International Ocean Discovery Program
Expedition 378 Scientific Prospectus

South Pacific Paleogene Climate

Deborah J. Thomas
Co-Chief Scientist
College of Geosciences
Texas A&M University
USA

Ursula Röhl
Co-Chief Scientist
MARUM-Center for Marine
Environmental Sciences
University of Bremen
Germany

Laurel Childress
Expedition Project Manager/Staff Scientist
International Ocean Discovery Program
Texas A&M University
USA

INTERNATIONAL OCEAN DISCOVERY PROGRAM

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Abstract

International Ocean Discovery Program (IODP) Expedition 378 is designed to recover the first comprehensive set of Paleogene sedimentary sections from a transect of sites strategically positioned in the South Pacific to reconstruct key changes in oceanic and atmospheric circulation. These high southern–latitude sites will provide an unparalleled opportunity to add crucial new data and geographic coverage to existing reconstructions of Paleogene climate.

As the world's largest ocean, the Pacific Ocean is intricately linked to major changes in the global climate system. Previous drilling in the low-latitude Pacific Ocean during Ocean Drilling Program (ODP) Legs 138 and 199 and Integrated Ocean Drilling Program Expeditions 320 and 321 provided new insights into the mechanisms of the climate and carbon system, productivity changes across the zone of divergence, time-dependent calcium carbonate dissolution, bio- and magnetostratigraphy, the location of the Intertropical Convergence Zone, and evolutionary patterns for times of climatic change and upheaval. Expedition 378 in the South Pacific Ocean uniquely complements this work because appropriate high-latitude records are unobtainable in the Northern Hemisphere of the Pacific Ocean.

To optimize the recovery of Paleogene carbonates buried under red clay sequences at present latitudes of 40°–52°S and enable a full range of paleoceanographic proxy-based investigations, Expedition 378 will drill a transect of sites primarily situated along magnetic Anomaly 25n on ~56 Ma crust. Additional sites are located on 40 Ma crust (Anomaly 18). The drilling strategy will also redrill the sedimentary record at Deep Sea Drilling Project (DSDP) Site 277 to obtain a continuous record of a previously spot-cored, classic Paleogene high-latitude site and provide a crucial, continuous record of the shallow Subantarctic South Pacific Ocean from the Paleocene to late Oligocene.

These new cores and data will significantly contribute to the challenges of the "Climate and Ocean Change: Reading the Past, Informing the Future" theme of the IODP Science Plan (How does Earth's climate system respond to elevated levels of atmospheric CO_2? How resilient is the ocean to chemical perturbations?). Furthermore, Expedition 378 will provide material from the far South Pacific Ocean in an area with no previous scientific drilling as part of a major regional slate of expeditions in the Southern Ocean to fill a critical need for high-latitude climate reconstructions.

The operational plan is to occupy seven primary sites (with two proposed alternate sites) along an east–west transect to recover the most complete sedimentary succession possible, which includes coring three holes at each site with wireline logging operations at the two deepest penetration sites. Basement will be tagged in at least one of the holes at each site.

Expedition schedule

International Ocean Discovery Program (IODP) Expedition 378 is based on IODP drilling Proposal 567-Full4 (**http://iodp.tamu.edu/scienceops/expeditions/south_pacific_paleogene_climate.html**). Following evaluation by the IODP Scientific Advisory Structure, the expedition was scheduled for the R/V *JOIDES Resolution*, operating under contract with the JOIDES Resolution Science Operator (JRSO).

At the time of publication of this *Scientific Prospectus*, the expedition is scheduled to start in Lyttelton, New Zealand, on 14 October 2018 and end in Papeete, Tahiti, on 14 December. A total of 61 days will be available for the initial port call, transit, drilling, coring, and downhole measurements described in this report. For the current detailed schedule, see **http://iodp.tamu.edu/scienceops/**. Further details about the facilities on board the *JOIDES Resolution* can be found at **http://iodp.tamu.edu/publicinfo/drillship.html**.

Introduction

The South Pacific Paleogene Climate (SPLAT) science program is based on IODP Proposal 567-Full4. The goal is to investigate the record of Cenozoic climate and oceanography through a drilling transect in the high-latitude southern Pacific Ocean. In particular, we will target shallowly buried, carbonate-bearing sediments deposited during the very warm late Paleocene and early Eocene, including the Paleocene/Eocene boundary and Eocene–Oligocene transition, to investigate how the Eocene Earth maintained high global temperatures and high heat transport to the polar regions despite receiving near-modern levels of solar energy input. Investigation of the recovered sediments also will constrain the subpolar Pacific Ocean climate, oceanographic structure, and biogeochemical cycling of much of the Cenozoic. Recovered sediments will be used to characterize water masses, deep and shallow ocean temperature, latitudinal temperature gradients, the strength of upwelling, and the strength of the zonal winds to study both the atmospheric and oceanic climatic subsystems.

Expedition 378 will investigate the system of convergences, divergences, and mixing zones in subpolar to polar latitudes. A zone of high biological productivity is associated with physical mixing at the polar front and the upwelling and divergence region poleward of the polar front. The array of seven primary sites and two alternate sites were chosen to encompass 33° of longitude (Deep Sea Drilling Project [DSDP] Site 277 at 166°E and proposed Site SP-14A at 133°W) and 12° of latitude (Site 277 at 52°S and proposed Site SP-15A at 40°S), providing comprehensive regional coverage to achieve the expedition objectives (Figure **F1**). The sites planned for Expedition 378 are located across the early Paleogene transition from subtropical to subpolar surface water masses. This transect spans the region where intermediate waters are formed in the modern ocean. Although it is debated where and how these waters might have formed in the Eocene, their locus of formation can be monitored by the strength of oceanic fronts and convergences in the South Pacific, as recorded by numerous proxies. The width of the subpolar front measures the strength of convergence and the extent to which Antarctic Intermediate Water is formed. In the process of measuring these gradients, the drill sites along the transect will define the physical size of the subtropical gyre and the subpolar climate zone during the very warm climates of the early Paleogene. One of the primary needs for both atmospheric and oceanic circulation models is robust sea-surface temperature (SST) control. These data form a major boundary condition for constraining these models, the most easily observable signal of circulation patterns. Temperature gradient can be measured in a relative sense even if the absolute calibrations are off with respect to the Subantarctic or equatorial region.

Redrilling Site 277 will allow for the direct sampling of intermediate water compositions in addition to making use of the latitudinal gradient. The Drake Passage (or Drake Isthmus) separated the abyssal South Atlantic from the abyssal South Pacific through much of the Paleogene (there was likely a shallow connection via the Transantarctic Seaway prior to the opening of the Drake Passage), and it is likely that South Pacific thermohaline structure was different from the South Atlantic. Expedition 378 will allow researchers to compare Atlantic and Pacific Ocean circulation during this critical time interval.

Background and geological setting

Reconstruction of environmental conditions and physical processes in the Paleogene oceans

The broad outlines of the major features of ocean circulation such as water mass distributions; regions of steep gradients in temperature, salinity, and biologic productivity; and the distribution of deep-water masses all leave records in seafloor sediments. Surface-water provinces are identified by their salinity and temperature in the modern ocean. Distinct assemblages of planktonic organisms are associated with these provinces; thus, microfossil assemblages of these organisms can be used to define the geographic extent of water masses in premodern sediments. Divergence of near-surface water usually supports higher organic productivity, which leaves a diagnostic geochemical and micropaleontological fingerprint in the underlying sediments. Steep gradients in the surface ocean are preserved in the records of planktonic microfossil assemblages and mark regions of vigorous near-surface transport as wind-driven open-ocean and boundary currents. Winds that drive these currents may be reconstructed through the geochemical composition of the dust from upwind continental areas and the grain size of that dust once the contributions of volcanic ash have been characterized.

Present heat transport to the poles is divided approximately equally between the atmospheres and the oceans. Wind-driven currents achieve about half of the ocean heat transport, whereas the balance of oceanic heat transport is driven by the overturning circulation. Obviously, all aspects of heat transport must be defined as well as possible in our effort to better understand ocean circulation and the role it plays in times of extremely warm climates. By focusing our efforts on a specific time interval in both the previously drilled equatorial and presently proposed subpolar–polar transects, we will be able to reconstruct Eocene heat transfer from the equatorial region to the Antarctic at orbital timescales, along with the circulatory response of the ocean and atmosphere.

At 56 Ma, the proposed transect was located in the southeastern South Pacific Ocean ~2000–3000 km west of South America and 3000 km east of New Zealand (Figure **F2**). We will study this important oceanographic transition zone during the period of maximum Cenozoic warmth near the time of the Paleocene/Eocene boundary. The proposed sites lie along magnetic Anomaly 25n (~56 Ma) to best resolve oceanographic processes in the time window between 56 and 46 Ma. Proposed Sites SP-13A and SP-14A will be located on 40 Ma crust to best document the Eocene/Oligocene boundary (Figure **F2**). This strategy is similar to that of ODP Leg 199 and Integrated Ocean Drilling Program Expeditions 320 and 321, which revealed important differences between the Eocene and present circulation patterns in the equatorial Pacific (e.g., Moore et al. 2004; Pälike et al. 2010).

