean Discovery Program.

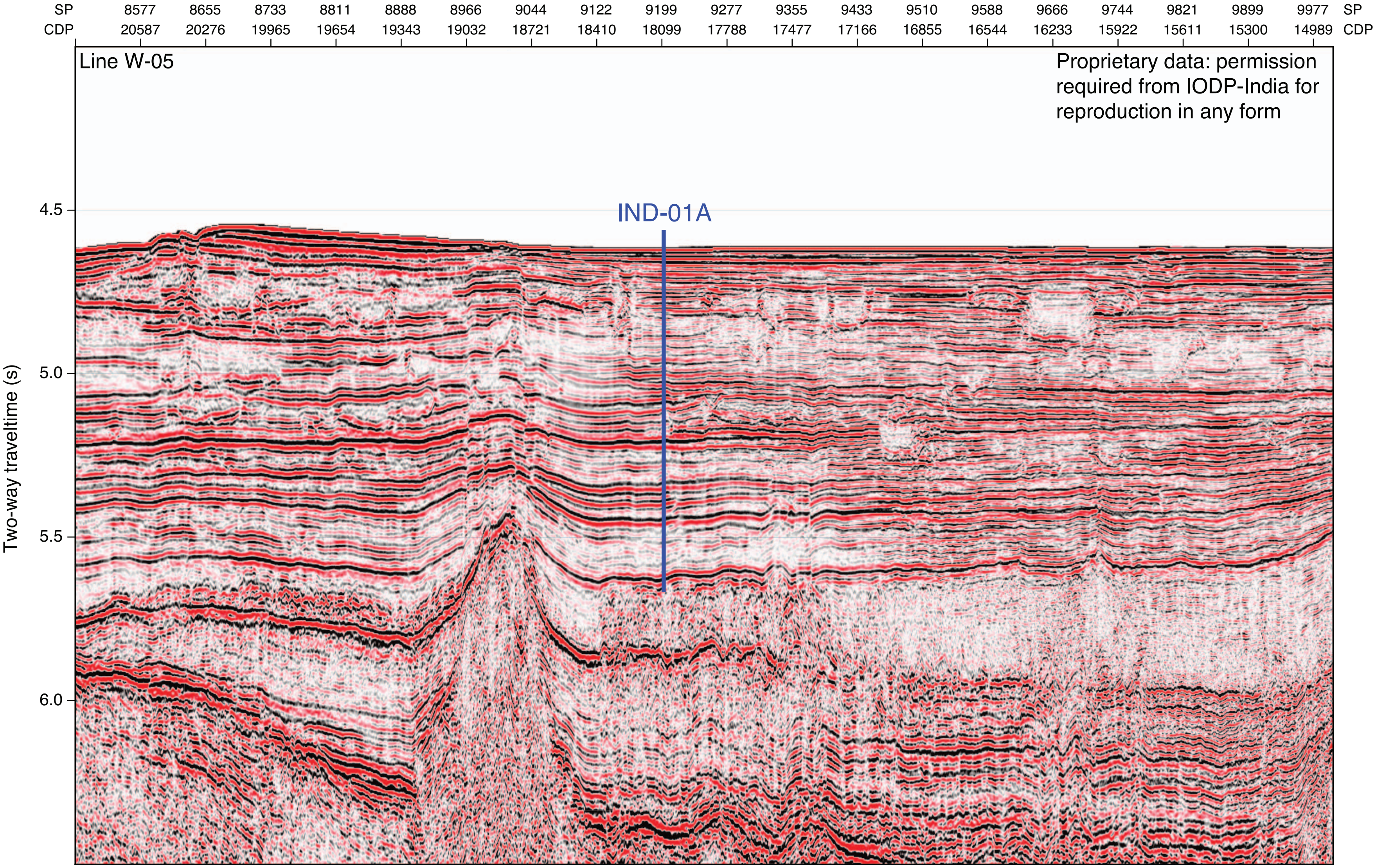


Figure AF3. Contoured bathymetric map showing seismic reflection profile Line W-05 (Fig. AF4) and the location of proposed alternate Site IND-02B.

