International Ocean Discovery Program Expedition 354 Scientific Prospectus

Bengal Fan

Neogene and late Paleogene record of Himalayan orogeny and climate: a transect across the Middle Bengal Fan

Christian France-Lanord
Co-Chief Scientist
Centre de Recherches Pétrographiques et Géochimiques
CNRS Université de Lorraine
BP 20
54501 Vandoeuvre les Nancy
France

Tilmann Schwenk
Co-Chief Scientist
Department of Geosciences
University of Bremen
Klagenfurter Strasse
28359 Bremen
Germany

Adam Klaus
Expedition Project Manager/Staff Scientist
Integrated Ocean Drilling Program
Texas A&M University
1000 Discovery Drive
College Station TX 77845
USA

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Abstract

Expedition 354 will drill a transect of holes in the Bay of Bengal to address interactions among the growth of the Himalaya and Tibet, the development of the Asian monsoon, and processes affecting the carbon cycle and global climate. Because sedimentation in the Bengal Fan responds to both climate and tectonic processes, its terrigenous sediment records the past evolution of both the Himalaya and regional climate. The histories of the Himalayan/Tibetan system and the Asian monsoon require sampling different periods of time with different levels of precision. Accordingly, we propose a transect of six holes in the fan at 8°N with two complementary objectives. (1) We will study the early stages of Himalayan erosion, which will bear on the India-Eurasia collision and the development of the Himalaya and Tibet as topographic features. We will drill a deep site (MBF-3A to ~1500 m) in the west flank of the Ninetyeast Ridge where a reflector interpreted as a Paleocene-Eocene unconformity could be reached at a reasonable depth. (2) We will study the Neogene development of the Asian monsoon and its impact on sediment supply and flux. Our east–west transect of drill sites at 8°N will include Site MBF-3A and two other 900 m penetration sites (MBF-1A and MBF-2A) to reach sediment at least as old as 10–12 m.y. Records from the Arabian Sea and the Indian subcontinent suggest that at ~7–8 Ma the intensity of the monsoon increased and C4 plants expanded. Moreover, these changes appear to be linked to changes in the erosional regime as recorded by Ocean Drilling Program Leg 116 and possibly to the tectonic evolution of southeast Asia. This transect will allow study of the extent to which a strengthening of the monsoon encompassed the Bay of Bengal, where increased rainfall, not strengthened wind, characterizes the monsoon, and will allow quantitative studies of the interrelations of climate change and sediment accumulation. In addition, three sites (MBF-4A, MBF-5A, and MBF-6A) will document how the depocenter migrated across this transect during the Pleistocene and will provide the most complete record of channel-derived terrigenous material through this time interval.

Schedule for Expedition 354

International Ocean Discovery Program (IODP) Expedition 354 is based on IODP drilling proposal Number 552-Full3 (available at **iodp.tamu.edu/scienceops/expeditions/bengal_fan.html**). Following ranking by the IODP Scientific Advisory Structure, the expedition was scheduled for the 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 start in Singapore on 29 January 2015 and end in Columbo, Sri Lanka, on 31 March 2015. A total of 50 days will be available for the drilling, coring, and downhole measurements described in this report (Table **T1;** for the current detailed schedule, see **iodp.tamu.edu/science-ops**). Further details about the facilities aboard the *JOIDES Resolution* and the USIO can be found at **www.iodp-usio.org.**

Introduction

Among regions of the world where tectonics and climate interact, southern Asia seems to illustrate the possible influences of one on the other more dramatically than any other region. The high elevation of the Tibetan Plateau and the rapid rise from the lowlands of northern India across the Himalaya profoundly affect both the average temperature structure of the atmosphere responsible for the seasonal winds and the localization of precipitation that characterize the south Asian monsoon. Concurrently, large seasonal variations in precipitation along the Himalaya affect erosion rates. Yet if the Tibetan Plateau and the Himalaya have influenced climate during Cenozoic time, the evidence suggesting such an influence is wholly inadequate to understand quantitatively how the development of these geographical features have done so.

Expedition 354 is designed to obtain data that can not only test proposed hypothetical links between climate and tectonics but also provide new data not easily anticipated but relevant to understanding a number of processes in the Earth. This expedition in the Bay of Bengal focuses on its record of the erosional history of the Himalaya and on the development of the Asian monsoon over Cenozoic time. Because geology lacks the tools for determining paleoelevations except in unusual and ideal circumstances, the sedimentary record of material eroded from a mountain belt holds the least ambiguous record of its paleotopography. Roughly 80% of the material eroded from the Himalaya has been deposited in the Bay of Bengal, making it the most complete record.

During Expedition 354, six sites will be drilled in an east–west transect at 8°N (Figs. **F1, F2**), including

- One deep site to ~1500 m to reach prefan deposits (Site MBF-3A),

- Two sites to ~900 m (Sites MBF-1A and MBF-2A) to recover sediment at least as old as 10–12 m.y. to study Neogene fan evolution and the impact of the monsoonal system on sediment supply and flux, and
- Three sites to ~300 m to recover a complete terrigenous record of the Himalayan flux over the last 1–2 m.y.

This expedition builds on knowledge acquired during earlier drilling and seismic explorations of the Bengal Fan (Deep Sea Drilling Project [DSDP] Leg 22, Ocean Drilling Program [ODP] Leg 116, and R/V *Sonne* Cruises SO93, SO125 and SO188) and on current studies of the tectonic, geologic, geomorphological, and sedimentological processes acting on the Himalaya, the floodplain and delta of the Ganga-Brahmaputra, and the Bengal Fan. This expedition is one part of an integrated effort for drilling syntectonic basins around the Himalaya to improve our knowledge of monsoon evolution and its interaction with Himalayan growth and erosion.

Background

Geological setting

The Bengal Fan covers the floor of the entire Bay of Bengal (Fig. **F1**), from the continental margins of India and Bangladesh to the sediment-filled Sunda Trench off Myanmar and the Andaman Islands and along the west side of the Ninetyeast Ridge. It spills out south of the Bay of Bengal at its distal end to ~7°S. Another lobe of the fan, called the Nicobar Fan, lies east of the Ninetyeast Ridge, but its primary source of turbidites from the head of the Bay of Bengal apparently was cut off during the Pleistocene by convergence between the northern end of the Ninetyeast Ridge and the Sunda Trench. The northeastern edges of the fans have been subducted, and some of the Tertiary turbidites cropping out in the Indo-Burman Ranges of Myanmar, the Andaman and Nicobar Islands, and in the outerarc ridge off Sumatra have been interpreted as old Bengal and Nicobar Fan sediments.

The Bengal and Nicobar Fans were delineated and named by Curray and Moore (1974), who also noted two horizons in reflection and refraction seismic data that pass into unconformities over the exposed and buried hills of folded sediments in the southern part of the fan and over the Ninetyeast Ridge. They concluded that these two horizons are regional and used them to divide the sedimentary section into three units in the Bay of Bengal. The ages of these unconformities were tentatively determined to be uppermost Miocene and upper Paleocene to middle Eocene during DSDP Leg 22 (Moore et al., 1974; Shipboard Scientific Party, 1974) at Sites 218 and 217, respectively (Fig. **F1**). They interpreted the older unconformity as dating the India-Asia collision, with the pre-Eocene sedimentary unit consisting of pelagic sediment and terrigenous material derived from India before the collision. Hence, the upper two sedimentary units define the Bengal Fan sensu stricto. They associated the upper Miocene unconformity with intraplate deformation, probably correlated with a plate edge event. These tentative age assignments were confirmed and refined by later drilling during ODP Legs 116 and 121 (Cochran, Stow, et al., 1990; Peirce, Weissel, et al., 1991), although the interpretation and significance of the older unconformity and the time of initiation of Bengal Fan deposition and progradation remain very controversial.

The older unconformity was drilled and sampled only on the Ninetyeast Ridge. Correlation of this unconformity off the ridge into the fan section is possible along some but not all seismic lines (e.g., Gopala Rao et al., 1994, 1997; Krishna et al., 1998; Schwenk and Spieß, 2009). DSDP sites from Leg 22 sampled the older unconformity. DSDP Site 215 showed a hiatus from early Eocene to late Miocene (Fig. **F3**). Site 211, located at the eastern distal edge of the Nicobar Fan, showed a hiatus from some time after the Maastrichtian until the Pliocene. The overlying younger sections have been interpreted as distal fan.

An Eocene initiation of Bengal Fan deposition is also suggested by the geology of Bangladesh, the Indo-Burman Ranges of India and Myanmar, and the Andaman-Nicobar Ridge. Hydrocarbon exploration on and offshore from southeastern Bangladesh (e.g., Kingston, 1986) shows total sediment thicknesses calculated from gravity to be >20 km, apparently with the Eocene and Oligocene Disang Series of deepwater shales and turbidites overlying oceanic crust. These are in turn overlain by Neogene prograding deposits of the Bengal Delta and the Ganga-Brahmaputra (Jamuna), Meghna, and their ancestral rivers. Some of this rock has been mildly metamorphosed and uplifted into the accretionary prism in the Indo-Burman Ranges, with some sparsely fossiliferous flysch units correlated with the Disang Series (e.g., Brunnschweiller, 1966; Bender, 1983; Najman et al., 2008). Similar turbidites, the Andaman Flysch or Port Blair Formation, are found in the Andaman and Nicobar Islands, again usually assigned Eocene and Oligocene ages (e.g., Karunakaran et al., 1975; Acharyya et al., 1991) and interpreted to represent parts of the early Bengal Fan, some of which have been incorporated into the Sunda arc accretionary complex.

The initiation of deposition and progradation of the Bengal Fan followed the collision of India with Asia and the formation of a large proto-Bay of Bengal. Continued convergence of the Indian and Australian plates with the Southeast Asian plate reduced the size of the bay and focused the source of turbidites into the present Bengal Basin, Bangladesh shelf, and the shelf canyon Swatch-of-no-Ground (Curray et al., 2003).

Fans grow by progradation, and the first sediments are deposited at the mouth of a canyon and at the base of the slope, in this case the continental slope. With time the fan progrades farther from the original base of the slope. Our limited information suggests that the Bengal Fan has prograded, as shown in Figure **F3.** The oldest rocks interpreted as Bengal Fan in the Indo-Burman Ranges are early Eocene; the oldest such turbidites in the Andaman and Nicobar Islands are middle Eocene. DSDP Sites 215 and 211 revealed upper Miocene and Pliocene turbidites, respectively. DSDP Site 218 did not reach the base of the fan, nor did the ODP Leg 116 sites. The interpretation that the Eocene unconformity marks the base of the fan suggests that it may represent a hiatus of variable duration (Fig. **F3**).

Seismic studies/Site survey data

The original IODP proposal for this expedition (552) was suggested based on a single 500 km long multichannel seismic line at 8°N (GeoB97-020+027), which was acquired during R/V *Sonne* Cruise SO125 in 1997 (Spiess et al., 1998) to gain a better understanding of the buildup of the fan with respect to channel-levee geometries and stacking patterns (Fig. **F2**). For stratigraphic calibration, this seismic profile crossed DSDP Site 218 (Leg 22), where sediments were cored and dated to 773 meters below seafloor (mbsf) (middle Miocene).

To further support IODP Proposal 552, a dedicated presite survey during R/V *Sonne* Cruise SO188 was carried out in June–July 2006. This cruise collected multichannel seismic, swath bathymetric, and subbottom profile data on crossing lines through Proposed Sites MBF-1A to MBF-6A. These additional data provided further understanding of the spatial variation of sediment structures, particularly the underlying complex structures of buried channels (Figs. **F2, F4**). Shallow penetration sediment cores were taken at selected sites to complement the data already available from DSDP Site 218 (Site MBF-1A).

The long seismic reflection Profile GeoB97-020/027 (Fig. **F2**) has been interpreted with respect to the presence of channels, channel-levee systems, and seismic stratigraphy (Schwenk and Spieß, 2009). Several major reflectors and unconformities were traced across the drilling transect, revealing increased average sedimentation rates as a function of distance from the basement ridges at 85°E and 90°E. Age constraints provided by correlation to DSDP Site 218 suggest that our shallow-penetration sites (MBF-6A, MBF-5A, and MBF-4A) should extend to ~1.8 Ma (Pleistocene/Pliocene boundary) and our mid-depth penetration sites (MBF-2A and MBF-1A) should extend to at least 8 Ma. Our deepest penetration and easternmost site (MBF-3A) has been selected to provide prefan sediments by drilling through the regional Reflector P (Eocene unconformity).

High-resolution seismic data were collected during two different surveys, and the two seismic data sets were processed slightly differently because of the availability of software and computer power.

R/V *Sonne* Cruise SO125:

- Streamer: 750 m long, active section 600 m, 48 channels.
- Seismic source: generator-injector (GI) gun, 2 × 0.41 L.
- Standard processing sequence:
  - Trace editing,
  - Spherical divergence correction,
  - Bandpass-filter (55/100–300/600),
  - Common midpoint (CMP)-stacking (20 m CMP-distance 97-020/027; 10 m 97-022), and
  - T-K migration.
- Processing was carried out with Seismic Unix on a Linux-PC.

R/V *Sonne* Cruise SO188:

- Streamer: 750 m long, active section 600 m, 96 channels.
- Seismic source: GI gun, 4.1 L (generator) + 1.7 L (injector)
- Standard processing sequence:
  - Trace editing,
  - Spherical divergence correction,
  - Bandpass-filter (55/100–300/600),
  - CMP-stacking with 10 m distance, and
  - F-K migration/FD migration.

- Processing was carried out with VISTA Seismic Processing 2D/3D (GEDCO) on a Windows PC.

Swath bathymetric data were gathered during Cruise SO125 using a Hydrosweep DS System and during Cruise SO188 using a Simrad EM120 echo-sounder system. The total multibeam coverage width is now 19 km, increasing in those areas where crossing lines were shot. Although bathymetry reveals a clear picture of the recent or Quaternary channel systems in the area, this information only applies to the upper few tens of meters of the section, which is otherwise a mix of stacked older channels and interlevee sequences.

Digital Parasound subbottom profiler data (4 kHz) were also routinely collected during both cruises.

Supporting site survey data for Expedition 354 are archived at the **IODP Site Survey Data Bank.**

Scientific objectives

We focus on (1) the erosional history of the Himalaya and its bearing on the development of the Himalaya and Tibet as topographic features and (2) the development of the Asian monsoon in Cenozoic time as recorded in the Bay of Bengal.