Sea-surface temperatures

The early Paleogene (65–35 Ma) was the most recent geologic interval during which atmospheric $p\mathrm{CO_2}$ levels were likely above ~1000 ppm (e.g., Pearson et al. 2009; Pagani et al. 2011; Hönisch et al., 2012). Theory and models indicate that elevated atmospheric greenhouse gas inventories would have produced higher surface temperatures. These results are confirmed by multiproxy reconstructions of SSTs and indicate that tropical SSTs ranged from ~34° to 38°C at ~50 Ma (Pearson et al., 2006; Huber, 2008), SSTs in the high-latitude South Pacific (~55°S) ranged from 20° to 35°C (Bijl et al., 2009; Hollis et al., 2012; Pross et al., 2012), and SST estimates from Seymour Island were ~15°C (Ivany et al., 2011). These SST estimates produce early Paleogene equator-to-pole thermal gradients significantly lower than that of the modern ocean (e.g., Hollis et al. 2009; Lunt et al. 2012). Fully coupled model simulations using strong greenhouse gas radiative forcing yield seasonal thermal gradients generally consistent with the available proxy data (Huber and Caballero, 2011; Hollis et al., 2012; Lunt et al., 2012) but with a tendency to produce meridional temperature gradients that remain somewhat too strong.

Ocean circulation

Oceanic meridional overturning circulation (MOC) is a crucial component of the climate system, impacting heat transport, nutrient transport, and global carbon cycling. The operating mode of the MOC was significantly different during the Late Cretaceous and early Paleogene (e.g., Thomas et al. 2014). In the modern oceans, Antarctica is surrounded by the world's strongest ocean current, the Antarctic Counter Current (ACC), which flows around Antarctica and reaches from the surface to abyssal depths. The current is sufficiently strong to cause erosion and sediment transport near its axis at 50°–55°S (e.g., Goodell et al. 1971; Watkins and Kennett 1977; Hollister and Nowell 1991). In the early Paleogene, the Southern Ocean was divided into Pacific and Atlantic-Indian sectors because Australia and South America were joined to Antarctica. Each Southern Ocean sector developed a unique subpolar gyre; the Pacific sector gyre is known as the proto-Ross Gyre (Huber et al. 2004; Stickley et al. 2004).

An increasing catalog of water mass proxy data combined with state-of-the-art numerical simulations provides a reconstruction of MOC characterized by convection in the South Pacific as well as the North Pacific during the latest Cretaceous through early Paleogene. Nd isotope data also suggest that MOC in the Pacific Ocean was distinct and separate from that in the Atlantic Ocean (Thomas et al., 2014). This reconstruction is supported by fully coupled Global Circulation Model simulations that indicate the "age" of deep water in the Pacific Ocean increased from high to low latitudes in both the South and North Pacific (Hague et al., 2012). Ocean-only model simulations employing a range of boundary conditions are able to reproduce the intermediate- and deep-water Nd isotope distribution (Thomas et al., 2014). The best model-data match results from imposing strong vertical mixing within the water column, and the condition of strong vertical mixing results in enhanced oceanic heat transport. Thus, in spite of diminished meridional thermal gradients, poleward oceanic heat transport may have contributed significantly to warm high-latitude SSTs.

A viable and accurate reconstruction of Late Cretaceous and early Paleogene MOC should be reflected in multiple proxies of water mass composition or water mass "aging." Unfortunately, comparison of the Nd isotope data to stable carbon isotope values recorded by benthic foraminifers in the same suite of North and South Pacific sites is not possible due to the lack of carbonate preservation in early Paleogene sediments. A very shallow carbonate compensation depth (CCD) during most of the Paleogene makes it difficult to obtain well-preserved sediments during these stratigraphic intervals, but the site location strategy for the current expedition is designed to occupy the most promising sites and obtain a unique sedimentary biogenic sediment archive for time periods just after the Paleocene/Eocene boundary event, Eocene cooling, and the Eocene–Oligocene transition.

Modern Antarctic circulation developed when deep-water passages were formed south of Australia (the Tasman Gateway) and through the Scotia Arc (Drake Passage). Interestingly, abyssal hiatuses along the thermohaline flow path at the base of the Campbell Plateau developed at the time of the Eocene/Oligocene boundary, but shallow-water hiatuses developed perhaps 3 My later. Furthermore, data along the ACC flow path suggests that the ACC developed in the late Oligocene or at the Oligocene/Miocene boundary (Pfuhl and McCave, 2005; Lyle et al., 2007).

Data from ODP Leg 189 (Stickley et al., 2004; Bijl et al., 2013) suggest the earliest throughflow of a westbound ACC began at ~49–50 Ma through a southern opening of the Tasmanian Gateway in conjunction with the simultaneous onset of regional surface water and continental cooling (2°–4°C). The timing of subsequent deepening of the Tasman Gateway and Drake Passage still is not well constrained, with estimates ranging from the middle Eocene to early Miocene for the development of circum-Antarctic deep-water passages and the formation of the full ACC (Lawver and Gahagan, 1998, 2003; Barker, 2001; Pfuhl and McCave, 2005; Scher and Martin, 2006). The impact of ACC formation on regional and global climate also remains debated. Proposed sites in the pelagic southwestern Pacific will provide the opportunity to study when the ACC formed and how it relates to tectonics (Lyle et al., 2007).

Water formation and hydrologic cycling

Deep and bottom water is likely to have formed south of the polar front (e.g., van de Flierdt et al., 2004; Thomas et al., 2014), and the character of this deeper water can be assessed by measuring geochemical signals preserved in benthic foraminifers, fossil fish teeth and bones, and Fe-Mn oxide minerals at the proposed drill sites. Together with the depth transects drilled by ODP Legs 198 and 208, this latitudinal transect will either demonstrate a mode of intermediate water formation comparable to that of the modern ocean or point to a completely different characterization of intermediate water in the extreme warmth of the early Eocene.

Assuming that the available estimates of atmospheric CO_2, SSTs, and terrestrial temperature records using available proxies accurately reflect the early Paleogene climate state, we can make predictions about the resulting prevailing winds and hydrologic cycling. For example, models and limited proxy data suggest that overall hydrologic cycling was more intense during the early Paleogene, resulting in higher precipitation in temperate and high latitudes (e.g., Pagani et al., 2006). Higher precipitation/humidity would have produced temperate and high-latitude continental regions with greater vegetative cover than in drier periods. Lower aridity in these dust source regions would result in diminished dust transport to the ocean basins. Conversely, an enhanced hydrological cycle implies a drying of the arid-to-semi-arid regions (Held and Soden, 2006) that may have enhanced the size of the subtropical dust source regions.

Only a few dust accumulation and provenance records exist for the Late Cretaceous and early Paleogene (e.g., Janecek and Rea, 1983; Hovan and Rea, 1992; Zhou and Kyte, 1992). In general, the compilation of long-term data indicates higher dust accumulation in the North Pacific (DSDP Site 576; piston Core LL44-GPC3) than the southern Indian Ocean (ODP Sites 756 and 757) during the Late Cretaceous and early Paleogene. Late Paleocene high-resolution data from Indian Ocean DSDP Site 215 show a transient increase in dust fluxes at ~59 Ma, but fluxes prior to and after the pulse seem to be consistent with the few other Southern Hemisphere locations (Hovan and Rea, 1992). Northern Hemisphere dust fluxes increased throughout the Neogene; however, the Indian Ocean sites record a slight decrease in flux throughout the Cenozoic. Thus, the southern high-latitude Paleogene transect of Expedition 378, set in the South Pacific Ocean, provides the best opportunity to integrate both atmospheric and oceanic indicators into a complete paleoenvironmental picture for this unusually warm time period. However, the discovery of a broad region that must have had very low biological productivity for all of its history (the "bare zone") will require rethinking South Pacific Ocean atmospheric and surface ocean circulation (Rea et al., 2006).

Chronostratigraphy

With the recovery of high-quality, multiple-hole cored sedimentary successions from the Atlantic (ODP Leg 171B, Blake Nose; ODP Leg 207, Demerara Rise; ODP Leg 208, Walvis Ridge; Integrated Ocean Drilling Program Expedition 342, Newfoundland) and the Pacific (ODP Leg 198, Shatsky Rise; Leg 199 and Expeditions 320 and 321, East Equatorial Pacific), highly suitable material with good preservation of foraminifer tests was found to generate high-resolution benthic stable isotope records. This high-quality material also has led to the development of astronomically calibrated age models for the 67–34 Ma interval (e.g., Röhl et al., 2000, 2003, 2007; Lourens et al., 2005; Zachos et al., 2005; Zachos et al., 2010; Westerhold et al., 2011, 2014; Littler et al., 2014; Lauretano et al., 2015, 2016; Barnet et al. 2017), including orbital cycle–based age models for the Paleocene-Eocene Thermal Maximum (Röhl et al., 2000, 2007; Westerhold et al., 2009, 2014). Expedition 378 will retrieve unique sections including crucial time intervals for the South Pacific area, and all efforts will be made to integrate expedition data, namely biomagnetostratigraphy, toward a robust chronostratigraphy.