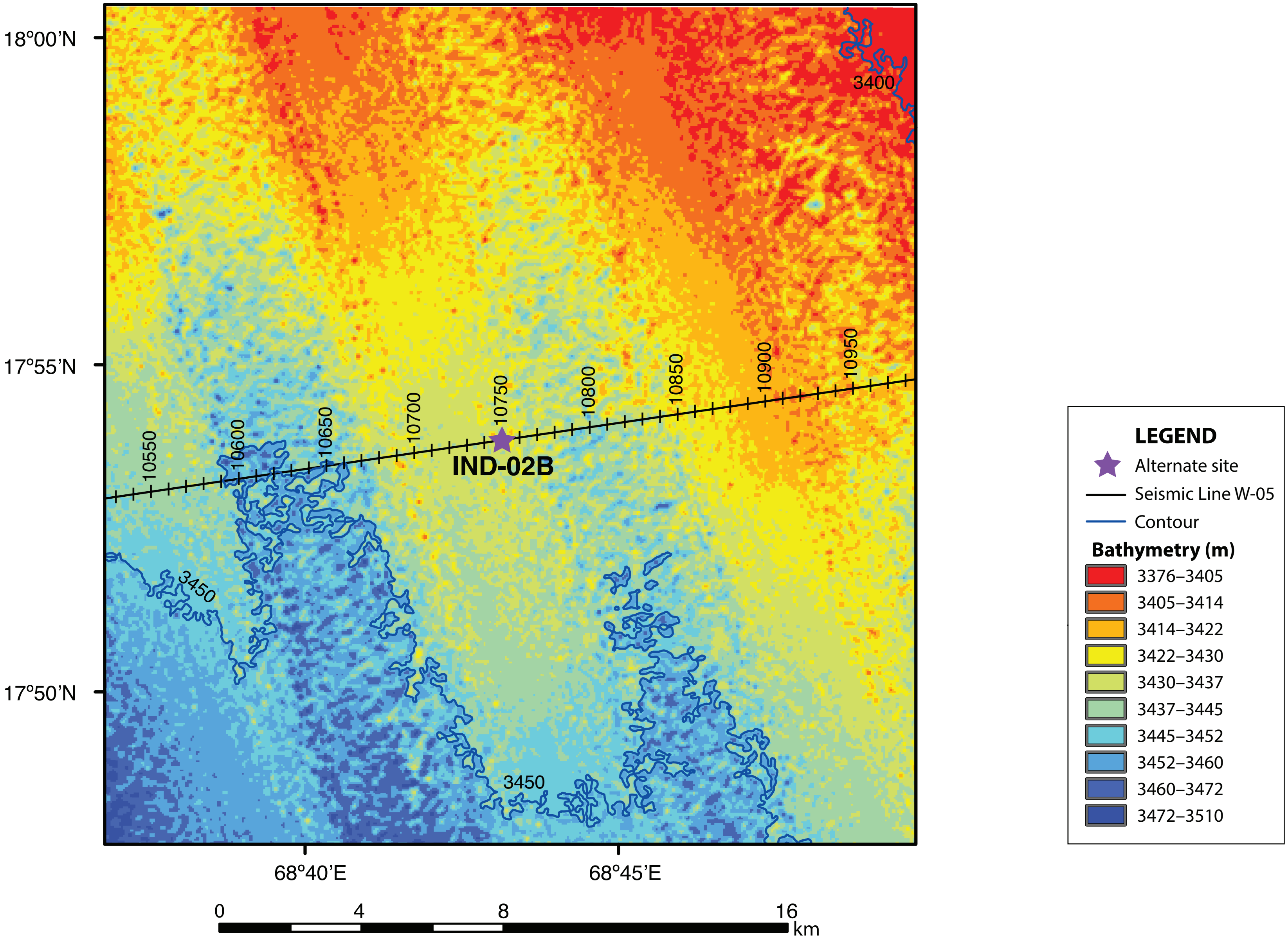


Figure AF4. Seismic profile Line W-05 (west–east) with location of proposed alternate Site IND-02B (17°53.8656′N, 68°43.1328′E; shotpoint [SP] 10750; water depth = 3431 m; target depth = 580 mbsf). CDP = common depth point. IODP = International Ocean Discovery Program.