1. Calibration of Neogene to present changes

Although the Miocene to recent sedimentary records in the Bengal Fan suggest that Himalayan erosion was quite comparable to the actual regime, tectonic and climatic changes have occurred that are both likely to have influenced sedimentation in the Bay of Bengal. This includes upper Miocene changes in accumulation rate, continental vegetation, and weathering intensity that are documented both in the continental basin and the Bengal Fan (e.g., Quade and Cerling, 1995; France-Lanord et al., 1993; Burbank et al., 1993; France-Lanord and Derry, 1994; Martinod and Molnar, 1995; Clift et al., 2008; Galy et al., 2010). The development of intense channel-levee deposition in the Bengal Fan starts appearing in the upper Miocene or Pliocene and represents a major change in sediment delivery to the Bay of Bengal (Schwenk and Spieß, 2009). Later, late Pliocene global cooling that led to the growth of Northern Hemisphere ice sheets was related to an increase of detrital sedimentation rate and grain size (Zhang et al., 2001). Although the reality of this change has been questioned

(Willenbring and von Blanckenburg, 2010) the evolution toward higher climate instability should prevent fluvial and glacial basins from reaching an equilibrium state and trigger their erosion. Such changes were observed in the distal Bengal Fan around ~0.8–1 Ma when the 100 k.y. cycle became strong. This expedition will document this critical period in the Earth's most intense erosion system, as tectonic and climate changes have left signatures in accumulation rates, grain sizes, clay mineralogy, isotopic ratios, organic carbon burial, and so on that can be measured (Cochran, Stow, et al., 1989; Derry and France-Lanord, 1997; France-Lanord et al., 1993).

First, to what extent are variations in accumulation rates, clay mineralogy, and grain sizes from ODP Holes 717–719 (Fig. F5) representative of other parts of the fan? Because those holes only recovered sediments from the most distal parts of the Bengal Fan within a growing syncline, sedimentation might have been affected both by the large distance from the source and by the barrier imposed by the surrounding anticlines. The decreases in accumulation rate and grain size at ~7 Ma and the synchronous increased percentage of smectite (Bouquillon et al., 1990) suggest that if the monsoon strengthened at that time, it apparently did so without creating a more energetic erosive system, as might be expected from the strong seasonal precipitation of the monsoon. Obviously, if we find the same pattern of low accumulation rates, small grain sizes, and a large percentage of smectite at 7–8 Ma in the holes cored at 8°N during Expedition 354, we must consider the possibility that if the monsoon strengthened at that time, it did so by decreasing, not increasing, erosion rates. If we find a sediment history different from that in Holes 717–719, it is possible that the sedimentary record at the distal edge of the fan does not record faithfully the changes input at the source of the fan.

The present-day monsoon, if named originally for the seasonally steady winds over the Arabian Sea, also evokes the image of heavy rain over the Indian subcontinent. We have no evidence to date, and perhaps conflicting evidence, showing that precipitation increased over the Ganga and Brahmaputra drainage basins and the Bay of Bengal at 7–8 Ma (Derry and France-Lanord, 1997; Dettman et al., 2001) in spite of enhanced Indian monsoon seasonality over this period (Zhisheng et al., 2001). Assessing paleomonsoon intensity is challenging and can be tracked with two approaches. First, the efficiency of sediment transport from the Himalaya to the Bay of Bengal is directly controlled by the seasonality and intensity of rainfall that creates high river discharge (Lupker et al., 2011). This transport in turn exerts a control on sediment fluxes to the Bay of Bengal that can be traced by accumulation rates. Second, $\delta^{18}O$ in planktonic foraminifers deposited in the Bay of Bengal in late Quaternary time are related to amounts of precipitation (Duplessy, 1982). If these microfossils can be recovered, they will provide another tool to assess the strength of the monsoon.

The main reason for drilling more than one site at 8°N is to minimize the effect of varying sedimentation rates associated with a pronounced increase in the vicinity of the active channel at any one time and the migration of the active channel and hence to avoid the biases that one site (or a set of adjacent sites) might give. Although the main focus of these sites is on the changes near 7–8 Ma, obviously we will obtain material from a longer period. Our easternmost site (MBF-3A) in the eastern Bay of Bengal will recover material older than 14 Ma, which will allow the kinds of studies described above to test whether the monsoon strengthened during the early Miocene, as proposed by Ramstein et al. (1997) and Fluteau et al. (1999).

In addition, we plan to study other temporal and spatial variations in the sediment over the last 7 m.y. Site 218 and sites cored during Leg 116 show changes that possibly reveal other variations in the erosion regime. Kroon et al. (1991) showed a dip in the abundance of *Globigerina bulloides* at ~5 Ma, which might indicate a lull in the monsoon, the temporary dominance of another upwelling-sensitive foraminifer (Kroon et al., 1991), or some other inadequacy of *Bulloides* to measure monsoon strength. We also seek quantitative measures of the interaction between climate change and sedimentation associated with the global cooling and onset of the Northern Hemisphere glaciation at ~2.7–3 Ma and with the change from precession- and obliquity-dominated climate variations to the strong 100 k.y. cycle at 0.8–1 Ma. This latter change appears to be marked in deposition rates, grain sizes, and clay mineralogy in ODP Holes 717–719 (France-Lanord et al., 1993). Again, one objective is to decide how representative the results from Sites 717–719 are. The same proxies for monsoon strength and for erosion will be available for study of this period. The results from Sites 717–719 reveal no evidence of a change in erosion rate at 2.7–3 Ma, in contrast with what might be expected if glacial erosion were important and increased at that time. Moreover, if the only important change in sedimentation rate, and hence presumably in erosion rate, occurred at 0.8–1 Ma, such a change would provide a clue to what kind of change was important. We anticipate being able to resolve temporal variations on the timescale of orbital variations, but obviously we must expect large variations in sedimentation rates. Hence, three sites on our transect (MBF-4A, MBF-5A, and MBF-6A) are proposed to limit the biases on long-term studies associated with penetrating buried channel-levee systems, and another three sites (MBF-1A, MBF-2A, and MBF-3A) will be drilled in between to optimize the temporal sampling of terrigenous sediment input and to analyze the impact of depocenter migration on sedimentary facies and recorded signals.

The 7 Ma transition is also marked by expansion of C4 photosynthetic plants in the Himalayan basin (Quade et al., 1989). Although C4 plant expansion may result from a global decrease in atmospheric pCO_2 (Cerling, 1997), studies suggest that pCO_2 was already low at that period (Pagani et al., 1999; Beerling and Royer, 2011). In the latter hypothesis, C4 plant expansion would instead require an adaptation to more arid conditions in the floodplain. Sediments sampled during Leg 116 show close links among variations in clay mineralogy (smectite/illite ratio), in total organic carbon, and in δC (C3 versus C4 plants) (Fig. **F5**) (France-Lanord and Derry, 1994; Freeman and Colarusso, 2001). These relationships suggest changes in sediment provenance, with a mountain end-member delivering material unaltered with low organic carbon content of C3 type and a floodplain end-member delivering altered material with high organic carbon content of C4 type. If confirmed by new drilling at the scale of the whole fan, such relations would favor the hypothesis of a regional climate change toward dryer conditions.

2. Forcing of the carbon cycle and climate

Drilling the Bengal Fan should allow investigation of the effect of the Himalayan erosion on the global carbon cycle, which has been debated in the literature (e.g., Raymo and Ruddiman, 1992; France-Lanord and Derry, 1997; Galy et al., 2007; Goddéris and Donnadieu, 2009). Erosion tends to consume atmospheric carbon by two mechanisms. Weathering of silicates produce fluvial alkalinity flux that can later precipitate as carbonate in seawater. Second, plant debris and organic carbon are transported with the particulate flux and can be buried in deep-sea sediment. Ultimately, both mechanisms will take up carbon from the atmosphere and store it over long periods in the sedimentary reservoir. Observation of modern fluxes of erosion as well as of Bengal sediments suggested that the Himalayan erosion mostly consumes atmospheric CO_2 through the burial of organic carbon preferentially to silicate weathering. Nevertheless, it remains impossible to assess the magnitude of these processes at a global scale because the past fluvial fluxes are unknown. The volume and the geochemistry of sediment can provide direct and interpretable records of these fluxes, if their accumulation rates in the Bengal Fan can be determined with sufficient accuracy. Our transect of drill sites at 8°N will document the regional scale of such fluxes during the Neogene that can be extrapolated throughout the entire fan. The deepest penetration site (MBF-3A) will allow exploration of weathering and carbon burial prior to the Neogene.

3. Sampling of the oldest sediment of the fan

Scenarios of the timing and geometry of the collision between India and the rest of Eurasia suggest that collision in the western Himalaya occurred between 50 and 55 Ma and perhaps later (~45 Ma) in the eastern Himalaya, near Everest for instance (Rowley, 1996, 1998). However, there are contrasting models for the slowdown of Indian plate motion and the geometry of the collision (e.g., Dupont-Nivet et al., 2010; Van Hinsbergen et al., 2011; Aitchison et al., 2007; Zhang et al., 2012). When the Himalaya emerged as a mountain range, however, remains less certain. Extending the record of sedimentation back in time should allow a determination not only of when erosion began, but also of when erosion penetrated deep enough into the crust to expose rapidly cooled minerals. In particular, we should be able to determine cooling ages of minerals whose closure temperatures are different, and from the isotopic signature, we should be able to identify what rock of the Himalaya has eroded. Differences between cooling ages and stratigraphic ages will then allow an estimate not only of when erosion began, but also of when erosion exhumed rock from different depths (Copeland and Harrison, 1990; Corrigan and Crowley, 1992; Galy et al., 1996).

Determining when emergence of the Himalaya took place might not provide any surprises. Nevertheless, recall that all of the rock cropping out in the Himalaya was carried by the Indian subcontinent and scraped off it following collision with Eurasia. Thus, given the convergence rate of ~50 km/m.y. that India has moved toward Eurasia since 45 Ma, if collision occurred at 45 Ma but erosion began only at 35 Ma, we might infer that as much as 500 km intact lithosphere was subducted beneath southern Eurasia before a significant mountain range formed. Conversely, if deposition of rock with a Himalayan isotopic fingerprint began shortly after 45 Ma, we must infer that some off-scraping of Indian crust occurred early in the history of the collision to build the initial Himalaya. Finally, we can imagine a flux of sediment early in the history of the collision, but of Tibetan, not Himalayan, origin. This would suggest some, if not necessarily easily quantified, subduction of India beneath southern Tibet before thrust faulting within India created the Himalaya.

The well-known increase in the $^{87}Sr/^{86}Sr$ ratio of seawater beginning at ~40 Ma (DePaolo and Ingram, 1985; Hodell et al., 1989) is commonly attributed to increased erosion and weathering in the Himalaya (Edmond, 1992; Galy et al., 1999; Krishnaswami et al., 1992). A strong Himalayan signature, not only beginning at ~40 Ma but also contributing a pulse near 18 Ma (Richter et al., 1992), should, therefore, be corroborated in the sedimentary record of Himalayan erosion. This would be supported if detrital silicates with high $^{87}Sr/^{86}Sr$ ratios increased both at ~40 Ma and near 18 Ma. By extending the sedimentary record in the Bay of Bengal through the Oligocene, we can examine the hypothesized correlation of the increased marine Sr isotopic ratio at 18 Ma with weathering of Himalayan rock rich in radiogenic strontium. If we can sample the early history of Himalayan erosion, we can test the assumption that the increasing Sr isotopic ratio beginning at ~38 Ma also results from weathering of Himalayan rock. The sensitivity of the seawater Sr isotopic budget to the Himalayan flux is so high (Galy et al., 1999) that the seawater evolution through time provides a unique system where erosion rate can be estimated using a proxy other than accumulation rates.

The Bengal Fan is one of the thickest sediment sections in the world, and is far too thick for sampling the very old section. The oldest part of the fan sampled to date was at Site 718 more than 2500 km from the present apex of the fan, where early Miocene sediment (~17 Ma) was recovered. Because of its southern position and great water depth, this site may not be adequate to penetrate the "oldest" sediment derived from the Himalaya because the fan may not have prograded so far south (e.g., Curray, 1994). Our deepest proposed site (MBF-3A) is located on the west flank of the Ninetyeast Ridge, ~1300 km from the apex of the fan, where the section is thinner and where a possible Paleocene–Eocene unconformity ("P" horizon) could be reached at a reasonable depth (Curray et al., 1982).

4. Determining fan architecture and spatial depocenter variability

Since the Pliocene, sedimentation in the Bengal Fan has been dominated by deposition in channel-levee systems (Schwenk and Spieß, 2009). During this period, the fan appears to have been built by an accumulation of lenses corresponding to distinct channel-levee episodes intercalated by more slowly accumulating intervals of fine-grained sediment (Fig. **F2**). Channels carry a flux of sediment for a brief period, apparently only for approximately thousands of years, and then fill with sediment as portions are abandoned and a new channel is cut into the levee system or outside it. Thus, accumulation at any point is likely very irregular, varying from rates >30 m/k.y. for periods as long as 3000 y (Hübscher et al., 1997; Michels et al., 1998; Spiess et al., 1998; Weber et al., 1997) to very low accumulation rates in intervening periods. Nd-Sr isotopic signatures demonstrate that sediment accumulated in levees is dominated by Himalayan material, whereas very low accumulation hemipelagic deposits have distinct isotopic signatures, showing that other sources are mixed with Himalayan flux (Pierson-Wickmann et al., 2001). Determining the distribution and typical lifetime of depocenters is vital for interpreting the older sedimentary record of the fan and assigning different types of sedimentary facies and successions found in deep drill holes to structural units. To address this objective, our six sites are distributed over a 200 km transect designed to obtain sufficient spatial resolution on the basis of a typical width of a channel-levee system on the order of ~50 km. The shallower, ~300 m penetration sites will record the stacking of more than two systems.

Expedition 354 should significantly improve and refine the poor existing age constraints (currently based only on spot-cored DSDP Site 218) of the stratigraphic and structural elements identified in the seismic data. This is especially critical for constraining the transition from early sheet-like turbidite deposition to the onset of channel-levee systems that occurred in the latest Miocene (Schwenk and Spieß, 2009). Because most surface channels reach this part of the fan, it is believed that this marks the start of the development of channel-levee systems on the Bengal Fan generally (Fig. **F2**). Two reasons might be responsible for the onset of the channel-levee systems: (1) the initial creation of a canyon as point source or (2) changes in the grain size of the delivered sediments transported by turbidity currents to the fan. The three drill sites targeting recovery of late Miocene sediments (MBF-1A, MBF-2A, and MBF-3A) will prove whether there were changes in grain sizes (as interpreted from ODP Leg 116 results) or whether the onset of the channel-levee systems represents the first margin setting with a canyon and probably associated delta. Additionally, because several levees will be penetrated, new insights about the lifetime of distinct channel-levee systems will be gathered, which is so far only known for the active channel (Weber et al., 1997).

Additional objectives

Although Expedition 354 has been designed principally to document Himalayan and Indian monsoon evolutions and interactions and turbiditic fan construction, drilling the Bengal Fan will allow additional important objectives to be addressed. This includes fan hydrology, Bengal Basin deformation, and deep biosphere issues.