Previous drilling

Prior to Integrated Ocean Drilling Program Expedition 329, there were no DSDP/ODP sites in the pelagic Pacific Ocean south of ~20°S, where DSDP Leg 92 drilled a transect of Oligocene and younger sediments down the west slope of the East Pacific Rise (Leinen et al., 1986). The last four drilling cruises to the 40°–60°S region recovered a reasonable amount of mid- to upper Eocene sediment only once, during Leg 177 in the Atlantic sector of the Southern Ocean. Leg 177 drilled a transect of sites extending south from the Cape of Good Hope, with the work at Site 1090 recovering middle Eocene calcareous ooze grading up into upper Eocene siliceous ooze (Shipboard Scientific Party, 1999a). In the Indian Ocean sector, ODP Leg 183 was a large igneous provinces experiment set on Kerguelen and Broken Ridge. Leg 183 recovered minor amounts of middle Eocene and younger carbonate ooze at Site 1135 but was rotary drilled. Other Leg 183 sites, also rotary drilled, had very low recovery (Shipboard Scientific Party, 2000). Leg 181, drilled east and south of New Zealand, recovered essentially no Eocene material (Shipboard Scientific Party, 1999b). In the South Pacific, DSDP Leg 35 Sites 322 and 323 west of the Antarctic Peninsula were spot cored, recovering less than 10% of the existing section, and did not recover any Eocene-age materials (Hollister et al., 1976). Forthcoming results from recently completed IODP Expedition 371 will contribute to regional paleoceanographic reconstructions.

The best known Paleogene paleoceanographic site in the entire region is DSDP Leg 29 Site 277. This site, located south of New Zealand, recovered upper Oligocene to upper Paleocene carbonates but was spot-cored through most of the section and had low recovery in the Eocene (Shipboard Scientific Party, 1975). The current water depth at this location is ~1215 m. The sediment sequence consists of ~10 m of Pliocene–Pleistocene carbonate ooze, disconformably separated from an expanded middle Paleocene to upper Oligocene sequence with sedimentation rates of 19 to 22 m/My. The sediments spanning the upper Eocene to upper Oligocene are stiff carbonate oozes, with the ooze to chalk transition nominally placed at 246 mbsf. Middle Paleocene to upper Eocene sediments are variably indurated but typically consist of chalks with low to moderate amounts of lithification (Shipboard Scientific Party, 1975). Materials from this site provided most of the samples for two classic oxygen isotope curves that first defined the unusually warm early Eocene period (Shackleton and Kennett, 1975; Savin, 1977). The original spot-coring at Site 277 yielded a valuable high-latitude southern record (e.g., Shackleton and Kennett, 1975) that will be redrilled during Expedition 378. Improvements in the advanced piston core (APC) and half-length APC core (HLAPC) technologies and better core-log integration have vastly improved the ability to develop triple-core stratigraphic splices, and the ability to correlate seismic reflection data. This capacity will allow us unprecedented insight into the details and timing of the major events preserved in the sedimentary record on the Campbell Plateau (Hollis et al., 2015).

Seismic studies and site survey data

The U.S. National Science Foundation funded the site survey cruise to the Southwest Pacific Basin aboard the R/V *Melville*, conducted February through March of 2005. During that cruise, 7000 km of seismic reflection profiles and 14,000 km of swath-map bathymetry were collected. Twelve areas were surveyed as potential drilling sites, and nine jumbo piston cores and six gravity cores were recovered. This is the best set of new piston cores from the region in the last 30 y. But it is important to note that short piston cores (<20 m) taken during site survey cruises often are not able to inform Paleogene drilling objectives because the targeted sediments typically lie deeper than the penetration of a single piston core.

Sediment thicknesses above basement vary from >480 m at Site 277 to ~30 m at proposed Site SP-5B. Although several Expedition 378 proposed sites have <100 m of sediment cover, a prominent regional unconformity of late Oligocene age separates slowly accumulating Neogene-aged sediments from more rapidly accumulating Paleogene sediments. Results from seismic survey Core MV0502-9JC (discussed below) demonstrate that the unconformity exists at a relatively shallow depth (12 cm below seafloor); therefore, we are confident that the majority of the sediment sequences at the targeted sites contain Paleogene material that accumulated sufficiently rapidly to resolve orbital cyclicity.

Results from Core MV0502-9JC (proposed Site SP-14A) consist of 14.2 m of recovered sediments that span several prominent seismic reflections corresponding to significant variations in biogenic carbonate and silica (Figure **F3**) (Lyle et al. 2007). Radiolarian and calcareous nannofossil biostratigraphy constrains the ages of the lithologic variations. Seismic Layer 1 is a 3 m carbonate-rich sediment layer deposited during the Pleistocene overlaying seismic Layer 2, which is composed of clays that date from the late Pliocene (~2 Ma) to the late Miocene (~9 Ma). The clay layer is 9 m thick where cored and accumulated at a slow rate of ~1 m/My.

Radiolarians preserved in the upper part of seismic Layer 2 (between 3 and 6 m below seafloor [mbsf]) are slightly younger than 2 Ma, with a few reworked species older than 10–12 Ma. Approximately 2 m of barren clay is beneath this layer, followed by a lower clay with radiolarian species that went extinct between 7 and 9 Ma. The piston core penetrated 2.2 m of nannofossil ooze associated with seismic Layer 3, dated as late Oligocene (nannofossil Zone NP25; 23.4–27.2 Ma). There is a hiatus of at least 15 My at the boundary between seismic Layer 2 clays and Layer 3 carbonates. Based on the age of the carbonates in seismic Layer 3 and the resemblance of the deeper seismic section to Paleogene Pacific sections in the equatorial Pacific Ocean (Lyle et al., 2002), we hypothesize that the boundary of seismic Layers 4 and 5 is the Eocene/Oligocene boundary. Typically, Eocene sediments are rich in biogenic silica and show poor layering, whereas Oligocene sediments are carbonate rich and well layered. If one assumes that the carbonate sediment package has a constant sedimentation rate, the Eocene/Oligocene boundary should lie a little over halfway between the 25 Ma top of the carbonates and the 40 Ma basement, roughly the depth to the base of seismic Layer 4.

With the exception of Core MV0502-9JC at proposed Site SP-14A, piston coring during the site survey did not penetrate below the Neogene surface layer and in most cases barely penetrated the Pleistocene. Nevertheless, a tentative interpretation is made based upon the age of the crust, core information, and seismic reflection data. Proposed Site SP-1B, for example, has a surface layer ~60 m thick of layered diatom clays and diatom ooze that could represent much of the Neogene (Figure **AF2**). Below this layer, we observed a sequence that is reminiscent of the carbonates at proposed Site SP-14A, when the site should have been shallower than the South Pacific CCD. Based on estimated correlations of the seismic stratigraphy, we calculate that there is ~170 m of Paleogene sediments. Paleogene-wide sedimentation rates then average ~7 m/My, sufficient to resolve all Milankovitch frequencies. All sites are situated in relatively rough terrain because seafloor spreading in the South Pacific was slow for much of the Paleogene, resulting in rugged abyssal hill topography.

Most Expedition 378 sites lie south of the Pleistocene northern limit of ice rafting. Using the modeled plate-motion backtrack to the south, moving the sites closer to Antarctica, an ice-rafting record may be found to reveal the history of glacial development on Antarctica. Opening, describing, and sampling the seismic survey cores showed that several cores contain ice-rafted debris. It was especially noticeable in the siliceous ooze recovered at 50.5°S and appeared in other cores as well. Core MV0502-07JC, from proposed Site SP-14A at 46.5°S, had a rounded pebble on top, suggesting further evidence for the deposition of ice rafting.

The standard square root of age subsidence curves (Figure **F4**) shows that we can anticipate encountering a nearly complete mid- to late Cenozoic carbonate section at the two sites on 40 Ma crust (proposed Sites SP-13A and SP-14A). We also expect that the early Eocene CCD will be deeper than the targeted sediment column, especially because the CCD away from the Pacific Equator appears to be shallower than the CCD on the Equator (Rea and Lyle, 2005) and because calcareous sediments are the dominant sediment type in the Paleocene and Eocene in the New Zealand sector of the Southern Ocean (Nelson and Cooke, 2001).

During the site survey, an area of at least two million square kilometers (2×10^6 km^2) between 31° and 39°S that had no discernable sediment was discovered (Rea et al., 2006). This "bare zone" provides evidence for an extended history of essentially no biogenic or terrigenous (dust) input to the region for most of the Cenozoic. The lack of sediment in the more northern survey area means that we may only find evidence for the southern margin of the subtropical gyre (Rea et al., 2006). Nevertheless, these relatively thin sedimentary sections along the north edge of the transect are needed to define the gyre edge through time and will still yield important information about the early Eocene. A similar site drilled during Leg 199 (Site 1215) had only a 70 m sediment column, but more than half the sediments were lower Eocene and Paleocene carbonates. Site 1215 contained an early Eocene record (50–56 Ma) that has been orbitally tuned (Raffi et al., 2005).

The supporting site survey data for Expedition 378 are archived at the IODP Site Survey Data Bank (**https://ssdb.iodp.org/SSDBquery/SSDBquery.php**; select 378 for proposal number).