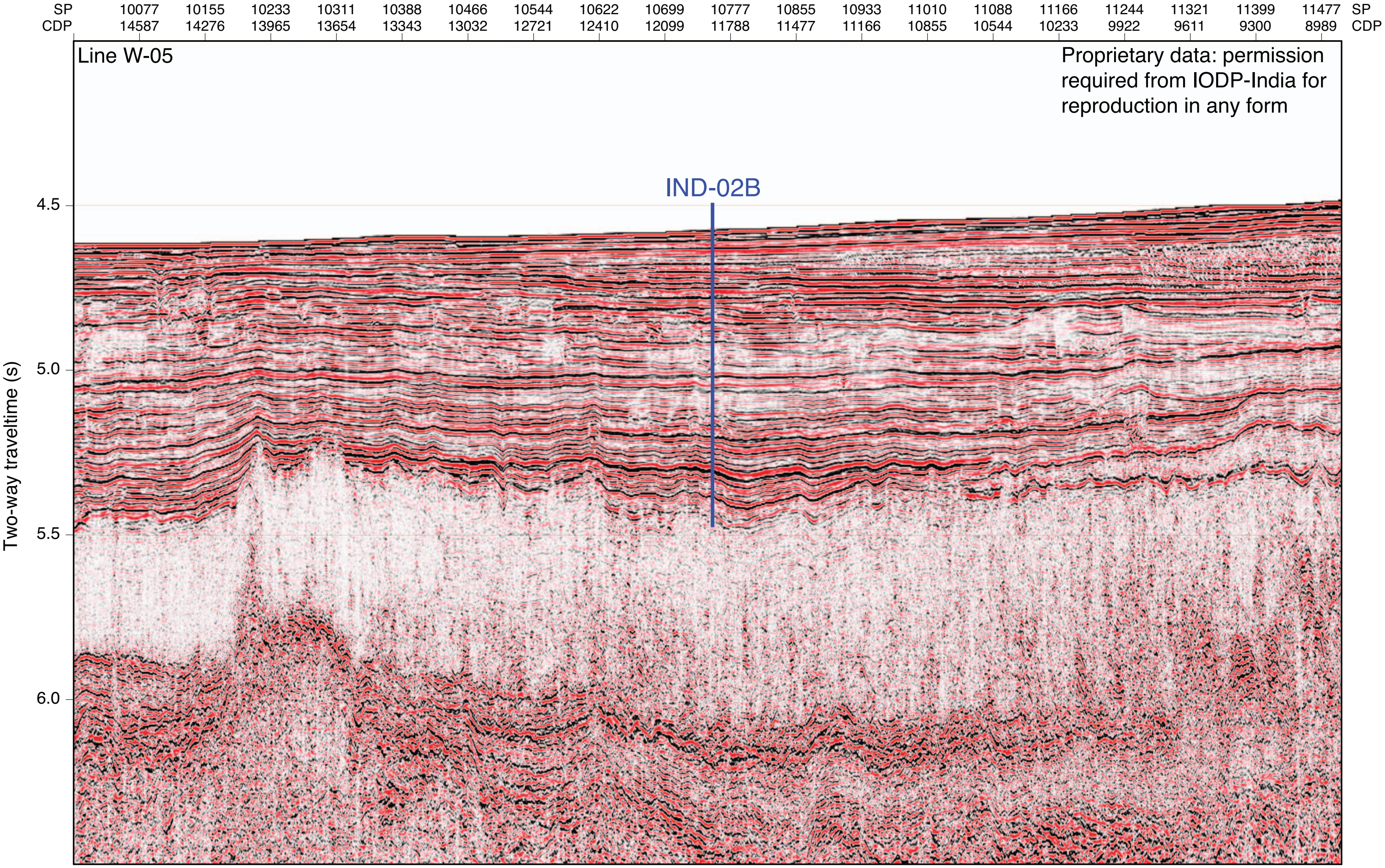


Figure AF5. Contoured bathymetric map showing seismic reflection profile Line W-06 (Fig. AF6) and the location of proposed primary Site IND-03C.