Fan hydrology and hydrochemistry

The Bengal Fan is a major sedimentary reservoir filled by continental material, including clays and organic matter that are likely to evolve during diagenesis. Pore water chemistry and O-H isotopic compositions documented on Leg 116 cores revealed a high variability of compositions that imply that low-salinity fluid is released through dehydration reactions probably deeper than in the cored sections and that fluid advection occurs under thermo-convective conditions at least in that portion of the fan (Boulègue and Barriac, 1990; Ormond et al., 1995). There are also indications for diverse diagenetic reactions that release significant amounts of Ca and Sr in the pore water reservoir. Pore water analyses and downhole temperature measurements will constrain the magnitude of compaction, dehydration reactions, and possible fluid advection. This will lead to refined estimates of geochemical fluxes from the fan to the ocean.

Bengal Basin deformation

Throughout the Neogene, the Bengal Basin underwent significant multiphase deformation resulting in the folding of the plate between the Ninetyeast Ridge and the 85°E ridge (Krishna et al., 2001). Beside the Miocene and Eocene unconformities (Curray et al., 2003), the site survey data revealed two additional regional unconformities. Using the DSDP Site 218 age control, these were dated as Pleistocene and Pliocene, respectively (Schwenk and Spieß, 2009). These unconformities are interpreted to be equivalent to unconformities found in the central Indian Ocean, which are related to deformation events of the ocean lithosphere there (Cochran, 1990; Stow et al., 1990; Krishna et al., 2001). Additionally, several faults were identified in the seismic data, especially above the western flank of the Ninetyeast Ridge. These faults terminate within Pleistocene sediments, which also suggest tectonic events at least until the Pleistocene. As Site 218 dating is poorly constrained, we expect Expedition 354 results to allow more precise dating of unconformities and fault terminations, which in turn will improve the understanding of deformation events in the Bengal Basin.

Deep biosphere

Deep biosphere objectives are not specifically planned during this expedition, but the Bengal Fan represents one of the largest fluxes of terrestrial matter to the ocean with relatively fast accumulation. The apparent high preservation of the associated organic matter is a peculiar aspect of Bengal Fan sedimentation (Galy et al., 2007). Microbial activity is intimately intertwined with diagenesis and organic carbon degradation. Because preservation and burial of organic matter is one crucial parameter of the impact of Himalayan erosion on the carbon cycle, there is high interest to study these processes.

Operations plan/Drilling strategy

Our planned sequence of drill sites, coring/downhole measurements, and time estimate is provided in Table **T1** and illustrated in Figure **F6.**

For operational efficiency, we intend to occupy the sites in sequence from east to west (MBF-3A, MBF-6A, MBF-2A, MBF-5A, MBF-4A, and MBF-1A).

All sites will start with a hole cored with the advanced piston corer (APC)/extended core barrel (XCB) system. If coring conditions (recovery, core quality, and penetration rate) permit, this first hole will be cored to the total target depth. All APC cores will be oriented, and a basic program of formation temperature measurements (with the advanced piston corer temperature tool [APCT-3]) will be made. A second hole will be required at our deepest penetration site (MBF-3A) and will consist of rotary core barrel (RCB) coring through the Eocene unconformity and to a total depth of 1500 m. Wireline logging is planned for our three deepest penetration sites (MBF-3A, MBF-2A, and MBF-1A).

Logging/Downhole measurements strategy

Formation temperature measurements

We plan a series of formation temperature measurements in each APC-cored hole using the APCT-3 tool. If necessary, we may deploy the Sediment Temperature Tool (SET), but this is not included in the current time estimate.

Core orientation

We plan to orient all APC cores with the FlexIT orientation tool and will make use of nonmagnetic coring hardware to the maximum extent possible.

Downhole wireline logging

At the time of writing this *Scientific Prospectus*, the contract for providing wireline logging services is not yet in place. We anticipate providing basic wireline logging tools similar to those provided during the previous Integrated Ocean Drilling Program. Wireline logging is planned for our three deepest penetration sites (MBF-3A, MBF-2A, and MBF-1A). This will consist of two logging runs including the triple combination (triple combo) and Formation MicroScanner (FMS)-sonic tool strings. If hole conditions allow, we also intend to conduct a check shot with the Versatile Seismic Imager (VSI) in two holes (MBF-3A and MBF-2A).

Risks and contingency

We consider that unconsolidated sediments (rapidly accumulating silt and sand, etc.) could create unstable borehole conditions that negatively impact core recovery/quality and may prevent reaching our depth objectives.

If this occurs at our deep penetration site (MBF-3A), we have the possibility of deploying a reentry cone and casing to stabilize the upper part of the hole, thereby enhancing our ability to recover deeper cores and logs. However, this would take an additional ~1 week of time. In addition, if this occurs at any of the other sites (MBF-6A, MBF-5A, MBF-4A, and MBF-1A), we might have to switch to RCB coring to reach the depth objectives—this would require an additional trip of the drill string. As neither of these operations are included in the current time estimate, other planned operations would therefore have to be reduced or eliminated.

If unconsolidated sands cause problems in APC core recovery and/or quality, we might choose to deploy the half-length APC system. We may also do this to extend high-quality piston cores to deeper depths. This will result in increased wireline times and is not currently in our time estimate; other planned operations would therefore have to be reduced or eliminated.

Sampling and data sharing strategy

All scientists requesting samples and data from the Bengal Fan expedition 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 the Co-Chief Scientists, Expedition Project Manager, and IODP Curator on shore and curatorial representative in place of the Curator onboard the ship.

Every member of the science party is obligated to carry out scientific research for the expedition and publish it. All scientists interested in obtaining samples/data must submit a detailed research plan at least 3 months before the beginning of the expedition (see **smcs.iodp.org**). Based on sample requests submitted by this deadline and input from the scientific party, the SAC will prepare a tentative sampling plan that will be revised on the ship as dictated by recovery and cruise objectives. The sampling plan will be subject to modification depending on the actual material recovered and collaborations that may evolve between scientists during the expedition. This planning process is necessary to coordinate the research to be conducted and to ensure that the scientific objectives are achieved.

Minimizing the overlap of measurements among the shipboard party and identified shore-based collaborators will be a factor in evaluating sample requests. Success will require collaboration, integration of complementary data sets, and consistent methods of analysis. Substantial collaboration and cooperation is expected.

The cores will be sampled on the ship for shipboard analyses and—to the extent possible—for samples for individual research projects. Shipboard sampling will be prioritized for acquiring ephemeral data types and obtaining sufficient samples for individual scientists to begin their postcruise research. Because of limited time and information available on the ship, some sampling may be deferred postcruise.

All collected data and samples will be protected by a 1 y moratorium period following the completion of the expedition. During this time, data and samples are available only to the Expedition 354 shipboard party and any approved shore-based participants. Modifications to the sampling plan during the expedition and the moratorium period require the approval of the SAC.

There may be considerable demand for samples from a limited amount of cored material for some critical intervals. Critical intervals may require special handling, a higher sampling density, reduced sample size, or continuous core sampling for a set of particular high-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.

Immediately following the expedition, all Expedition 354 cores will be sent to the IODP Kochi Core Center in Kochi, Japan.

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Table T1. Operations and time estimates, Expedition 354.

Site	Location	Seafloor Depth (mbrf)	Operations description		Transit (days)	Drilling coring (days)	Logging (days)
	Singapore		Begin Expedition	5.0	Port call days		
			Transit ~1016 nmi to Middle Bengal Fan Site MBF-3A @ 10.5 knots		4.0		
MBF-3A EPSP Depth Approved to 1500 mbsf	08°0.4200′N 088°44.5020′E	3629	Hole A - APC/XCB core to ~500 mbsf; APC core orientation; formation temperature measurements (APCT-3)			4.7	
			Hole B - Drill down to ~500 mbsf and RCB core to ~1500 mbsf; wireline log			13.7	2.6
			APC section begins with nonmagnetic core barrels.				
			Subtotal days on site:	21.1			
			Transit ~38 nmi to MBF-6A @ 10.5 knots		0.1		
MBF-6A EPSP Depth Approved to 500 mbsf	08°0.4200′N 088°6.6000′E	3676	Hole A - APC/XCB core to ~300 mbsf; APC core orientation; formation temperature measurements (APCT-3)			3.0	
			APC section begins with nonmagnetic core barrels.				
			Subtotal days on site:	3.0			
			Transit ~26 nmi to MBF-2A @ 10.0 knots		0.1		
MBF-2A EPSP Depth Approved to 1200 mbsf	08°0.4200′N 087°40.2480′E	3682	Hole A - APC/XCB core to ~900 mbsf; APC core orientation; formation temperature measurements (APCT-3); wireline log			7.8	1.9
			APC section begins with nonmagnetic core barrels.				
			Subtotal days on site:	9.7			
			Transit ~29 nmi to MBF-5A @ 10.5 knots		0.1		
MBF-5A EPSP Depth Approved to 500 mbsf	08°0.4200′N 087°10.9020′E	3696	Hole A - APC/XCB core to ~300 mbsf; APC core orientation; formation temperature measurements (APCT-3)			3.0	
			APC section begins with nonmagnetic core barrels.				
			Subtotal days on site:	3.0			
			Transit ~23 nmi to MBF-4A @ 10.5 knots		0.1		
MBF-4A EPSP Depth Approved to 500 mbsf	08°0.4200′N 086°47.8980′E	3705	Hole A - APC/XCB core to ~300 mbsf; APC core orientation; formation temperature measurements (APCT-3)			3.0	
			APC section begins with nonmagnetic core barrels.				
			Subtotal days on site:	3.0			
			Transit ~31 nmi to MBF-1A @ 10.5 knots		0.1		
MBF-1A EPSP Depth Approved to 1200 mbsf	08°0.4200′N 086°16.9980′E	3756	Hole A - APC/XCB core to ~900 mbsf; APC core orientation; formation temperature measurements (APCT-3); wireline log			8.1	1.7
			APC section begins with nonmagnetic core barrels.				
			Subtotal days on site:	9.8			
			Transit ~470 nmi to Colombo, Sri Lanka @ 10.5 knots		1.9		
	Colombo, Sri Lanka		End Expedition		6.3	43.4	6.3
			Port call: 5.0 Subtotal on site: 49.7	Total operating days: 56.0 Total expedition: 61.0			

EPSP = Environmental Protection and Safety Panel. APC = advanced piston corer, XCB = extended core barrel, APCT-3 = advanced piston corer temperature tool, RCB = rotary core barrel.

Figure F1. Map of the Himalayan erosion system showing the position of existing DSDP and ODP sites documenting the Bengal and Indus Fans or the monsoon history. Red box = location of Expedition 354 Middle Bengal Fan (MBF) drill site transect at 8°N. Bengal Fan sediment isopachs (blue lines; in kilometers) are simplified from Curray et al. (2003) and represent the total sedimentary and meta-sedimentary rocks above the oceanic basalt as interpreted from seismic reflection and refraction data.

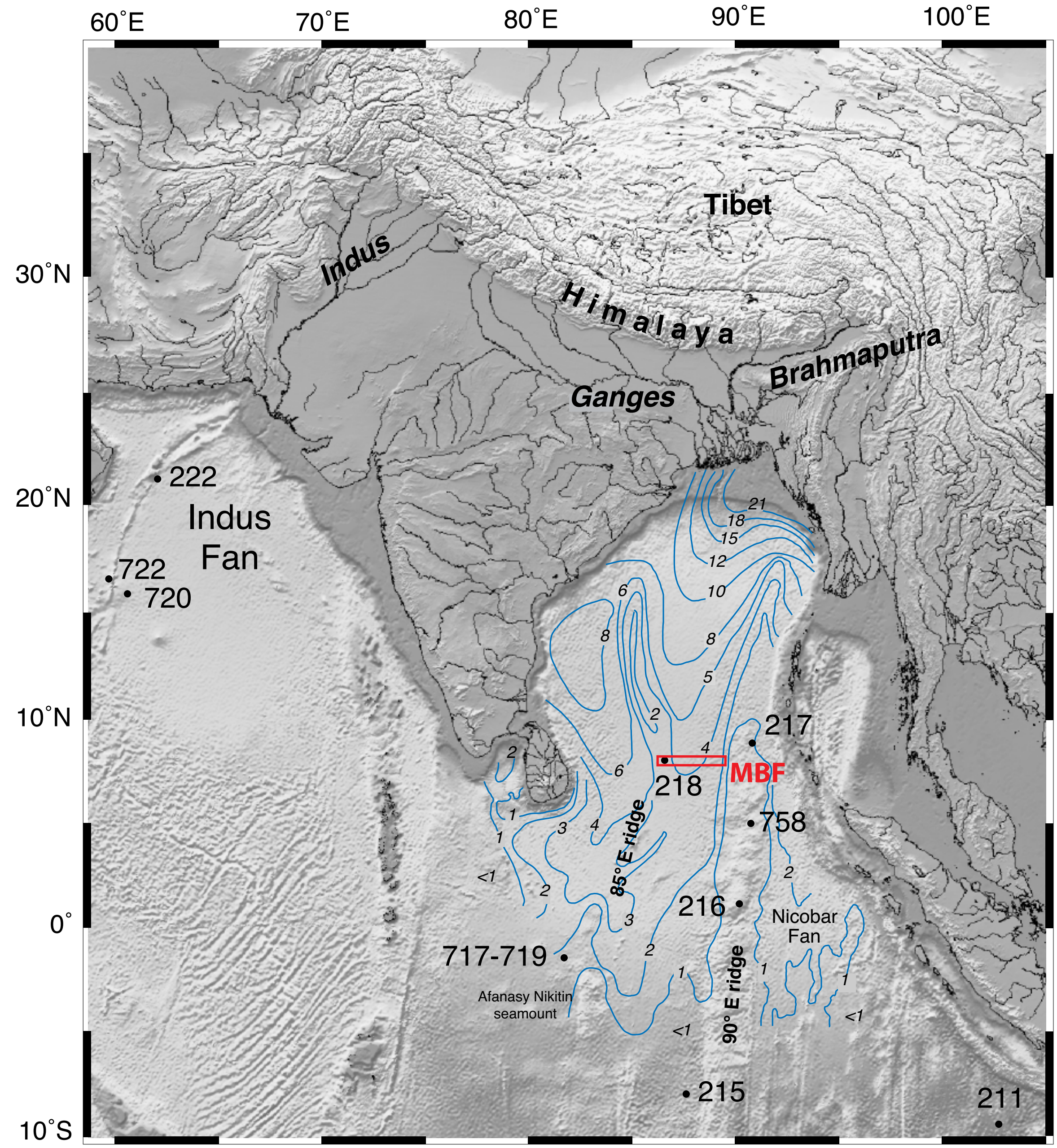


Figure F2. Top: Seismic Profile GeoB097-020/027 showing the positions of Expedition 354 drill sites in relation to regional fan architecture. The tops of the Pliocene and Miocene, as well as the 10 Ma horizon, are traced through the profile based on results from DSDP Site 218 (Moore et al., 1974). The distinct unconformity in the east that is penetrated only by the deepest part of proposed site MBF-3A is inferred to represent the Eocene onset of fan deposition. Bottom: Interpreted line drawing of Profile GeoB97-020/027 showing the later stage channel-levee systems, regional unconformities and faults. Modified from Schwenk and Spieß (2009). TWT = two-way traveltime, VE = vertical exaggeration. Horizontal scale = common midpoint (CMP) numbers, CMP distance = 20 m. Naming of channels follows Curray et al., 2003.