Scientific objectives

Expedition 378 seeks to elucidate the temperate to subpolar climate and oceanography of the very warm Eocene, as well as the middle and late Cenozoic, in the far southern Pacific Ocean. Drill sites are positioned along Anomaly 25 (56 Ma) between 56° and 70°S paleolatitudes (using the Ocean Drilling Stratigraphic Network webpage backtrack scheme). The overall aim is to obtain a continuous well-preserved sediment section that will address the following primary scientific objectives (of equal priority):

1. To reconstruct the early Eocene surface water temperature gradient around Antarctica to monitor ocean heat transport and to extrapolate subsurface water structure (proposed Sites SP-1B, SP-2B, SP-3B, and DSDP 277 and, to a lesser extent, proposed Sites SP-4B, SP-5B, and SP-15A).
2. To establish the early Eocene vertical temperature gradient (proposed Sites DSDP 277, SP-1B, and SP-2B).
3. To evaluate early Eocene biological productivity and determine nutrient exchange and mixing of surface and subsurface waters (proposed Sites SP-1B, SP-2B, SP-3B, and DSDP 277 and, to a lesser extent, proposed Sites SP-4B, SP-5B, and SP-15A).
4. To track the development and variability of South Pacific thermohaline circulation during the Paleogene (proposed Sites SP-1B, SP-2B, SP-3B, SP-15A, SP-4B, and SP-5B).
5. To document the response of the proto-Ross Gyre (South Pacific Subantarctic gyre) to the Paleocene/Eocene Thermal Maximum (proposed Sites DSDP 277, SP-1B, SP-2B, and SP-3B and, to a lesser extent, proposed Sites SP-4B, SP-5B, and SP-15A).
6. To reconstruct changes in South Pacific temperature, circulation, and productivity associated with the greenhouse–icehouse transition (Eocene/Oligocene boundary (proposed Sites SP-1B, SP-2B, SP-3B, SP-13A, SP-14A, and DSDP 277 and, to a lesser extent, proposed Sites SP-4B, SP-5B, and SP-15A).
7. To establish the development of ACC (proposed Sites SP-14A, SP-13A, DSDP 277, SP-1B, SP-2B, and SP-3B).
8. To reconstruct the evolution of Paleogene wind field (proposed Site SP-15A and all other sites).

The obtained sediment section will also address the following additional objectives:

1. To develop a common chronostratigraphic framework for Paleogene Southern Ocean magnetostratigraphy, biostratigraphy, and cyclostratigraphy (all proposed sites).
2. To resolve geographic distribution of important Paleogene and early Neogene hiatuses in concert with Ocean Drilling Program (ODP) Leg 181 results and DSDP drilling (primarily proposed Sites DSDP 277, SP-1B, SP-2B, SP-3B, SP-13A, and SP-14A).
3. To better determine Paleogene Pacific plate motion (all proposed sites).
4. To determine, if possible, Paleogene and Neogene development of ice rafting from Antarctica (primarily proposed Site SP-1B).

Operations plan and drilling strategy

The areas we propose to drill now lie between 40° and 52°S and backtrack to 56°–70°S at 55 Ma (Figure **F1**). The array of seven primary sites and two alternate sites was chosen to encompass 33° of longitude (proposed Site DSDP 277 at 166°E and proposed Site SP-14A at 133°W) and 12° of latitude (proposed Site DSDP 277 at 52°S and proposed Site SP-15 at 40°S), thus providing comprehensive regional coverage for the detailed reconstructions laid out in the expedition objectives. Each drill site (primary and alternate) for this expedition was located from within a gridded 150–250 km^2 site survey region where swath-mapping, gridded seismic reflection profiles, and sediment cores were taken (except for proposed Site SP-2B). In addition, underway seismic reflection profiles were taken between most sites to determine regional trends in sedimentation.

Our primary drilling and coring strategy consists of triple-hole APC coring to basement, with orientation, at all sites (Figure **F5**; Table **T1**). Based on observations made in the first hole of each site, orientation may not be continued in subsequent holes. In one hole at each site, we will drill an additional 2 m of basement with the extended core barrel (XCB) system. Basement will be tagged in at least one of the holes at each site. Alternate sites will follow the same drilling strategy.

An exception to this strategy is made for proposed Site DSDP 277. Here, the upper 250 m consists of unlithified nannofossil ooze, and the APC system will be used to this depth. A fourth hole of coring is planned to 580 mbsf, drilling through the upper 240 m and using the rotary core barrel to core from 240 to 580 mbsf. Proposed Site DSDP 277 is currently approved to 480 mbsf, and drilling to 580 mbsf is contingent on Environmental Protection and Safety Panel approval.

Logging/downhole measurements strategy

Formation temperature measurements

During APC coring in the first hole at each site deeper than 100 mbsf, a series of formation temperature measurements using the advanced piston corer temperature tool (APCT-3) are planned.

Wireline logging

Downhole logging data will be collected at the two sites deeper than 200 mbsf (proposed Sites DSDP 277 and SP-1B). The wireline logging plan aims to provide information on in situ formation properties (lithologies, structures, and petrophysics) and allow for core-log-seismic integration. The standard IODP tool string configurations for the triple combination (triple combo) and Formation MicroScanner (FMS)-sonic will be deployed. For more specific information on tools and logging, please refer to **http://iodp.tamu.edu/tools/logging**.

Risks and contingency

Drilling in remote areas of the South Pacific Ocean presents several risks and challenges. Encountering rough seas during transit and while on site could result in a loss of operational hours. For example, cyclone-related rough sea conditions hindered the ability of the site survey cruise to recover piston cores. Drilling in deep water (six primary proposed sites at >4500 m water depth) coupled with rough sea state presents further challenges. Within the South Pacific Gyre (Expedition 329), this resulted in increased high tension on the core line; however, this was mitigated by orientation changes and compensator adjustment. Seismic survey data from the region illustrate the ubiquity of rough seafloor topography in the region caused by slow seafloor spreading throughout the Paleogene. The site survey report also notes the loss of a piston core and 4.7 km of trawl line near proposed Site SP-14A. In addition to operational risks, the remote location of the drill sites presents a risk to personnel in the event of illness/injury. All expedition members should ensure they are physically and mentally healthy to sail.

Sampling and data sharing strategy

Shipboard and shore-based researchers should refer to the IODP Sample, Data, and Obligations Policy and Implementation Guidelines at **http://www.iodp.org/program-documents**. This document outlines the policy for distributing IODP samples and data. The document also defines the obligations that sample and data recipients incur. The Sample Allocation Committee (SAC; composed of Co-Chief Scientists, Expedition Project Manager/Staff Scientist, and IODP Curator on shore and curatorial representative on board the ship) will work with the entire scientific party to formulate a formal expedition-specific sampling plan for shipboard and postexpedition sampling.

Each member of the science party is obligated to perform scientific research for the expedition and publish the results. To initiate this process, all shipboard scientists (and any potential shore-based scientists) will be required to submit a research plan and associated sample and data request ~6 months before the expedition (see **http://iodp.tamu.edu/curation/samples.html**). Based on these research plans (shore based and shipboard), the SAC will prepare a tentative sampling plan, which will be revised on the ship as dictated by sediment recovery and any consequent impact on achieving the expedition objectives. The sampling plan will be subject to modification depending upon the actual material recovered and collaborations that will evolve between scientists during the expedition. Modification of the strategy during the expedition must be approved by the Co-Chief Scientists, Expedition Project Manager/Staff Scientist, and curatorial representative on board the ship.

The minimum permanent archive will be the standard archive half of each core. 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 measurement 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.

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 by a single investigator. A sampling plan coordinated by the SAC may be required before critical intervals are sampled.

Shipboard sampling will be restricted to those required for shipboard measurements; any samples that are ephemeral; and possibly very limited, very low resolution samples for personal research that are required to define plans for the postexpedition sampling meeting. Whole-round samples may be taken for, but not limited to, interstitial water measurements, microbiology, and petrophysical measurements as dictated by the primary expedition objectives, approved research plans, and the shipboard sampling plan that must be finalized during the first few days of the expedition. Nearly all sampling for postexpedition research will be postponed until a shore-based sampling meeting that will be implemented ~3–5 months after the end of Expedition 378 at the IODP Gulf Coast Repository in College Station, Texas (USA).

Expedition scientists and scientific participants

The current list of participants for Expedition 378 can be found at **http://iodp.tamu.edu/scienceops/expeditions/south_pacific_paleogene_climate.html**.

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Table T1. Operations and time estimates for primary and alternate sites, Expedition 378. LWD/MWD = logging-while-drilling/measurement-while-drilling. EPSP = Environmental Protection and Safety Panel. APC = advanced piston corer, XCB = extended core barrel, APCT-3 = advanced piston corer temperature tool, FMS = Formation MicroScanner.