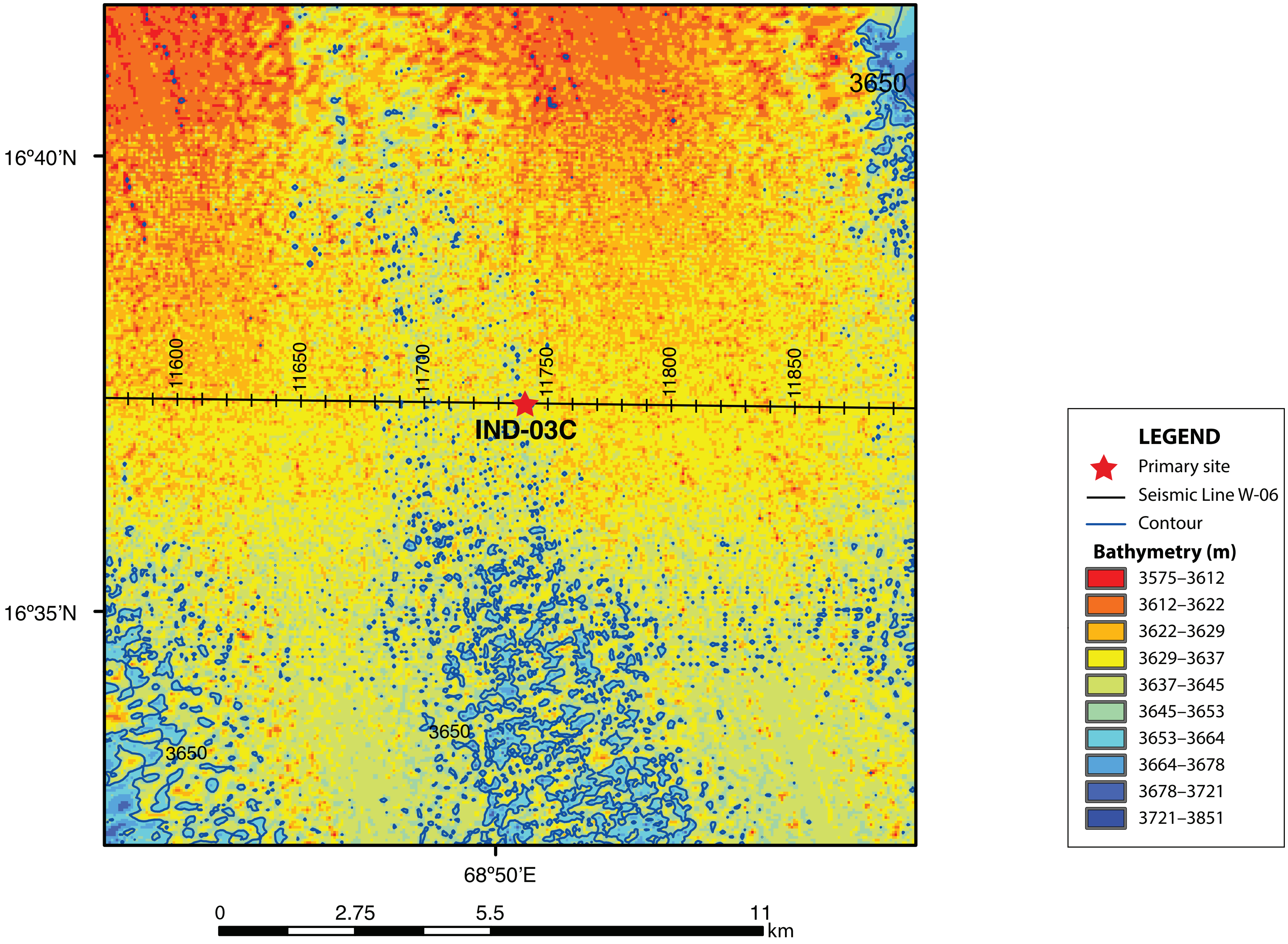


Figure AF6. Seismic profile Line W-06 (west–east) with location of proposed primary Site IND-03C (16°37.2858′N, 68°50.3376′E; shotpoint [SP] 11741; water depth = 3630 m; target depth = 1570 mbsf). CDP = common depth point. IODP = International Ocean Discovery Program.