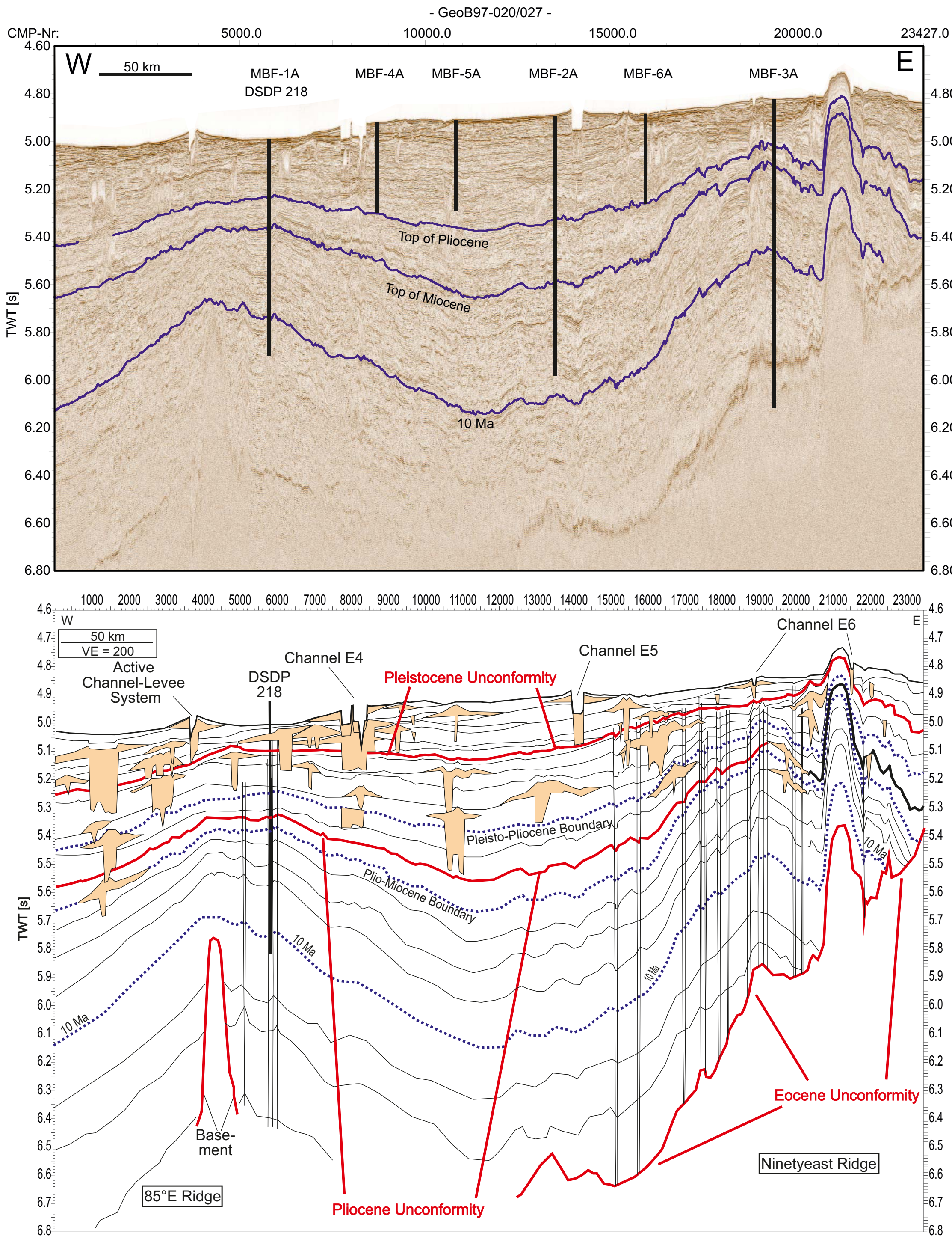


Figure F3. Estimated age span of Bengal Fan sedimentation vs. distance from the present apex or source of the fan. Shaded area at each site = known age span of fan sedimentation. The duration of the apparent hiatus was short near the source and long in the lower and distal fan. This plot is oversimplified because the distance from the fan apex changed through time with convergence of the Indian and Eurasian plates and with progradation of the delta in Bangladesh. IB Ranges = Indo-Burman Rangers, A-N Ridge = Andaman-Nicobar Ridge.

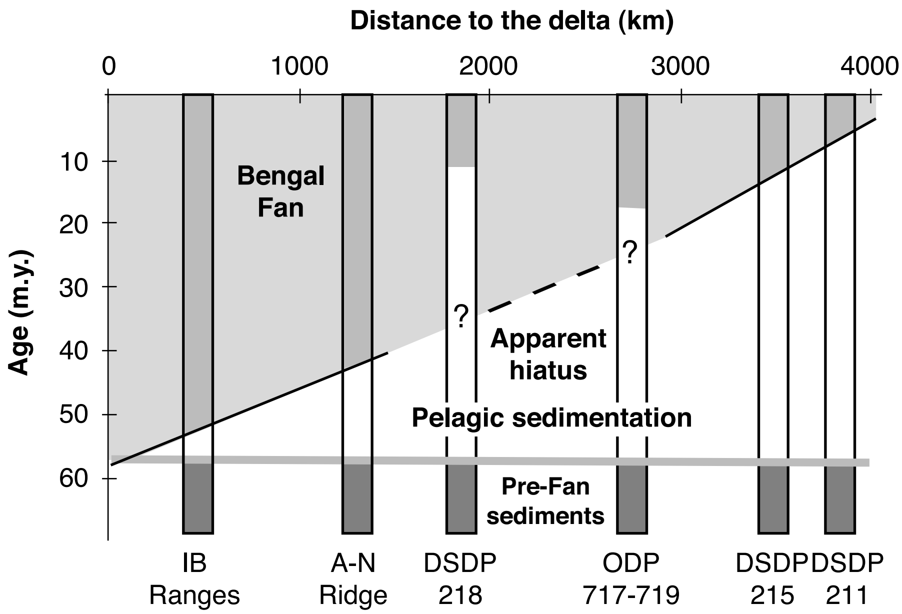


Figure F4. Map showing Expedition 354 drill sites on top of multibeam bathymetry. Available seismic lines from R/V *Sonne* Cruises SO125 (black) and SO188 (red) are indicated. Profiles crossing the sites are highlighted. See **"Site summaries"** and appendix figures for seismic data at each proposed site.

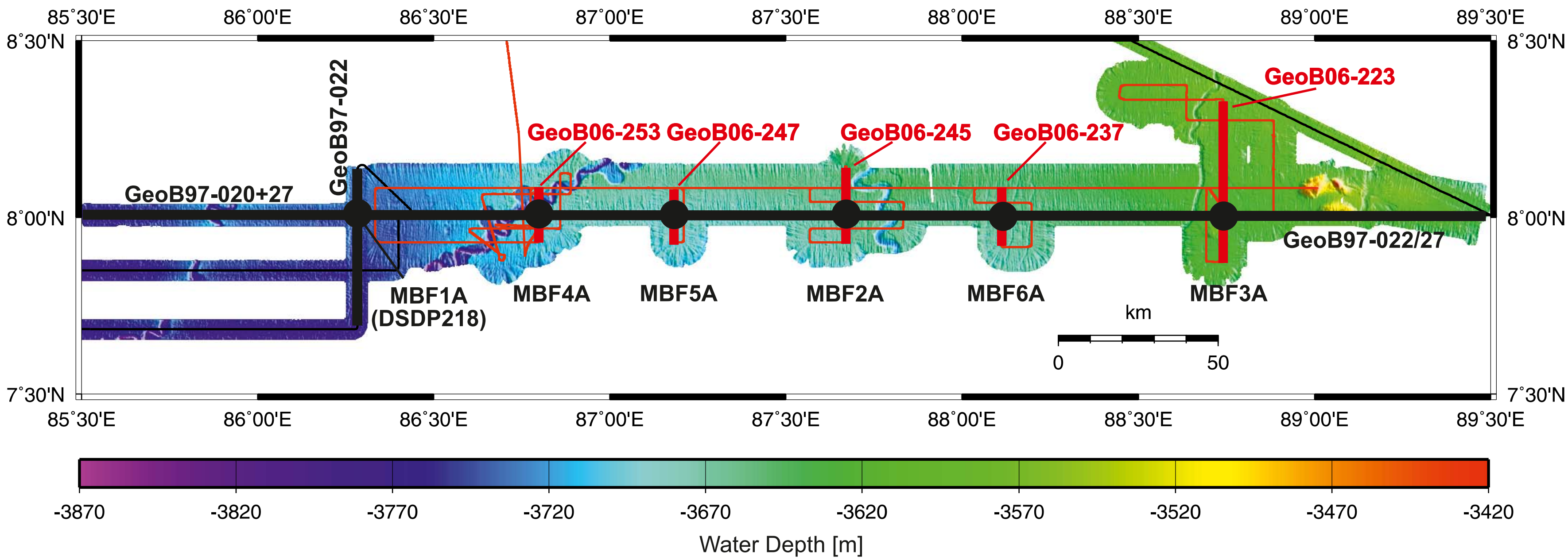


Figure F5. Accumulation rate (Gartner, 1990), clay mineralogy (Bouquillon et al., 1990), Nd isotopic data (Derry and France-Lanord, 1996; France-Lanord et al., 1993; Galy et al., 1996), and total organic carbon isotopic composition (France-Lanord and Derry, 1994), ODP Holes 717C and 718C. Ages recalculated using timescale of Cande and Kent (1992). Low sedimentation rates, smectite-kaolinite clays, and organic carbon derived from C4 plants characterize the interval from 7.4 to 0.9 Ma. Nd isotopic composition does not change during the entire time recovered, suggesting the eroded source of material is not significantly changing. Biostratigraphic constraints on sediment accumulation are uncertain for the early Miocene. The apparent increase in sedimentation rate near 12 Ma could be an artifact of poor biostratigraphic control prior to that time.

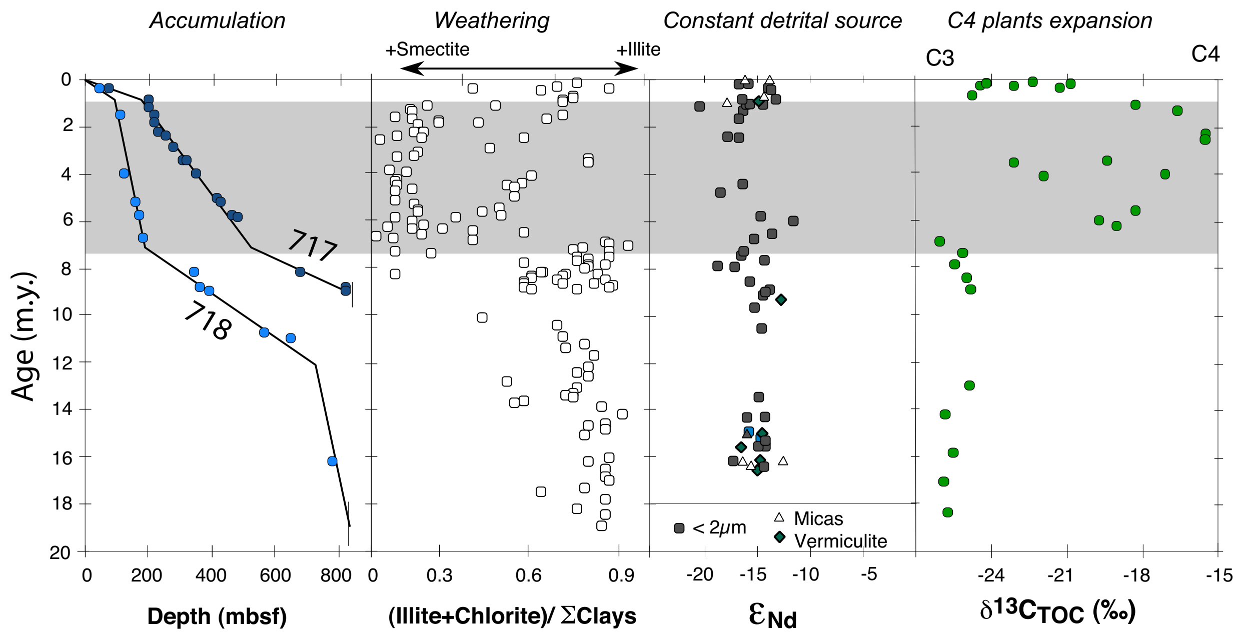
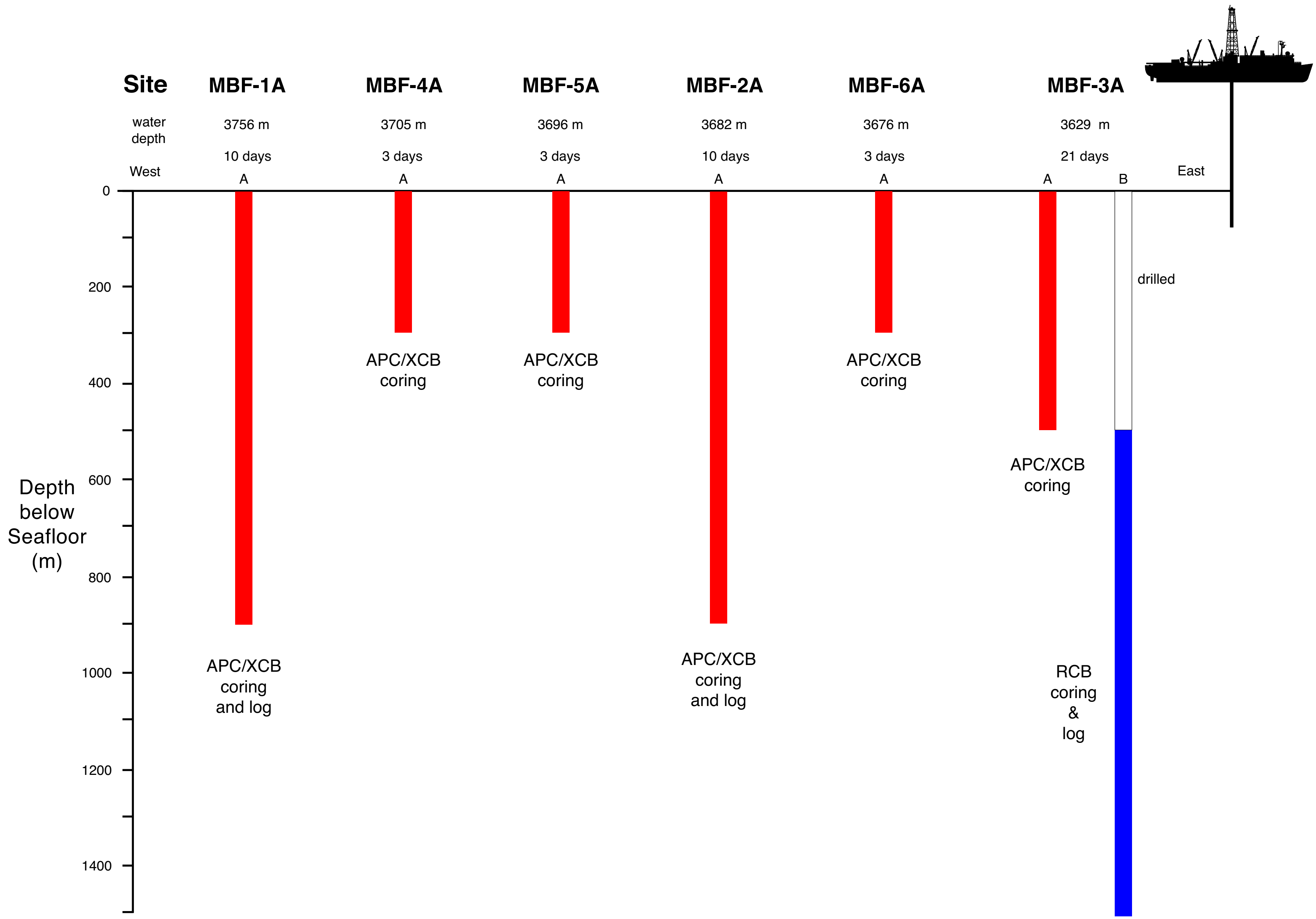