Exp 378 South Pacific Paleogene (P567-Full4)
Operations Plan Summary

Site No.	Location (Latitude Longitude)	Seafloor Depth (m)	Operations Description	Transit (days)	Drilling Coring (days)	LWD/ MWD Log (days)
Lyttelton			Begin Expedition 4.0	port call days		
			Transit ~607 nmi to DSDP 277 @ 10.5 kt	2.4		
DSDP 277	52.223833° S	1214	Hole A - APC to 250 mbsf w/ orientation and APCT-3 measurements		1.4	
EPSP	166.191333° E		Hole B - APC to 250 mbsf w/ orientation		0.9	
to 480 mbsf			Hole C - APC to 250 mbsf w/ orientation		1.1	
Pending to			Hole D - RCB Drill down to ~240 mbsf, core to 580 mbsf and log with triple combo		2.6	1.0
580 mbsf			and FMS-sonic			
			Sub-Total Days On-Site: 7.0			
			Transit ~1140 nmi to SP-1B @ 10.5 kt	4.5		
SP-1B	50.485667° S	4971	Hole A - APC/XCB to 245 mbsf w/ orientation and APCT-3 measurements		2.8	
EPSP	163.279500° W		Hole B - APC to 243 mbsf w/ orientation		2.0	
to 247 mbsf			Hole C - APC to 243 mbsf and log with triple combo, and FMS-sonic		2.5	1.0
			Sub-Total Days On-Site: 8.3			
			Transit ~249 nmi to SP-2B @ 10.5 kt	1.0		
SP-2B	49.938583° S	5075	Hole A - APC/XCB to 145 mbsf w/ orientation and APCT-3 measurements		1.8	
EPSP	156.843016° W		Hole B - APC to 143 mbsf w/ orientation		1.1	
to 147 mbsf			Hole C - APC to 143 mbsf w/ orientation		1.6	
			Sub-Total Days On-Site: 4.5			
			Transit ~193 nmi to SP-13A @ 10.5 kt	0.8		
SP-13A	50.776750° S	4772	Hole A - APC/XCB to 162 mbsf w/ orientation and APCT-3 measurements		1.9	
EPSP	151.967033° W		Hole B - APC to 160 mbsf w/ orientation		1.3	
to 164 mbsf			Hole C - APC to 160 mbsf w/ orientation		1.7	
			Sub-Total Days On-Site: 4.9			
			Transit ~393 nmi to SP-3B @ 10.5 kt	1.6		
SP-3B	49.387367° S	4703	Hole A - APC/XCB to 83 mbsf w/ orientation		1.3	
EPSP	141.989066° W		Hole B - APC to 81 mbsf w/ orientation		0.7	
to 85 mbsf			Hole C - APC to 81 mbsf w/ orientation		1.1	
			Sub-Total Days On-Site: 3.1			
			Transit ~347 nmi to SP-14A @ 10.5 kt	1.4		
SP-14A	47.100583° S	4658	Hole A - APC/XCB to 179 mbsf w/ orientation and APCT-3 measurements		2.0	
EPSP	133.998916° W		Hole B - APC to 177 mbsf w/ orientation		1.4	
to 181 mbsf			Hole C - APC to 177 mbsf w/ orientation		1.8	
			Sub-Total Days On-Site: 5.2			
			Transit ~996 nmi to SP-15A @ 10.5 kt	4.0		
SP-15A	40.010233° S	4775	Hole A - APC/XCB to 89 mbsf w/ orientation		1.1	
EPSP	154.041683° W		Hole B - APC to 87 mbsf w/ orientation		0.7	
to 91 mbsf			Hole C - APC to 87 mbsf w/ orientation		1.2	
			Sub-Total Days On-Site: 3.0			
			Transit ~1601 nmi to Papeete @ 10.5 kt	5.4		
Papeete			End Expedition	21.0	34.0	2.0

Port Call:	4.0	Total Operating Days:	57.0
Sub-Total On-Site:	36.0	Total Expedition:	61.0

Figure F1. Map of Expedition 378 proposed drill sites. Yellow circles = sites on 56 Ma crust, orange circles = sites on 40 Ma crust, black circle = DSDP Site 277, light blue circles = ports.

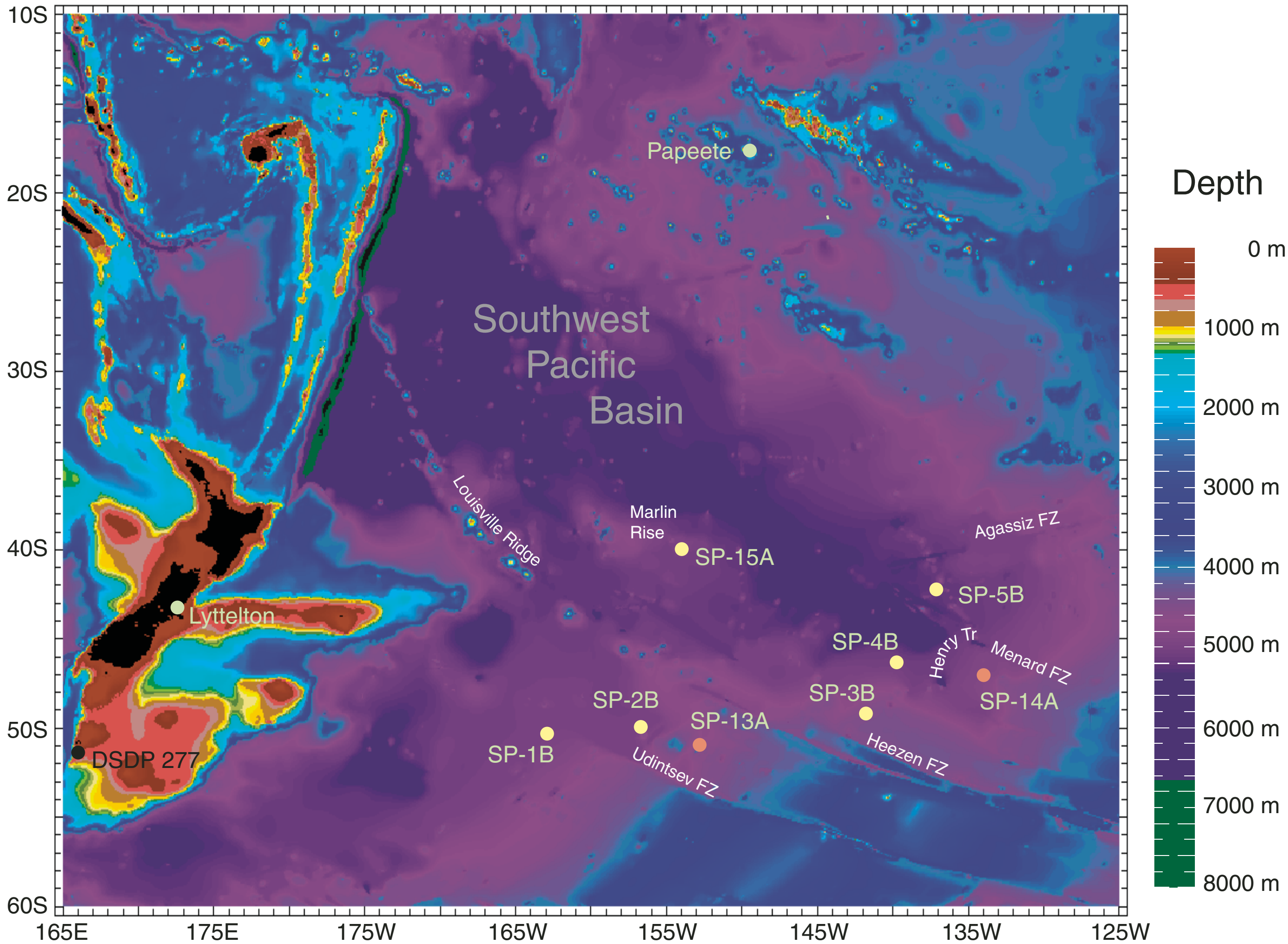
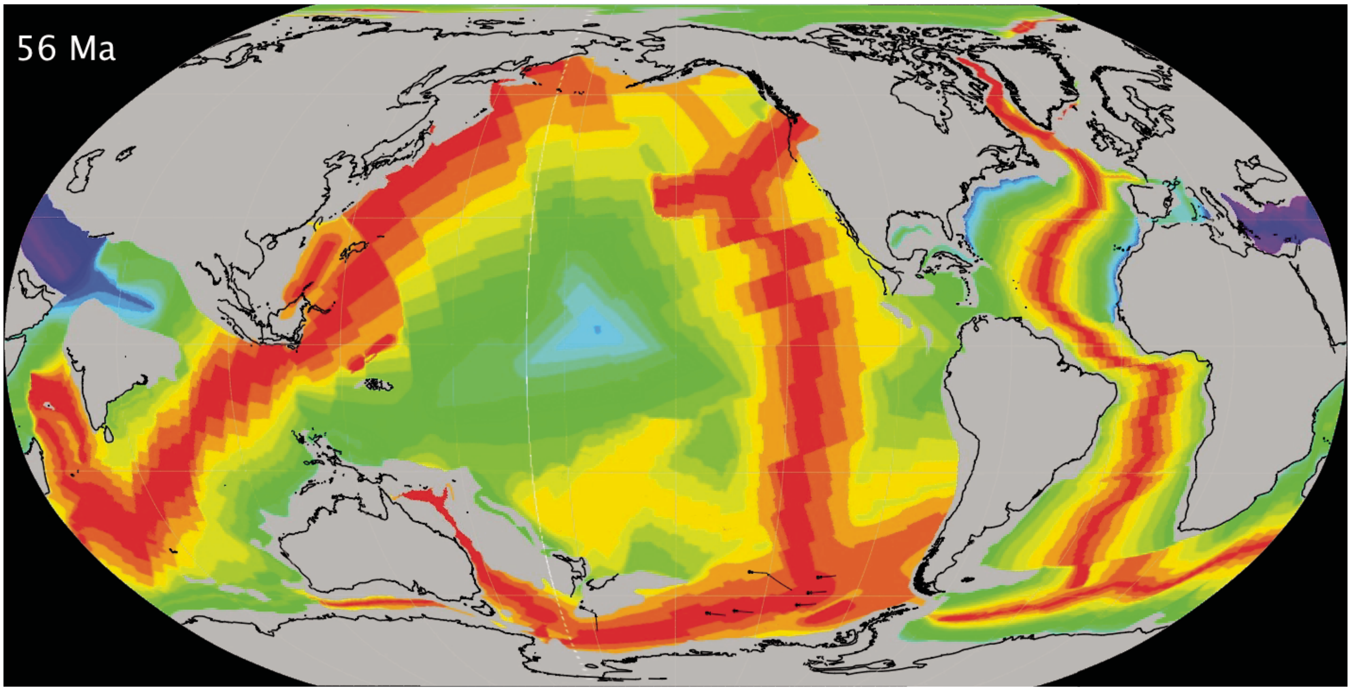


Figure F2. Paleogeographic reconstructions for 56 and 34 Ma indicating the ancient locations of Expedition 378 proposed drill sites (maps generated from GPlates).