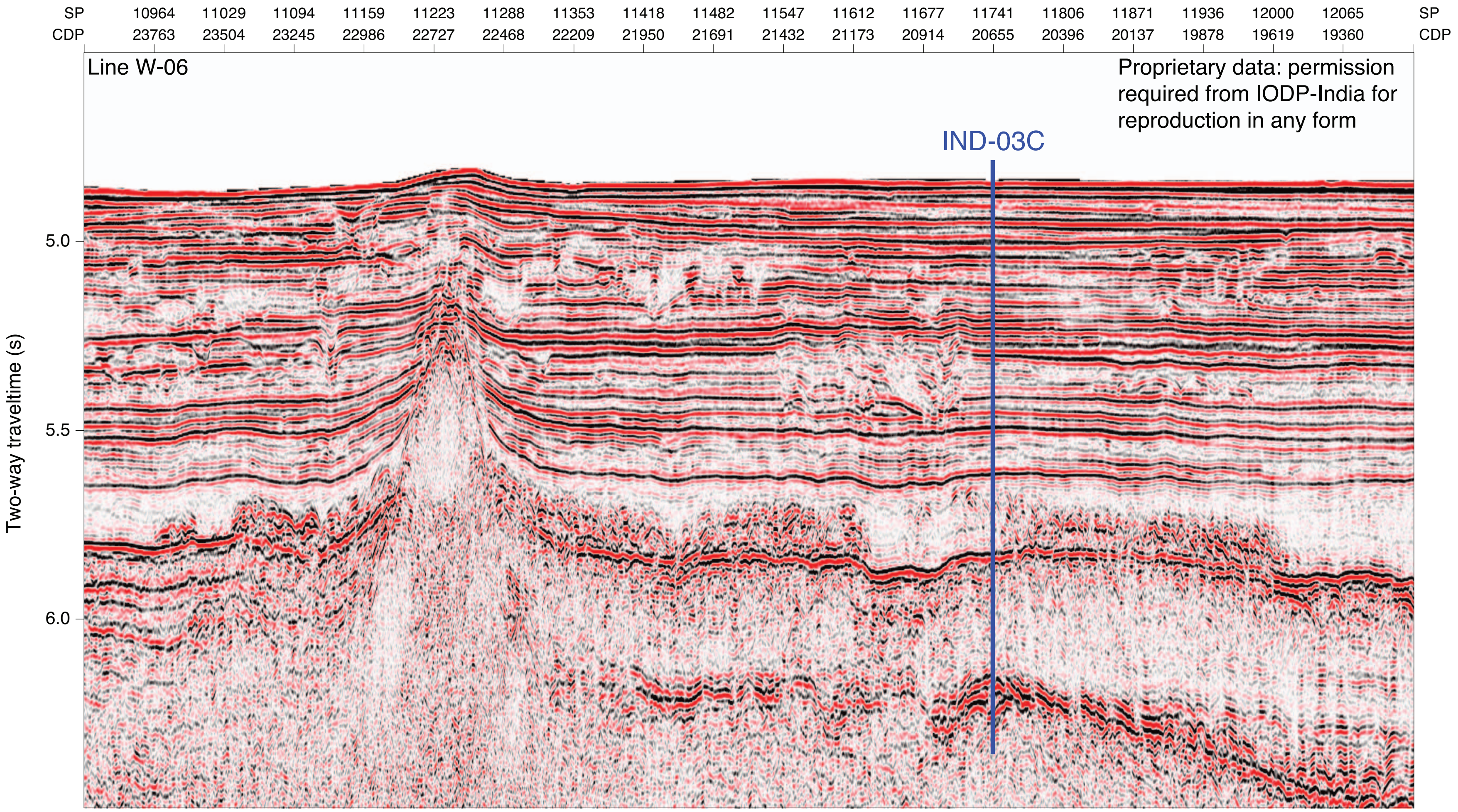


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Figure AF7. Contoured bathymetric map showing seismic reflection profile Line W-06 (Fig. AF8) and the location of proposed primary Site IND-04A.