Figure F6. Schematic illustration of drill sites planned for Expedition 354. APC = advanced piston corer, XCB = extended core barrel, RCB = rotary core barrel.



Site summaries

Site MBF-3A

Priority:	Primary
Position:	08°0.4200′N, 088°44.5020′E
Water depth (m):	3618
Target drilling depth (mbsf):	1500
Approved maximum penetration (mbsf):	1500
Survey coverage (track map; seismic profile):	• Map (Fig. **AF1**) • Seismic Line GeoB97-20+27, CMP 19338 (Fig. **AF2**) • Seismic Line GeoB06-223, CMP 1428 (Fig. **AF3**)
Objective(s):	• Neogene history • Early fan history • Depocenter migration
Drilling program:	Hole A: APC/XCB to 500 m Hole B: RCB to 1500 m
Logging program and downhole measurements program:	• APC core orientation and formation temperature measurements (APCT-3) • Wireline log with triple combo, FMS-sonic, check shot with VSI
Nature of rock anticipated:	Mud turbidites

Site summaries (continued)

Site MBF-6A

Priority:	Primary
Position:	08°0.4200′N, 088°6.6000′E
Water depth (m):	3665
Target drilling depth (mbsf):	300
Approved maximum penetration (mbsf):	500
Survey coverage (track map; seismic profile):	• Map (Fig. **AF1**) • Seismic Line GeoB97-20+27, CMP 15862 (Fig. **AF4**) • Seismic Line GeoB06-237, CMP 987 (Fig. **AF5**)
Objective(s):	Depocenter migration
Drilling program:	Hole A: APC/XCB to 300 m
Logging program and downhole measurements program:	APC core orientation and formation temperature measurements (APCT-3)
Nature of rock anticipated:	Mud turbidites

Site summaries (continued)

Site MBF-2A

Priority:	Primary
Position:	08°0.4200′N, 087°40.2480′E
Water depth (m):	3671
Target drilling depth (mbsf):	900
Approved maximum penetration (mbsf):	1200
Survey coverage (track map; seismic profile):	• Map (Fig. AF1) • Seismic Line GeoB97-20+27, CMP 13449 (Fig. AF6) • Seismic Line GeoB06-245, CMP 859 (Fig. AF7)
Objective(s):	• Neogene history • Depocenter migration
Drilling program:	Hole A: APC/XCB to 900 m
Logging program and downhole measurements program:	• APC core orientation and formation temperature measurements (APCT-3) • Wireline log with triple combo, FMS-sonic, check shot with VSI
Nature of rock anticipated:	Mud turbidites

Site summaries (continued)

Site MBF-5A

Priority:	Primary
Position:	08°0.4200′N, 087°10.9020′E
Water depth (m):	3685
Target drilling depth (mbsf):	300
Approved maximum penetration (mbsf):	500
Survey coverage (track map; seismic profile):	• Map (Fig. **AF1**) • Seismic Line GeoB97-20+27, CMP 10760 (Fig. **AF8**) • Seismic Line GeoB06-247, CMP 832 (Fig. **AF9**)
Objective(s):	Depocenter migration
Drilling program:	Hole A: APC/XCB to 300 m
Logging program and downhole measurements program:	APC core orientation and formation temperature measurements (APCT-3)
Nature of rock anticipated:	Mud turbidites

Site summaries (continued)

Site MBF-4A

Priority:	Primary
Position:	08°0.4200′N, 086°47.8980′E
Water depth (m):	3694
Target drilling depth (mbsf):	300
Approved maximum penetration (mbsf):	500
Survey coverage (track map; seismic profile):	• Map (Fig. **AF1**) • Seismic Line GeoB97-20+27, CMP 8652 (Fig. **AF10**) • Seismic Line GeoB06-253, CMP 847 (Fig. **AF11**)
Objective(s):	Depocenter migration
Drilling program:	Hole A: APC/XCB to 300 m
Logging program and downhole measurements program:	APC core orientation and formation temperature measurements (APCT-3)
Nature of rock anticipated:	Mud turbidites

Site summaries (continued)

Site MBF-1A

Priority:	Primary
Position:	08°0.4200′N, 086°16.9980′E
Water depth (m):	3745
Target drilling depth (mbsf):	900
Approved maximum penetration (mbsf):	1200
Survey coverage (track map; seismic profile):	• Map (Fig. **AF1**) • Seismic Line GeoB97-20+27, CMP 5817 (Fig. **AF12**) • Seismic Line GeoB97-22, CMP 732 (Fig. **AF13**)
Objective(s):	• Neogene history • Depocenter migration
Drilling program:	Hole A: APC/XCB to 900 m
Logging program and downhole measurements program:	• APC core orientation and formation temperature measurements (APCT-3) • Wireline log with triple combo and FMS-sonic
Nature of rock anticipated:	Mud turbidites

Figure AF1. Bathymetric map showing the seafloor around Sites MBF-1A–MBF-6A. Data were gathered with a Hydrosweep DS system during Cruise SO125 (1997) and a Simrad EM120 system during Cruise SO188 (2006). Data are processed and gridded using a node size of 150 m. Black = seismic profiles shot during Cruise SO125, red = seismic profiles shot during Cruise SO188. Profiles crossing the drill sites are highlighted and annotated.

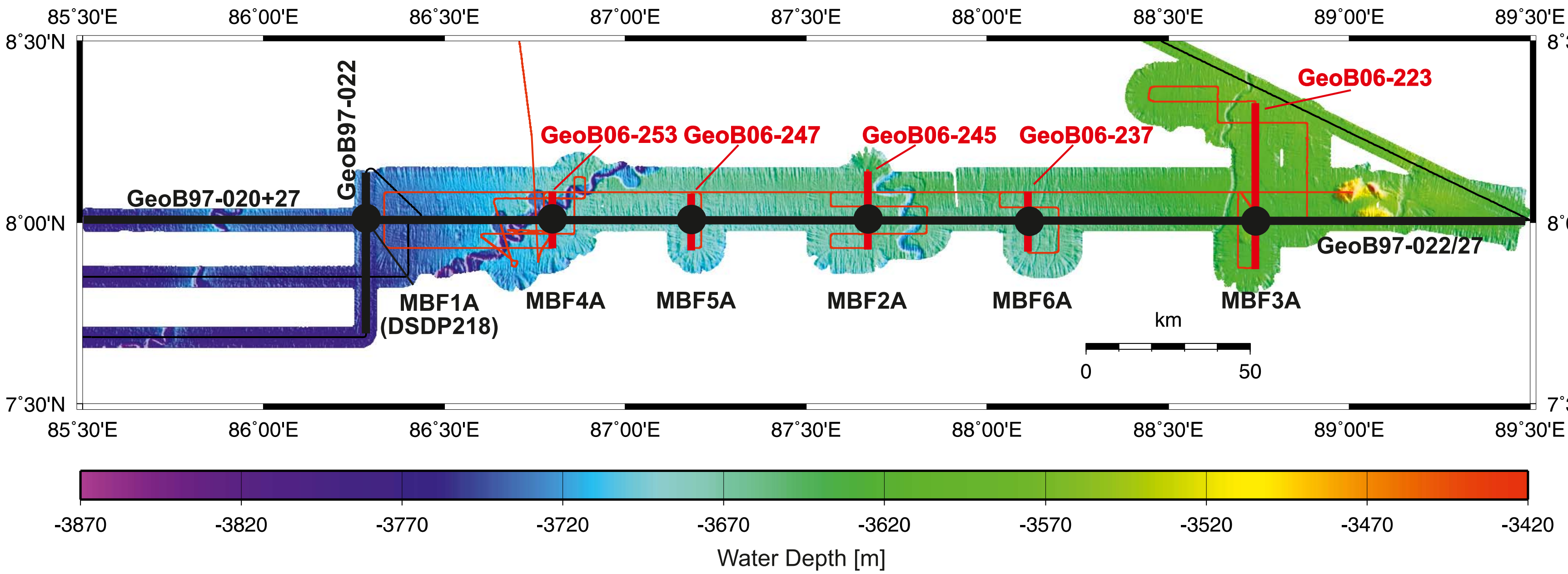


Figure AF2. Close-up of seismic Profile GeoB97-020+27 crossing Site MBF-3A. Data were collected during Cruise SO125 (1997) using a 0.4 l GI gun and 600 m analog streamer. CMP = common midpoint, TWT = two-way traveltime.

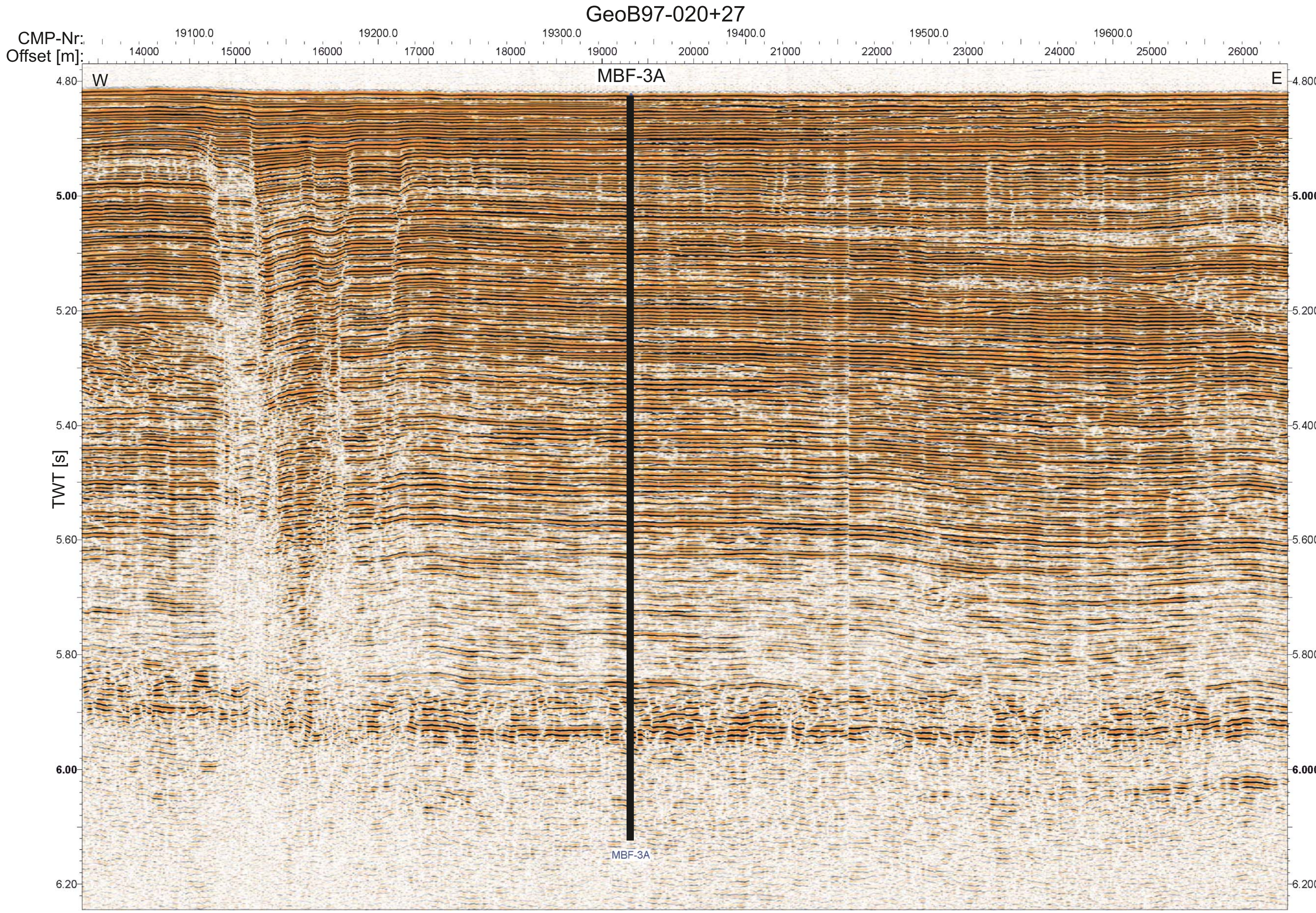


Figure AF3. Seismic Profile GeoB06-223 crossing Site MBF-3A. Data were collected during Cruise SO188 (2006) using a 4.1 l GI gun and 600 m analog streamer. CMP = common midpoint, TWT = two-way traveltime.