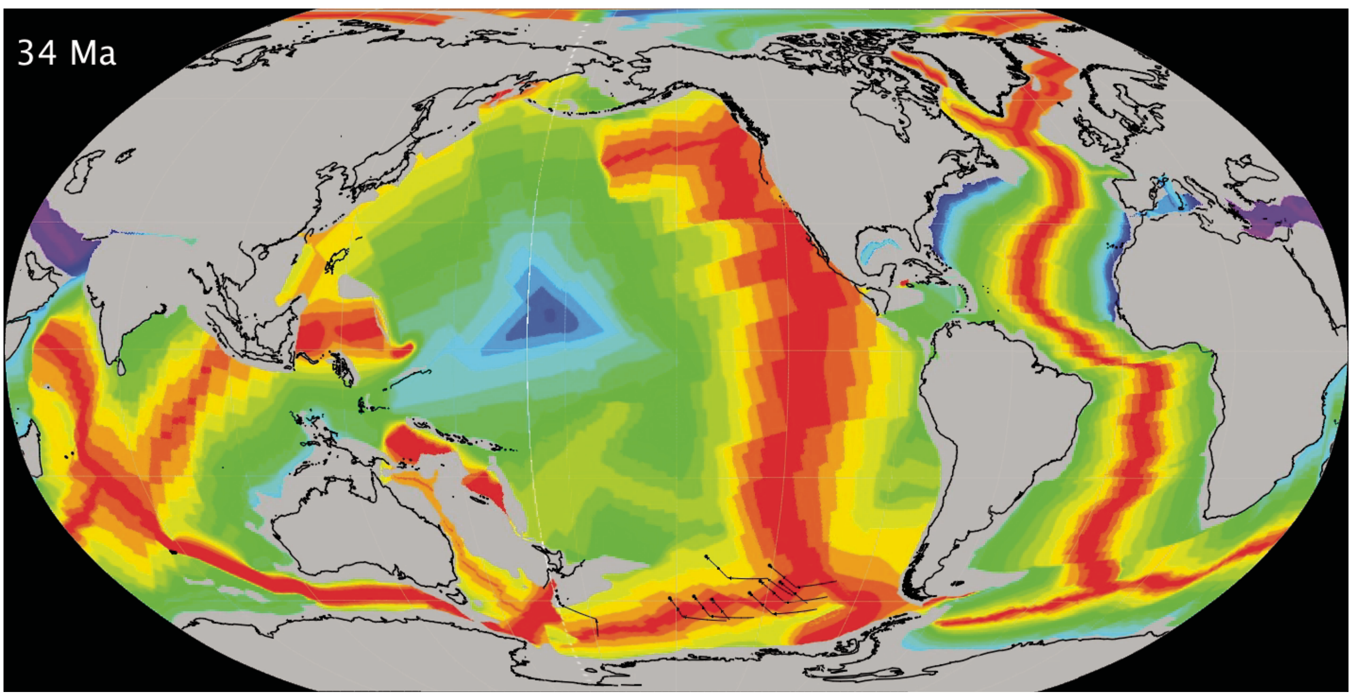


Figure F3. Seismic profile and weight percent carbonate data from piston core MV0502-9JC, 15 km northeast of proposed Site SP-14A sited along the same abyssal hill. The dramatic increase in carbonate at 12 m below seafloor is indicated by a prominent seismic reflection. CDP = common depth point. SL = seismic layer.

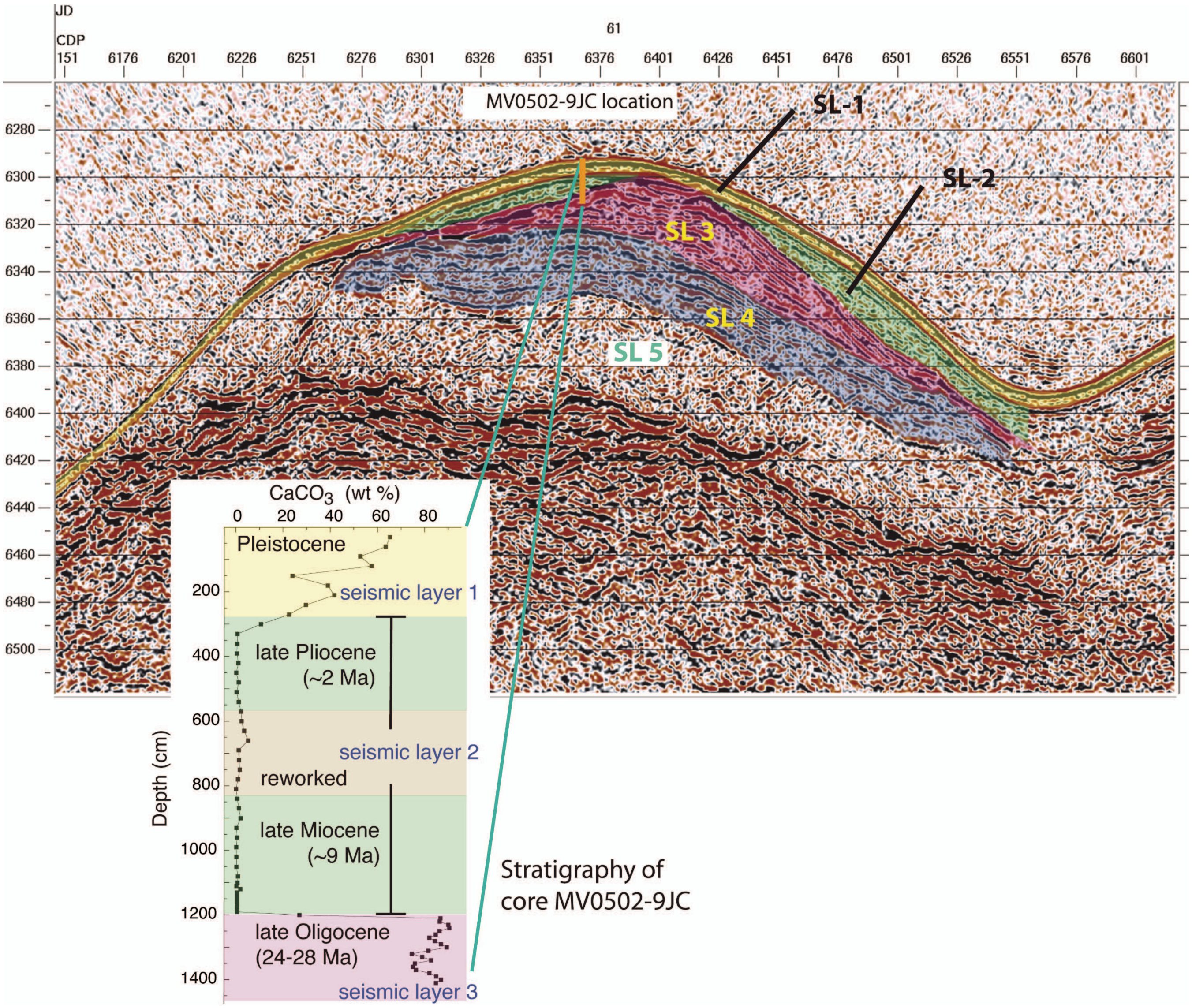


Figure F4. Crustal subsidence curves for late Eocene and late Paleocene crust shown with likely carbonate compensation depth (CCD) history. The modern CCD is from the R/V *Melville* site survey cruise.