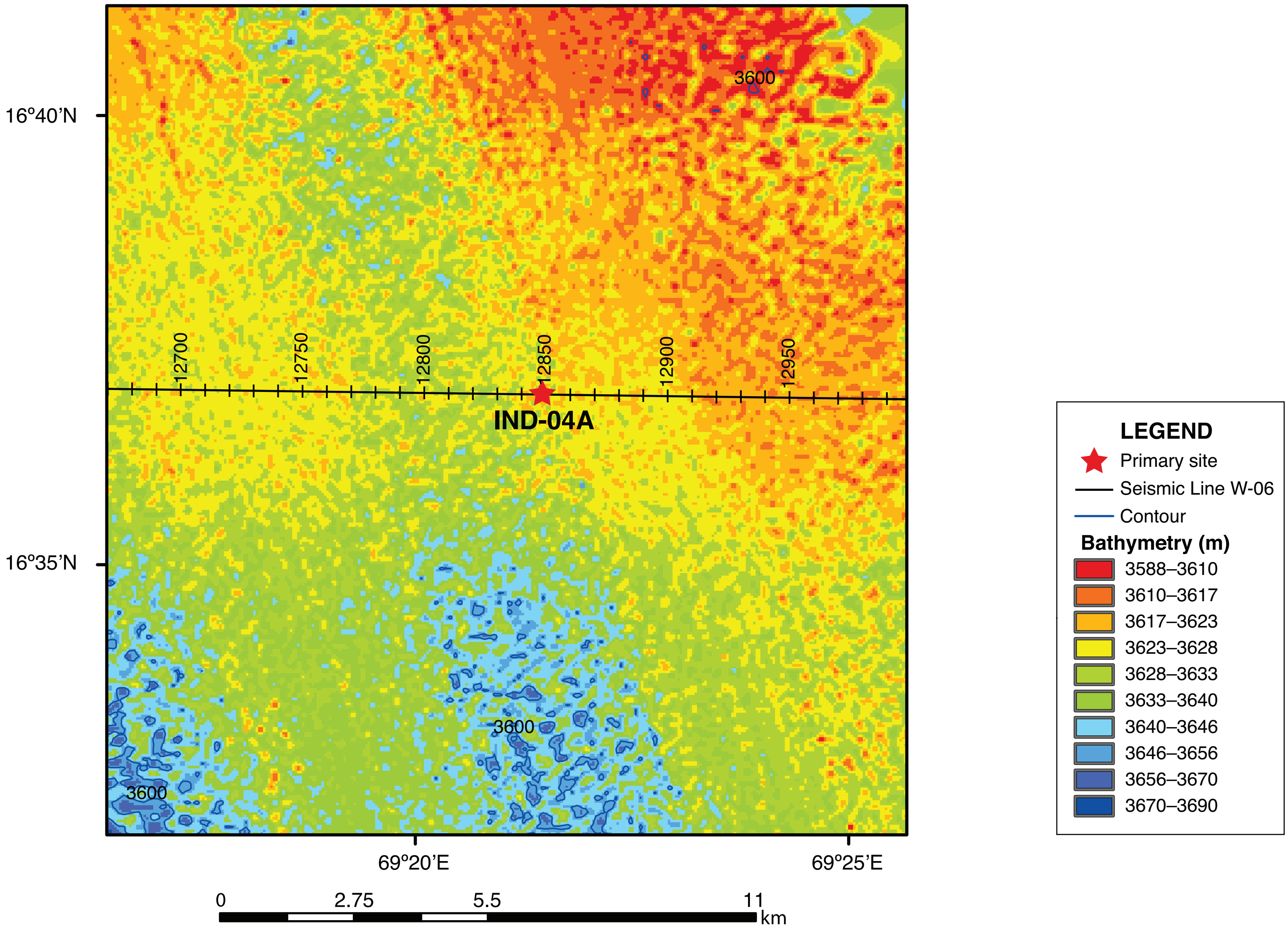
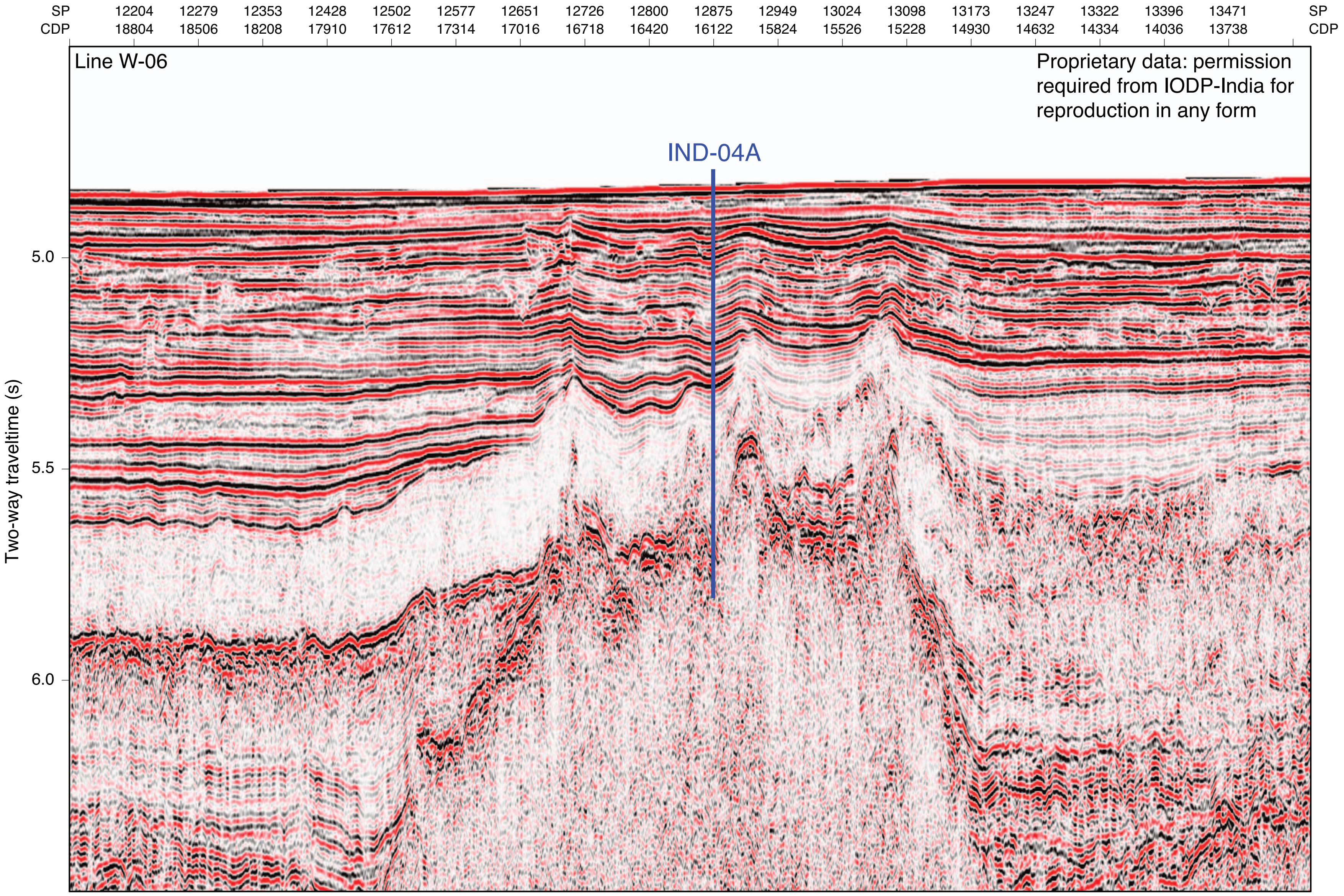


Figure AF8. Seismic profile Line W-06 (west–east) with location of proposed primary Site IND-04A (16°36.8820′N, 69°21.5100′E; shotpoint [SP] 12875; water depth = 3622 m; target depth = 950 mbsf). CDP = common depth point. IODP = International Ocean Discovery Program.



Expedition scientists and scientific participants

The current list of participants for Expedition 355 can be found at: **iodp.tamu.edu/science-ops/expeditions/arabian_sea.html.**