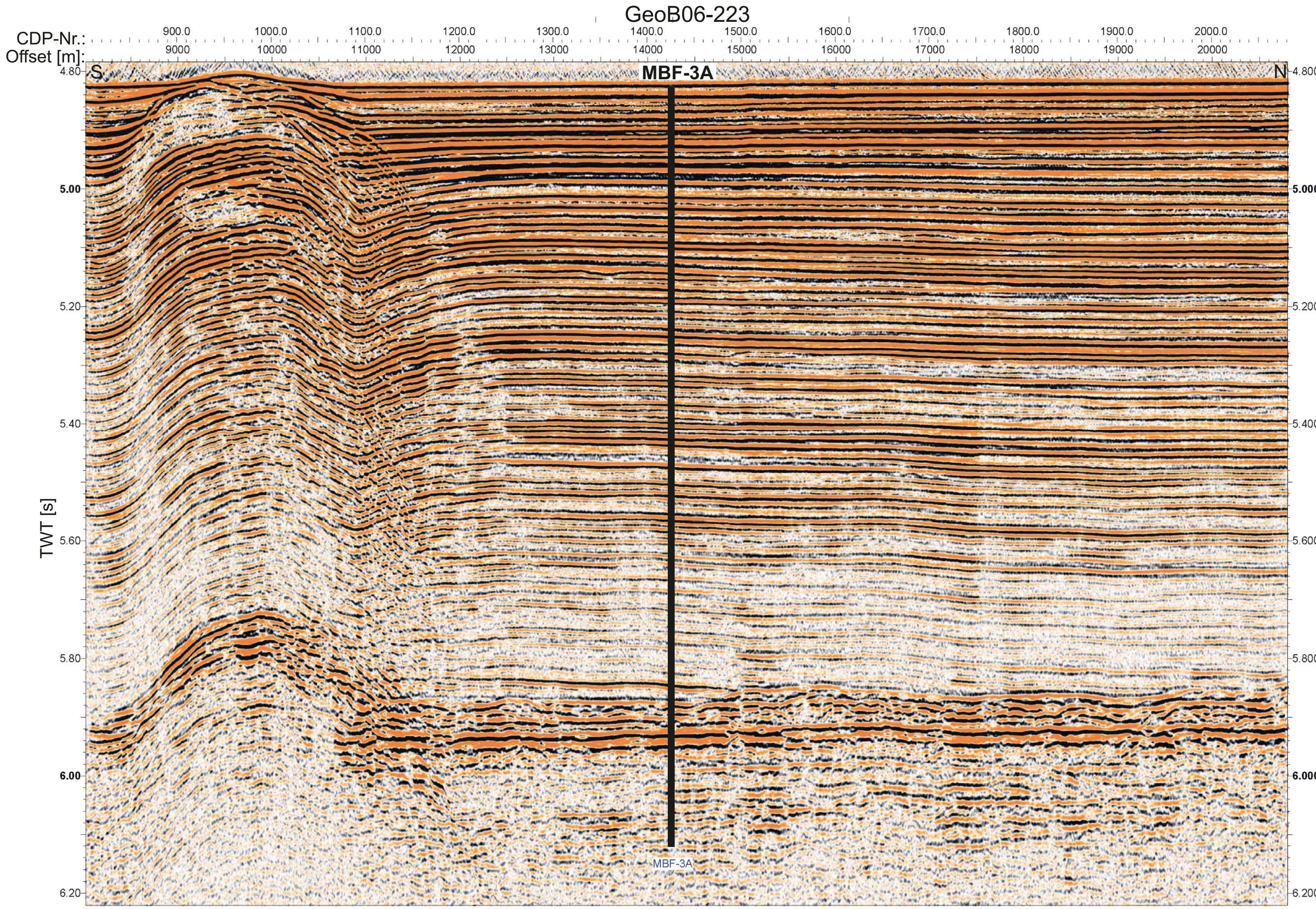


Figure AF4. Close-up of seismic Profile GeoB97-020+27 crossing Site MBF-6A. Data were collected during Cruise SO125 (1997) using a 0.4 l GI gun and 600 m analog streamer. CMP = common midpoint, TWT = two-way traveltime.

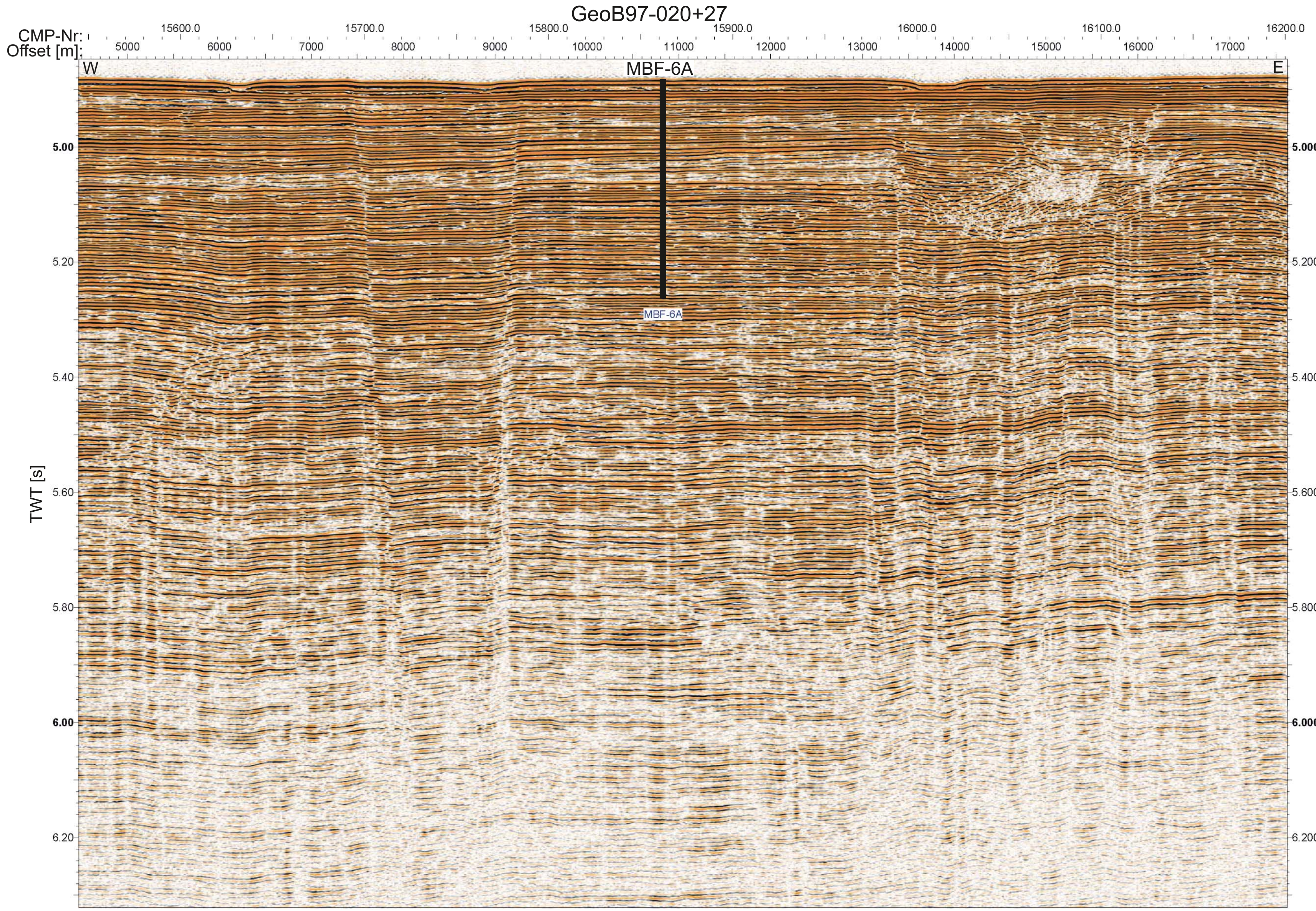


Figure AF5. Seismic Profile GeoB06-237 crossing Site MBF-6A. Data were collected during Cruise SO188 (2006) using a 4.1 l GI gun and 600 m analog streamer. CMP = common midpoint, TWT = two-way traveltime.

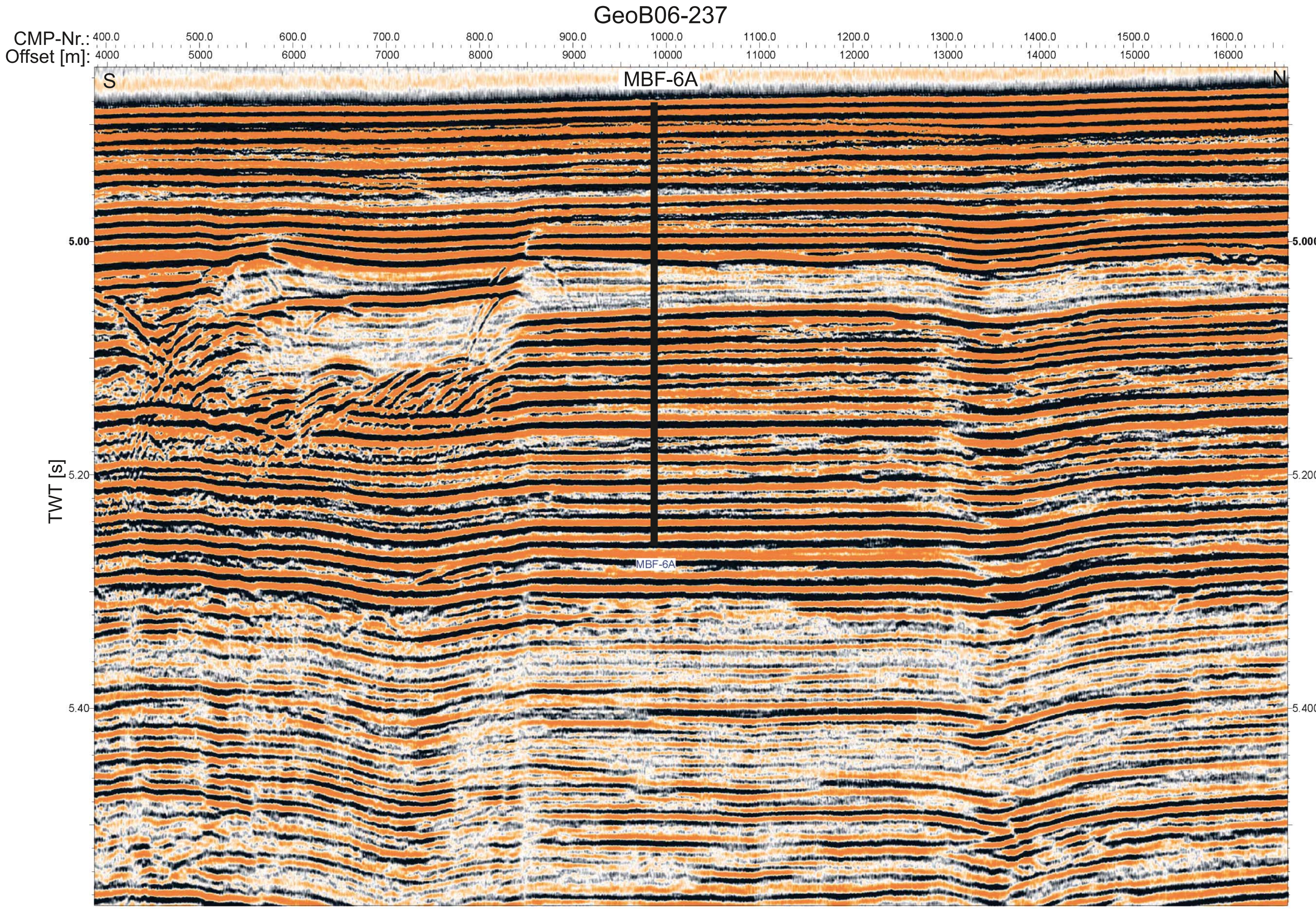


Figure AF6. Close-up of seismic Profile GeoB97-020+27 crossing Site MBF-2A. Data were collected during Cruise SO125 (1997) using a 0.4 l GI gun and 600 m analog streamer. CMP = common midpoint, TWT = two-way traveltime.

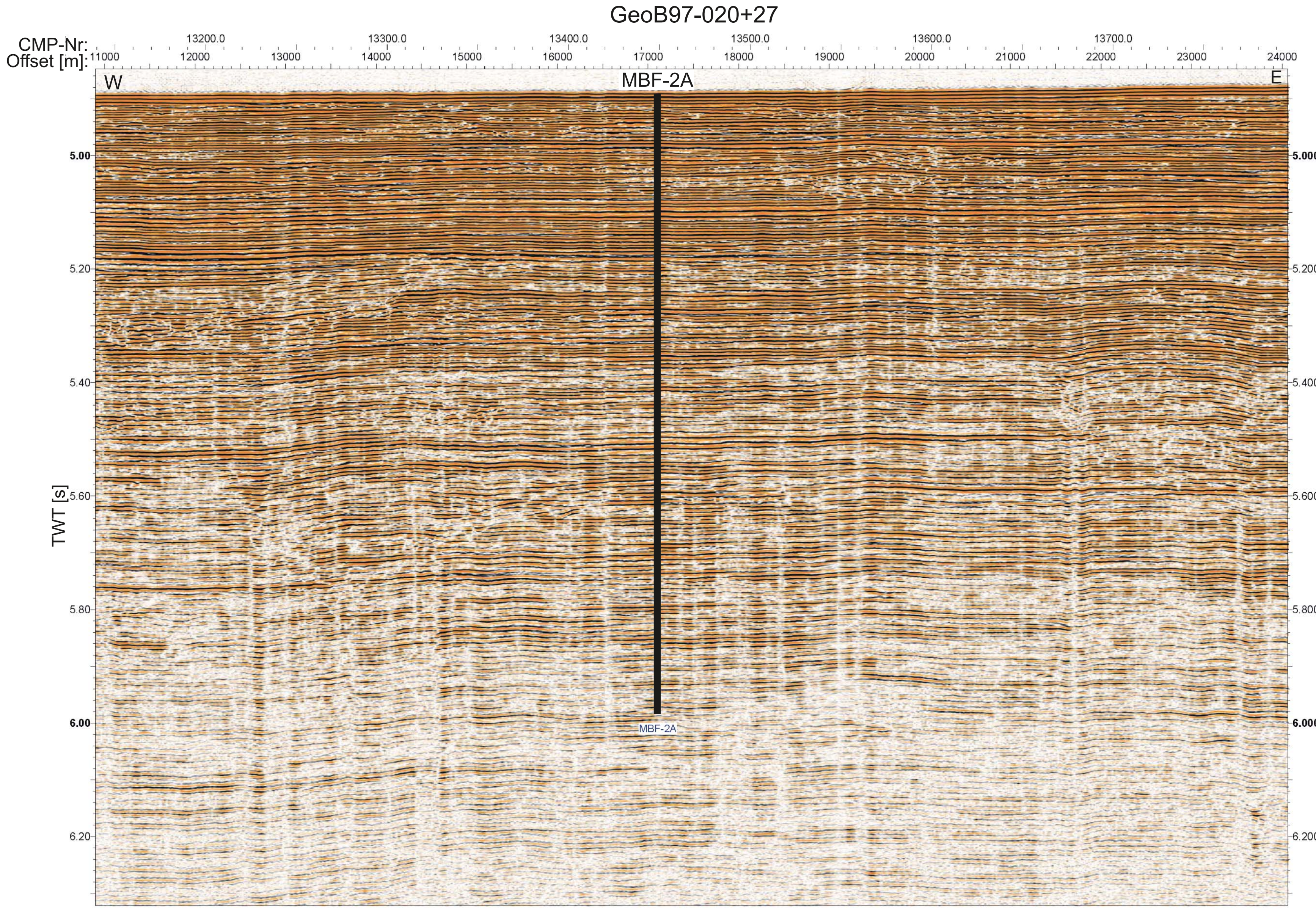


Figure AF7. Seismic Profile GeoB06-245 crossing Site MBF-2A. Data were collected during Cruise SO188 (2006) using a 4.1 l GI gun and 600 m analog streamer. CMP = common midpoint, TWT = two-way traveltime.