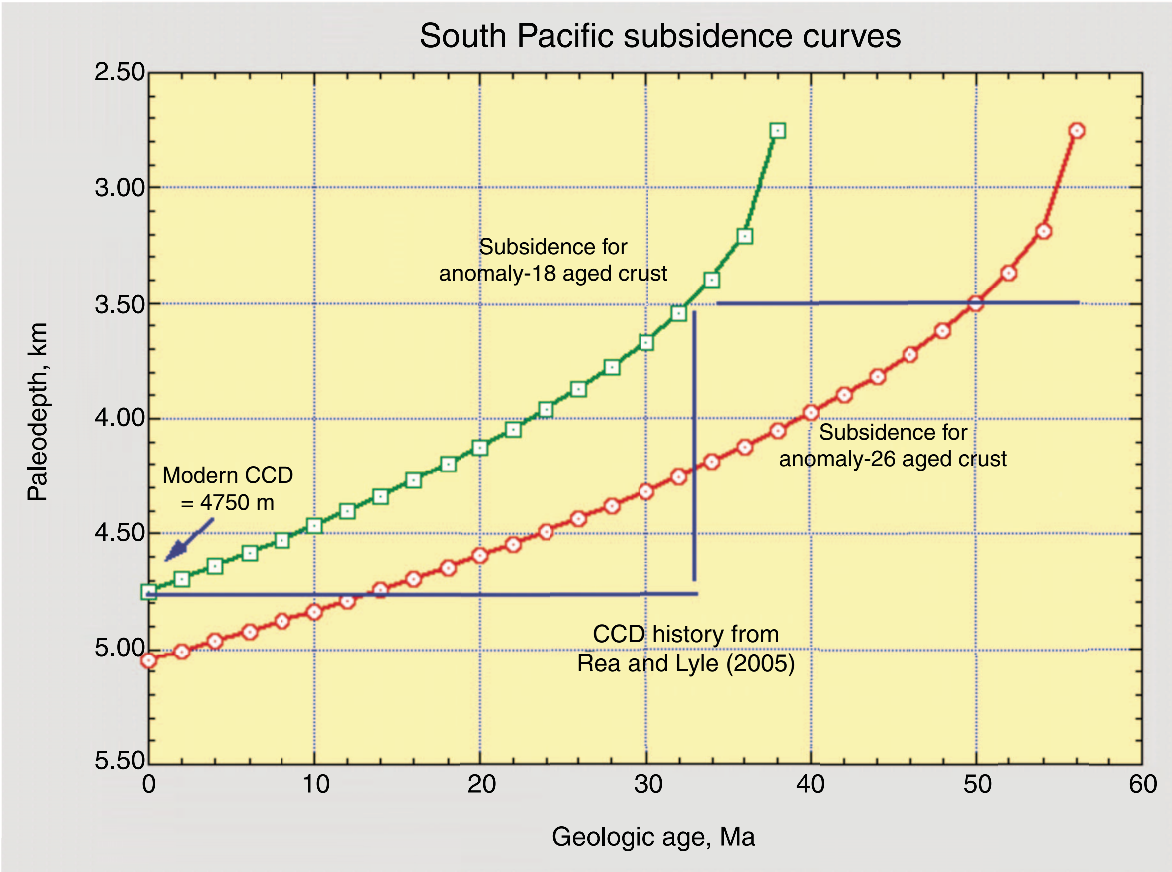
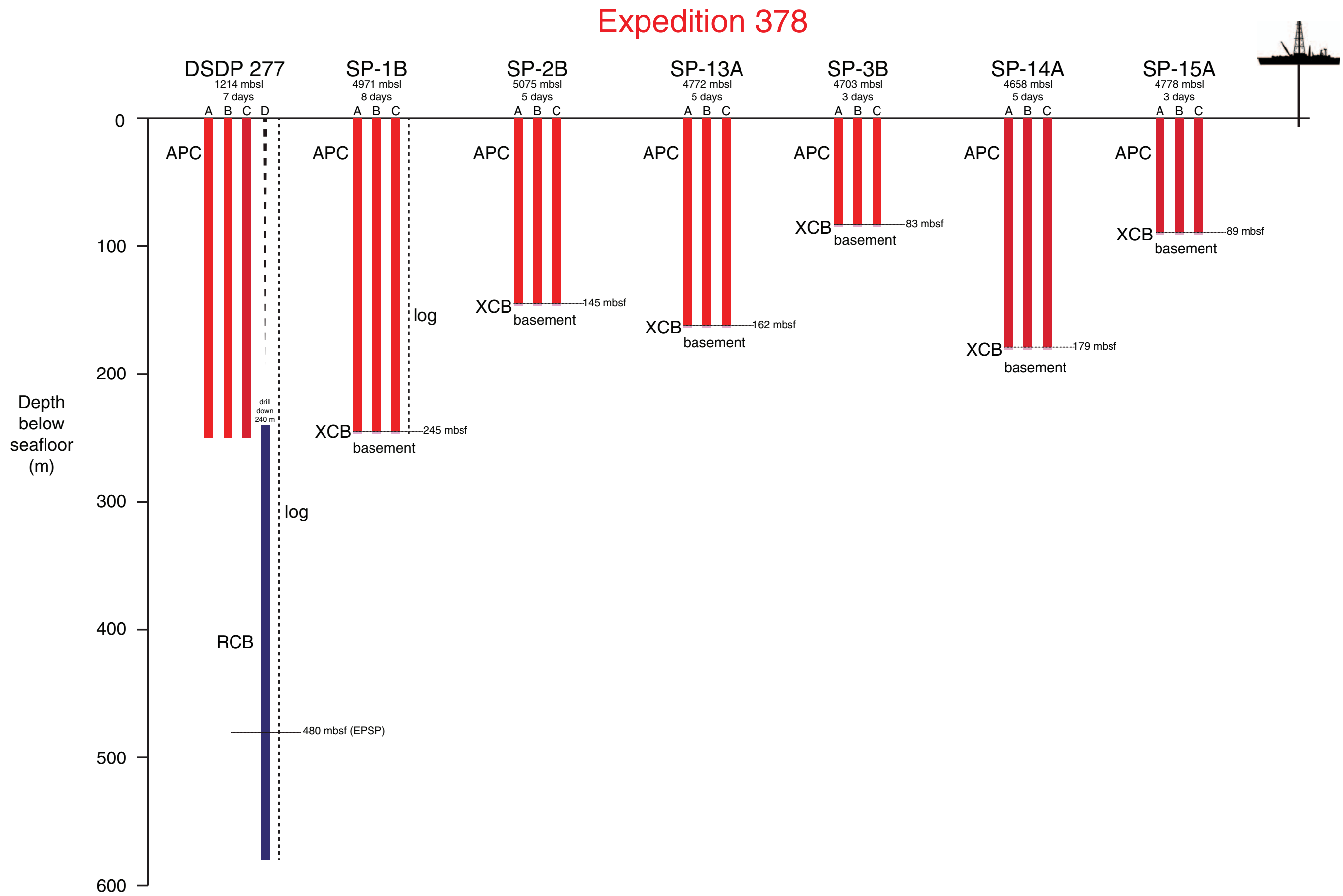


Figure F5. Planned drilling strategy for Expedition 378. APC = advanced piston coring system, RCB = rotary core barrel system, XCB = extended core barrel system. EPSP = Environmental Protection and Safety Panel.



Site summaries

Site DSDP 277

Priority:	Primary
Position:	52°13.43′S, 166°11.48′E
Water depth (m):	1214
Target drilling depth (mbsf):	580
Approved maximum penetration (mbsf):	480
Survey coverage (track map; seismic profile):	Figure **AF1**
Objective(s):	Carbonate sedimentary record of Paleogene and Upper Cretaceous; complement to deeper sites of transect
Drilling program:	Triple APC with orientation to 250 mbsf with single XCB to 480 mbsf
Logging/Downhole measurements program:	APCT-3 measurements in one hole; triple combo and FMS-sonic in 480 m hole
Nature of rock anticipated:	Pelagic carbonates; ooze–chalk transition at ~250 mbsf

Site SP-1B

Priority:	Primary
Position:	50°29.140′S, 163°16.770′W
Water depth (m):	4971
Target drilling depth (mbsf):	245
Approved maximum penetration (mbsf):	245; basement mid-ocean-ridge basalt (MORB)
Survey coverage (track map; seismic profile):	Figure **AF2**
Objective(s):	Water properties and paleoproductivity in early Eocene Antarctic subpolar gyre; 55 Ma
Drilling program:	Triple APC with orientation to refusal; XCB to basement, 2 m MORB basement
Logging/Downhole measurements program:	APCT-3 measurements in one hole; triple combo and FMS-sonic in one hole
Nature of rock anticipated:	Pelagic biosiliceous and carbonate-rich clay

Site SP-2B

Priority:	Primary
Position:	49°56.315′S, 156°50.581′W
Water depth (m):	5075
Target drilling depth (mbsf):	145
Approved maximum penetration (mbsf):	145; basement MORB
Survey coverage (track map; seismic profile):	Figure **AF3**
Objective(s):	Water properties and paleoproductivity in early Eocene Antarctic subpolar gyre; 55 Ma
Drilling program:	Triple APC with orientation to refusal; XCB to basement, 2 m MORB basement
Logging/Downhole measurements program:	APCT-3 measurements in one hole
Nature of rock anticipated:	Pelagic clay, biosiliceous ooze, and carbonates

Site SP-13A

Priority:	Primary
Position:	50°46.605′S, 151°58.022′W
Water depth (m):	4772
Target drilling depth (mbsf):	162
Approved maximum penetration (mbsf):	162; basement MORB
Survey coverage (track map; seismic profile):	Figure **AF4**
Objective(s):	Water properties and paleoproductivity in late Eocene–early Oligocene; 40 Ma
Drilling program:	Triple APC with orientation to refusal; XCB to basement, 2 m MORB basement
Logging/Downhole measurements program:	APCT-3 measurements in one hole
Nature of rock anticipated:	Siliceous and carbonate ooze

Site SP-3B

Priority:	Primary
Position:	49°23.242′S, 141°59.344′W
Water depth (m):	4703
Target drilling depth (mbsf):	83
Approved maximum penetration (mbsf):	83; basement MORB
Survey coverage (track map; seismic profile):	Figure **AF5**
Objective(s):	Water properties and paleoproductivity in early Eocene Antarctic subpolar gyre; 55 Ma
Drilling program:	Triple APC with orientation to refusal; XCB to basement, 2 m MORB basement
Logging/Downhole measurements program:	None
Nature of rock anticipated:	Pelagic clay, biosiliceous ooze, and carbonate

Site SP-14A

Priority:	Primary
Position:	47°06.035′S, 133°59.935′W
Water depth (m):	4658
Target drilling depth (mbsf):	179
Approved maximum penetration (mbsf):	179; basement MORB
Survey coverage (track map; seismic profile):	Figure **AF6**
Objective(s):	Water properties and paleoproductivity in late Eocene–early Oligocene; 40 Ma
Drilling program:	Triple APC with orientation to refusal; XCB to basement, 2 m MORB basement
Logging/Downhole measurements program:	APCT-3 measurements in one hole
Nature of rock anticipated:	Pelagic carbonates and biosiliceous ooze