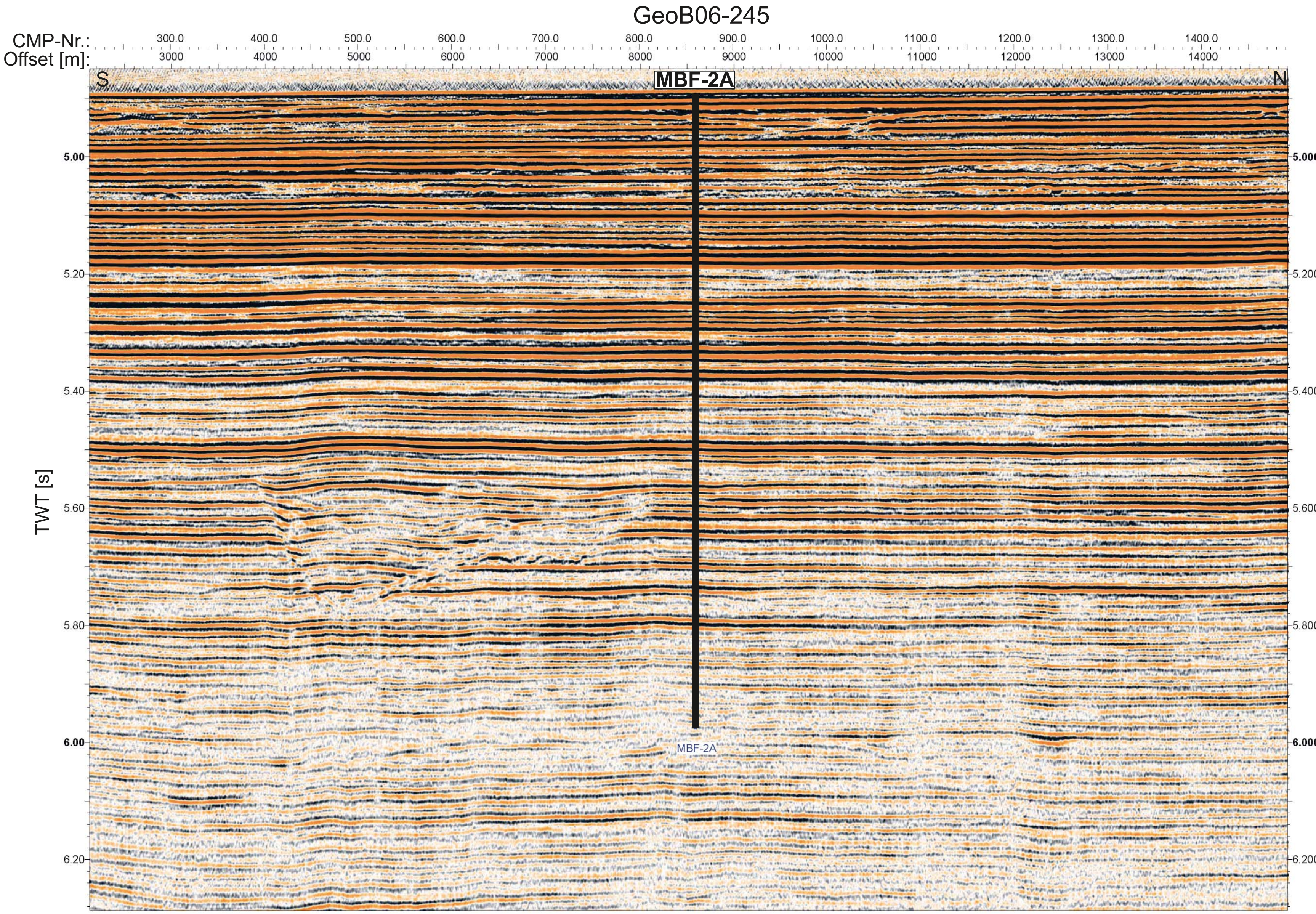


Figure AF8. Close-up of seismic Profile GeoB97-020+27 crossing Site MBF-5A. Data were collected during Cruise SO125 (1997) using a 0.4 l GI gun and 600 m analog streamer. CMP = common midpoint, TWT = two-way traveltime.

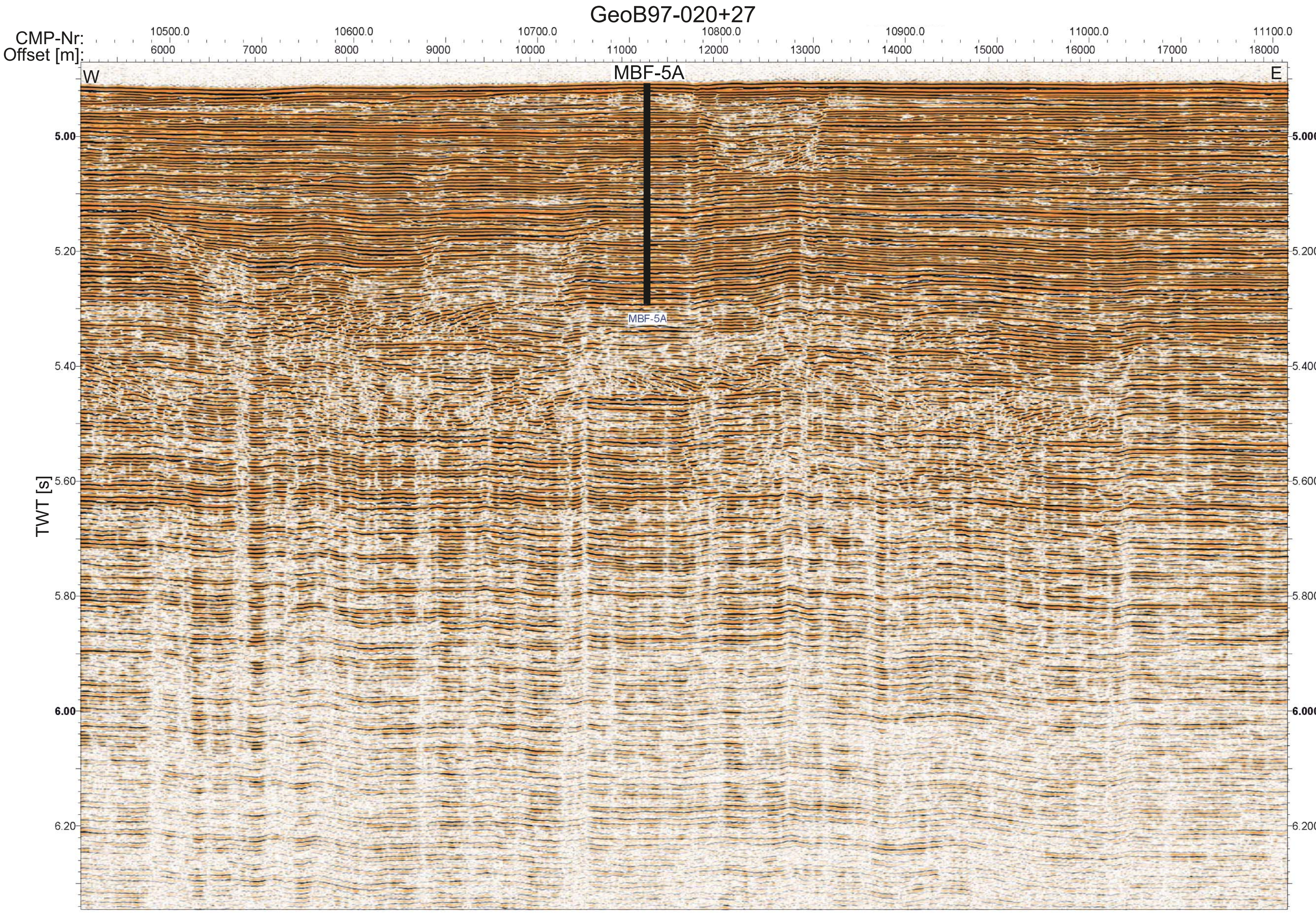


Figure AF9. Seismic Profile GeoB06-247 crossing Site MBF-5A. Data were collected during Cruise SO188 (2006) using a 4.1 l GI gun and 600 m analog streamer. CMP = common midpoint, TWT = two-way traveltime.

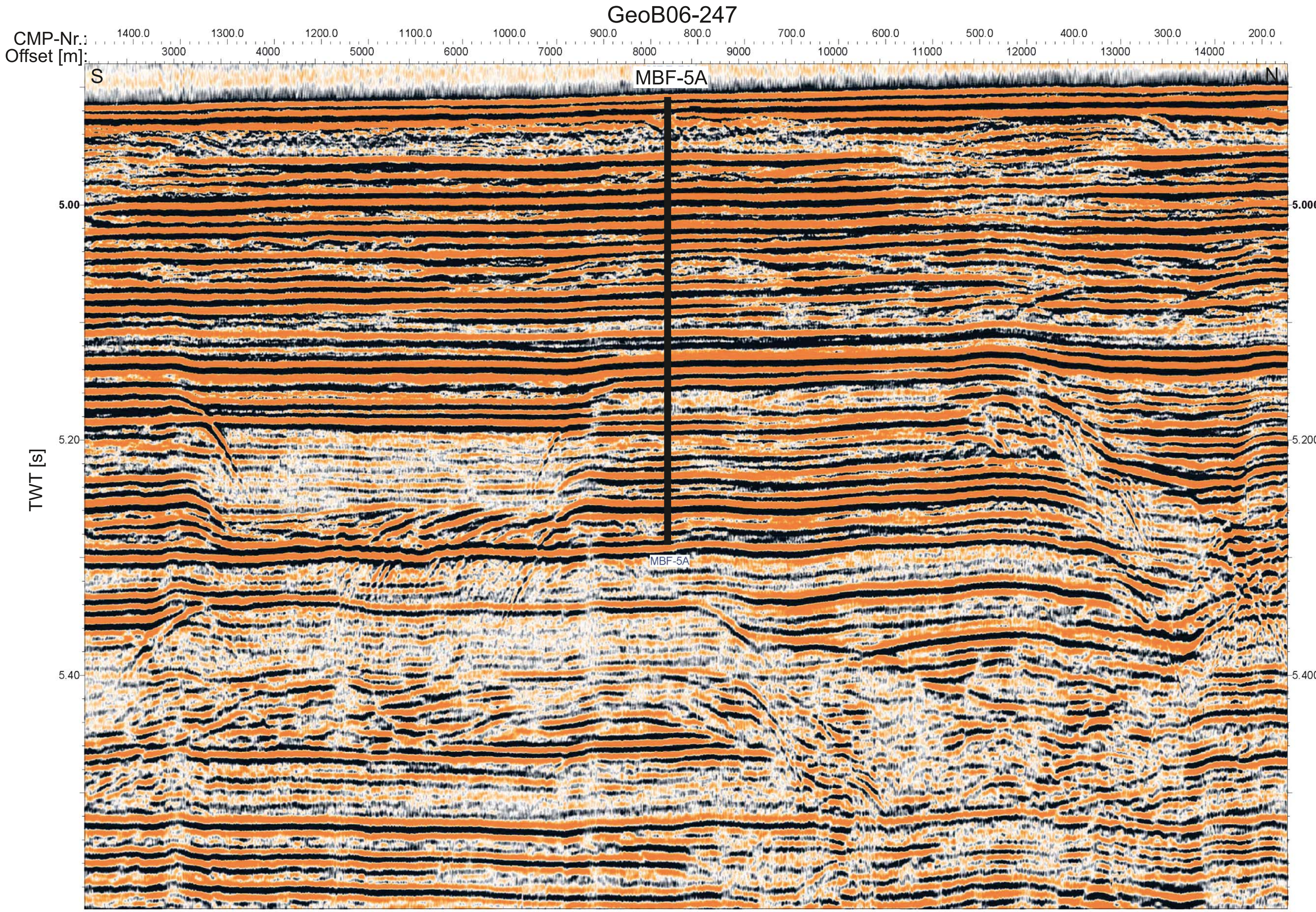


Figure AF10. Close-up of seismic Profile GeoB97-020+27 crossing Site MBF-4A. Data were collected during Cruise SO125 (1997) using a 0.4 l GI gun and 600 m analog streamer. CMP = common midpoint, TWT = two-way traveltime.

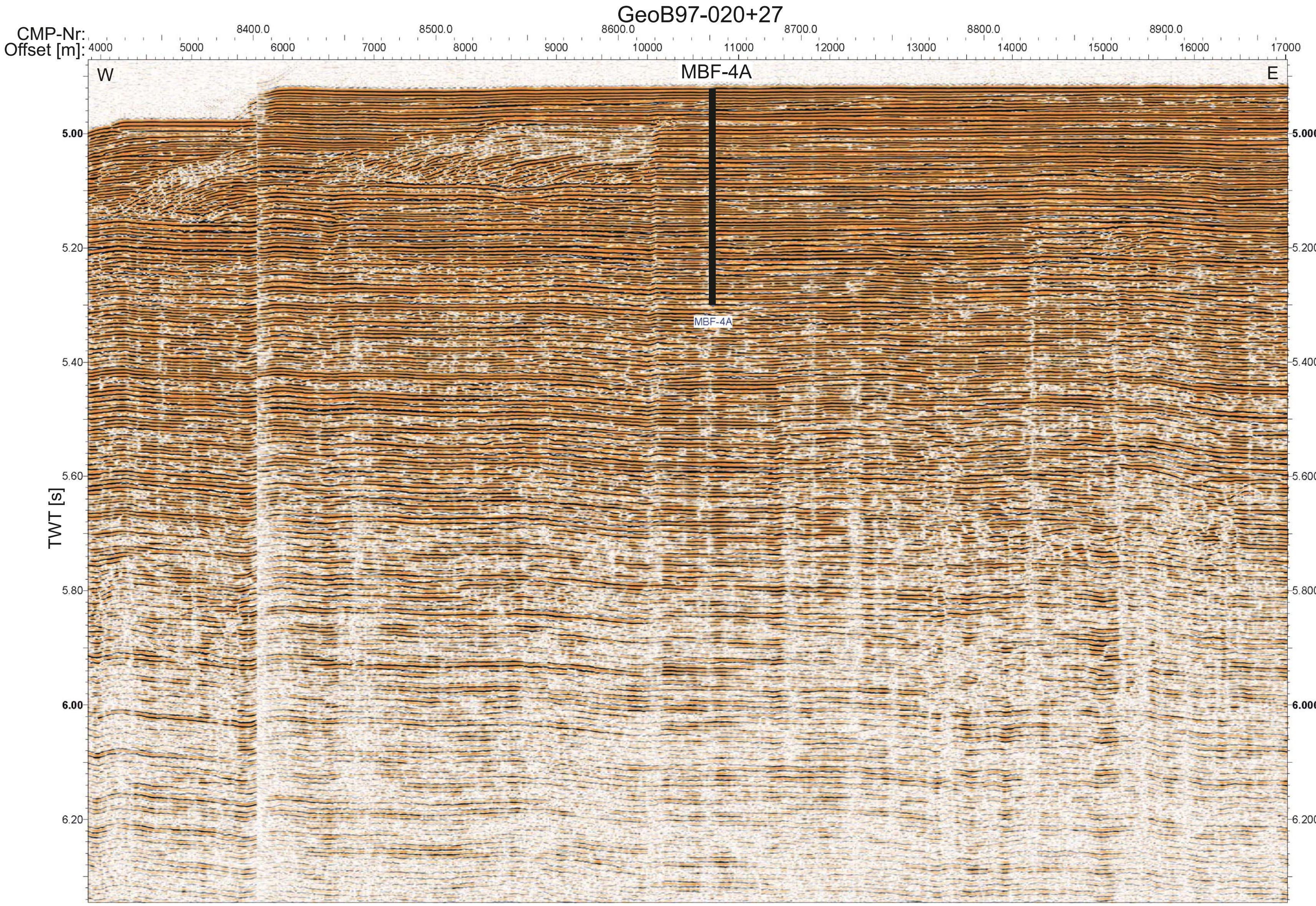


Figure AF11. Seismic Profile GeoB06-253 crossing Site MBF-4A. Data were collected during Cruise SO188 (2006) using a 4.1 l GI gun and 600 m analog streamer. CMP = common midpoint, TWT = two-way traveltime.

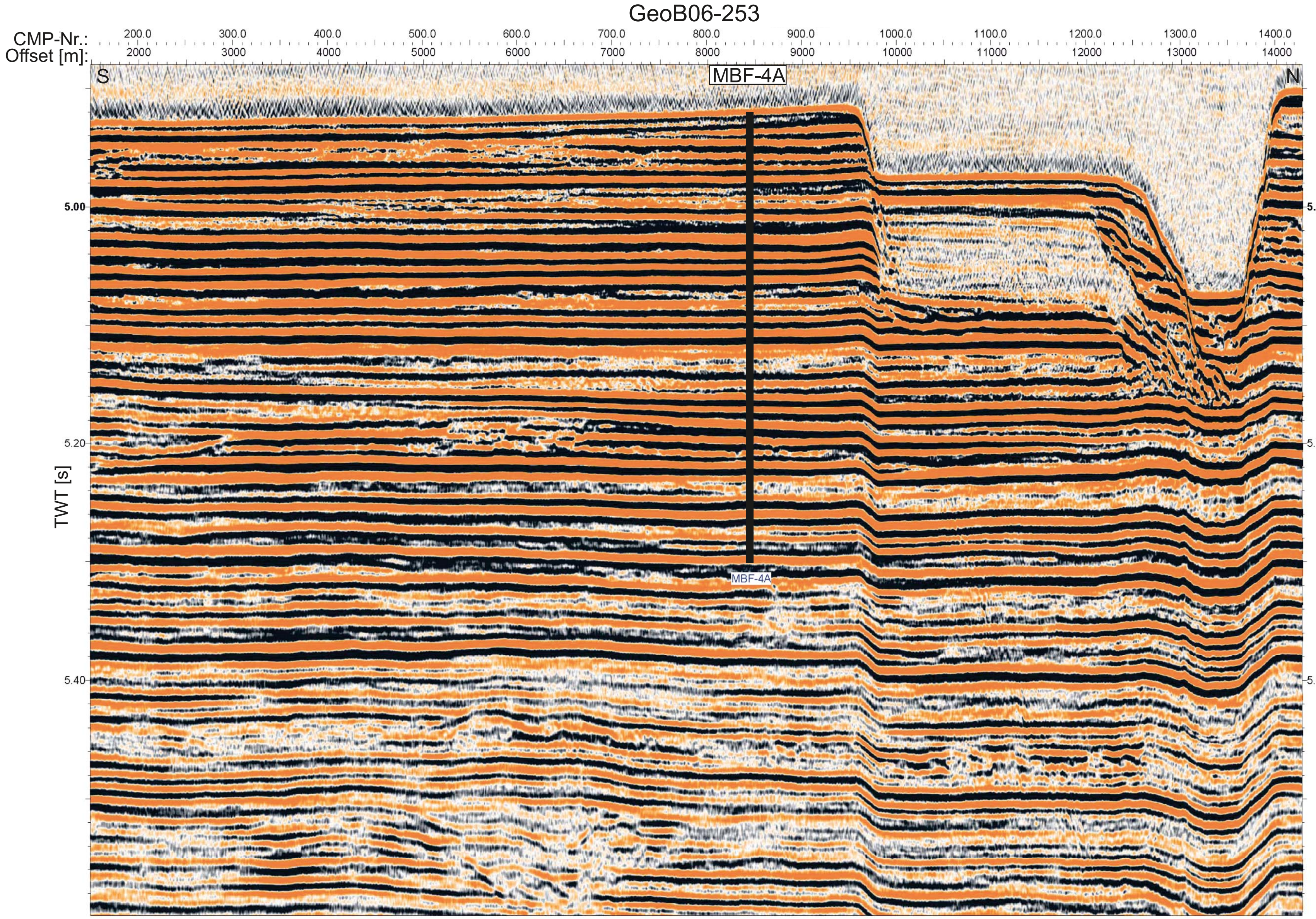


Figure AF12. Close-up of seismic Profile GeoB97-020+27 crossing Site MBF-1A. Data were collected during Cruise SO125 (1997) using a 0.4 l GI gun and 600 m analog streamer. CMP = common midpoint, TWT = two-way traveltime.

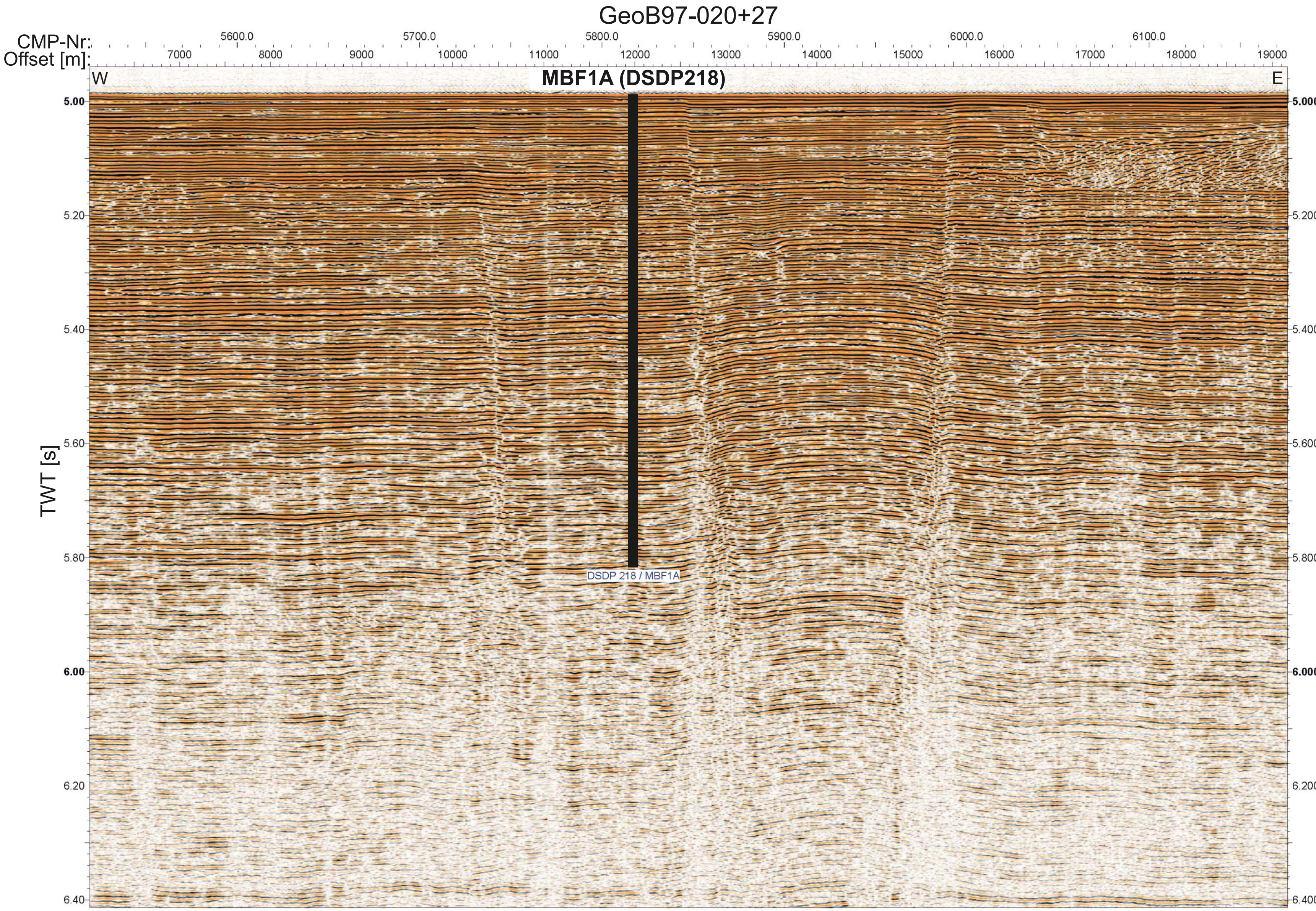
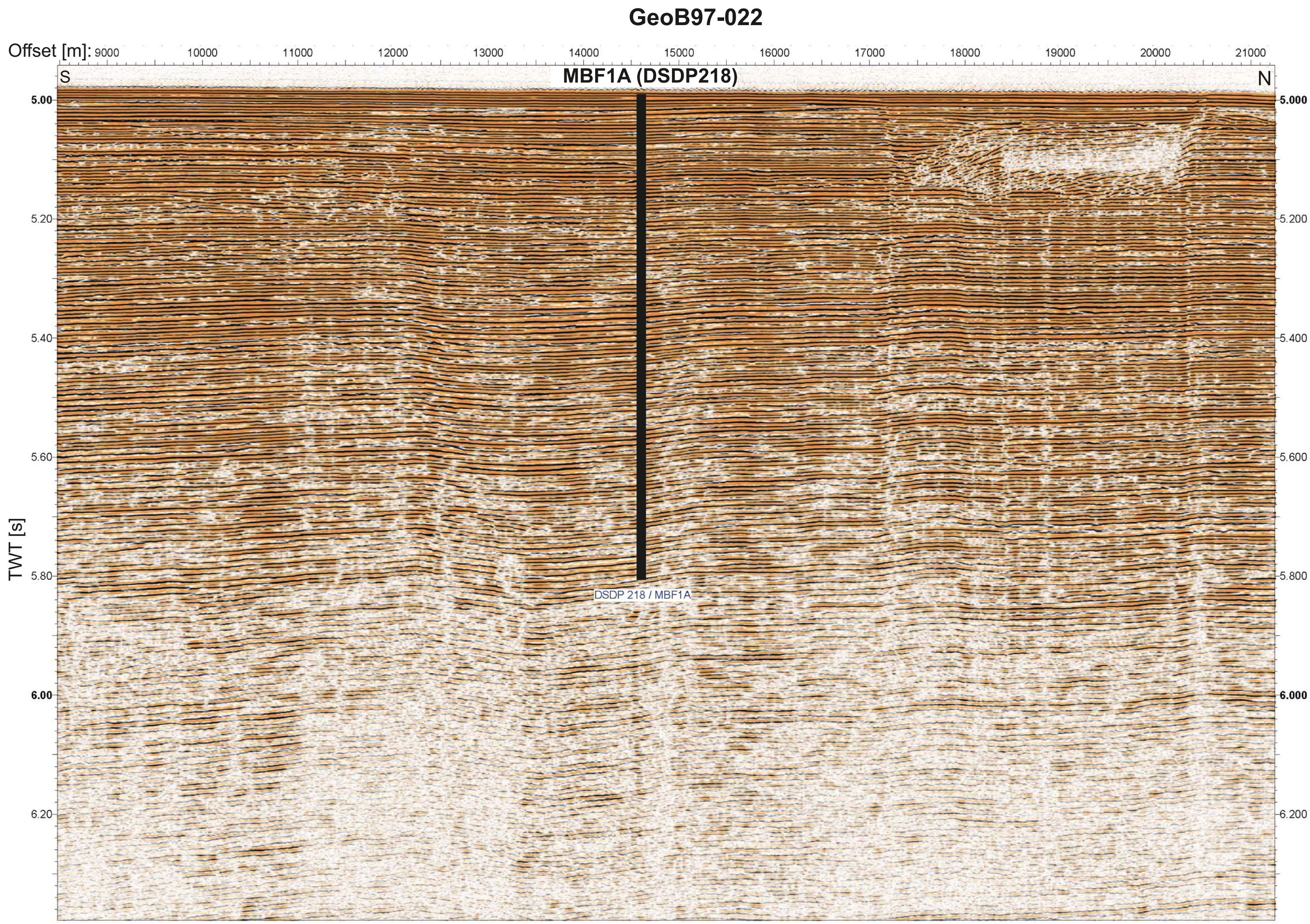


Figure AF13. Close-up of seismic Profile GeoB97-022 crossing Site MBF-1A. Data were collected during Cruise SO125 (1997) using a 0.4 l GI gun and 600 m analog streamer. TWT = two-way traveltime.



Expedition scientists and scientific participants

The current list of participants for Expedition 354 can be found at: **iodp.tamu.edu/scienceops/expeditions/bengal_fan.html.**