Site SP-15A

Priority:	Primary
Position:	40°00.614′S, 154°2.501′W
Water depth (m):	4775
Target drilling depth (mbsf):	89
Approved maximum penetration (mbsf):	89; basement MORB
Survey coverage (track map; seismic profile):	Figure **AF7**
Objective(s):	South Pacific paleowind for Cenozoic, Late Cretaceous subantarctic–temperate transition
Drilling program:	Triple APC with orientation to refusal; XCB to basement, 2 m MORB basement
Logging/Downhole measurements program:	None
Nature of rock anticipated:	Pelagic clays and carbonates

Site SP-4B

Priority:	Alternate
Position:	46°30.372′S, 139°21.210′W
Water depth (m):	5186
Target drilling depth (mbsf):	58
Approved maximum penetration (mbsf):	58; basement MORB
Survey coverage (track map; seismic profile):	Figure **AF8**
Objective(s):	Water mass properties and paleoproductivity in early Eocene Antarctic subpolar gyre
Drilling program:	Triple APC with orientation to refusal; XCB to basement, 2 m MORB basement
Logging/Downhole measurements program:	None
Nature of rock anticipated:	Pelagic clay, biosiliceous ooze, and carbonates

Site SP-5B

Priority:	Alternate
Position:	42°45.272′S, 137°9.322′W
Water depth (m):	5210
Target drilling depth (mbsf):	30
Approved maximum penetration (mbsf):	30; basement MORB
Survey coverage (track map; seismic profile):	Figure **AF9**
Objective(s):	Water mass properties and paleoproductivity in early Eocene Antarctic subpolar gyre
Drilling program:	Triple APC with orientation to refusal; XCB to basement, 2 m MORB basement
Logging/Downhole measurements program:	None
Nature of rock anticipated:	Pelagic clay, carbonates, and biosiliceous ooze

Figure AF1. Map adapted from ODP Leg 181 (Shipboard Science Party, 1999b). Shallow subbottom profiler record of proposed Site DSDP 277 from Shipboard Scientific Party (1975).

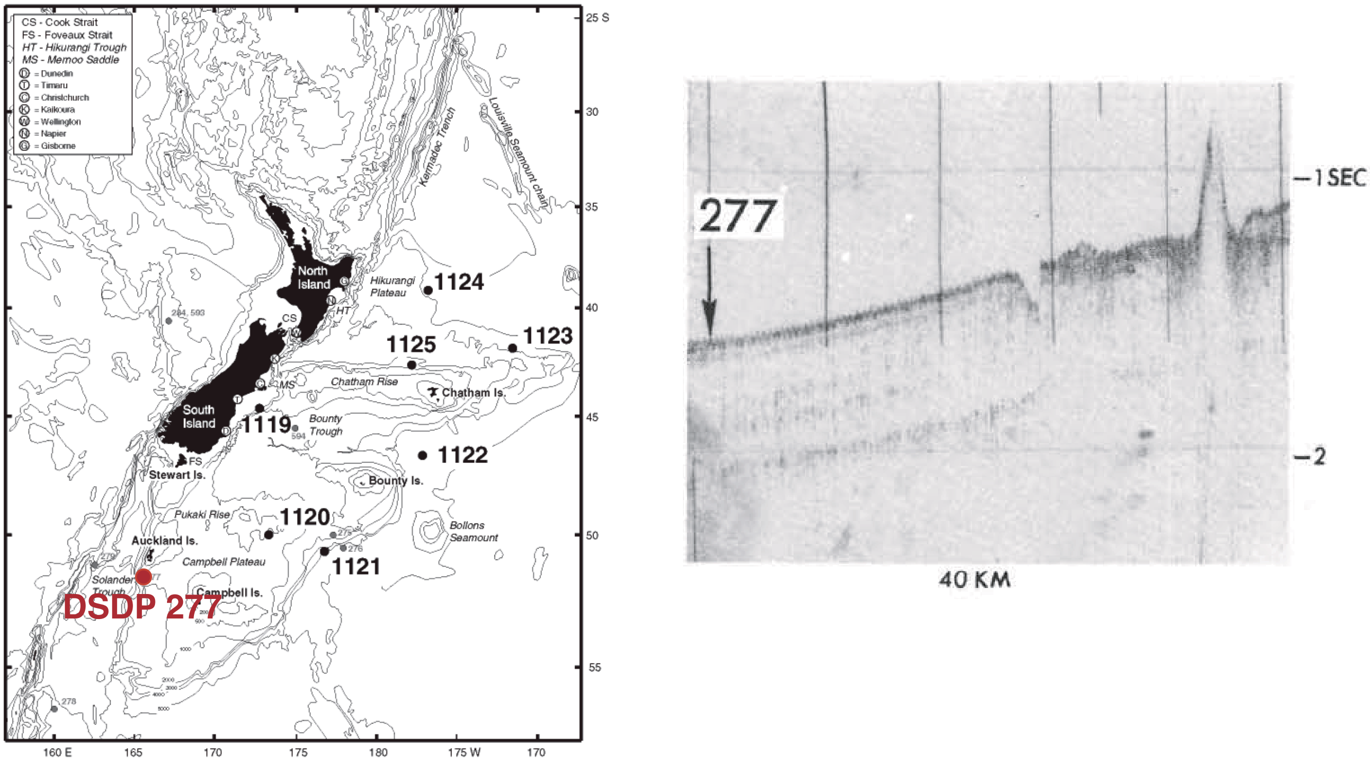


Figure AF2. Track map and seismic profiles from crossing TUIM-03 SP1B Lines 6 and 2 for proposed Site SP-1B. Red bars = proposed site location based on seismic reflectors.

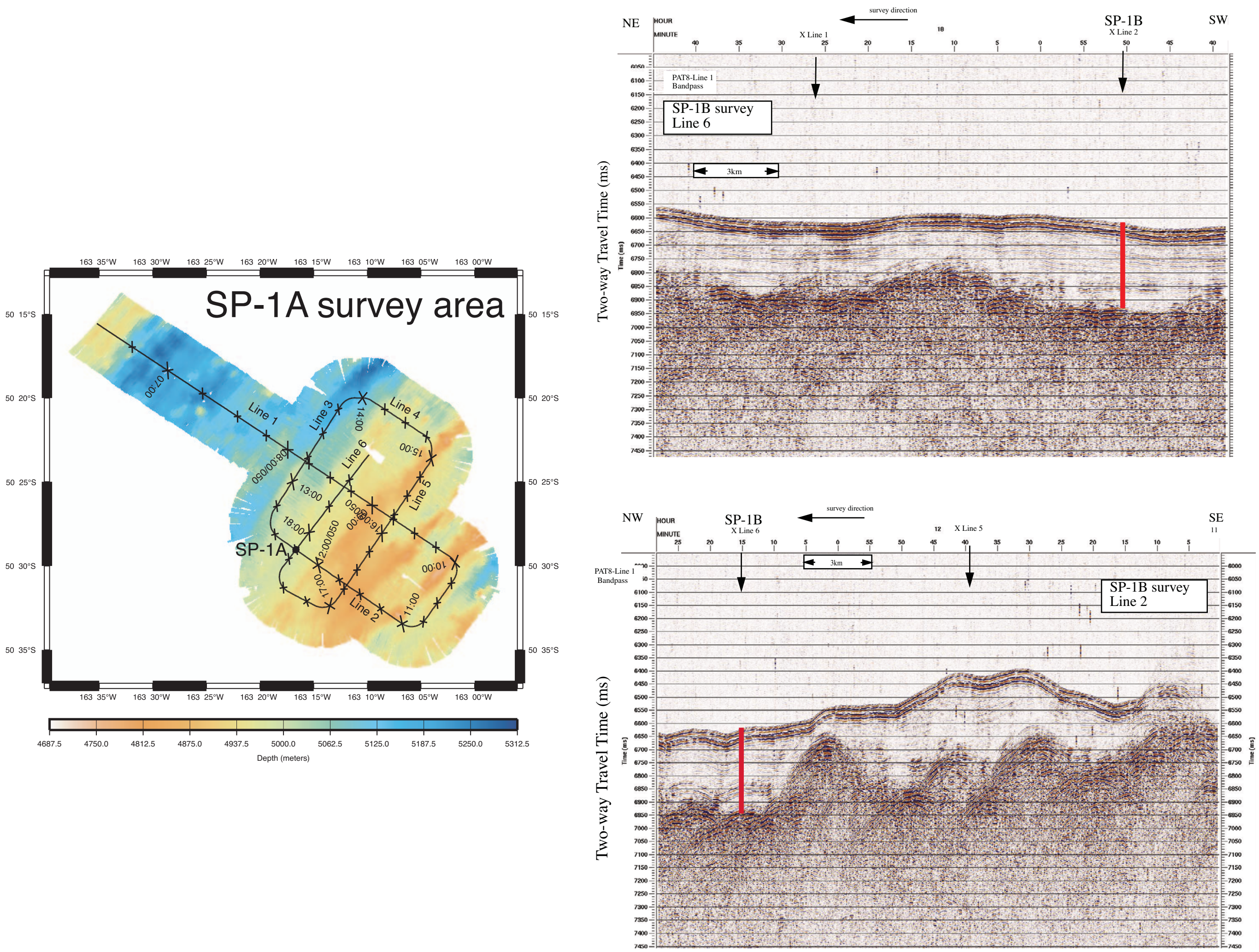


Figure AF3. Track map and seismic profiles from crossing TUIM-03 SP2B Lines 3 and 1 for proposed Site SP-2B. Red bars = proposed site location based on seismic reflectors.

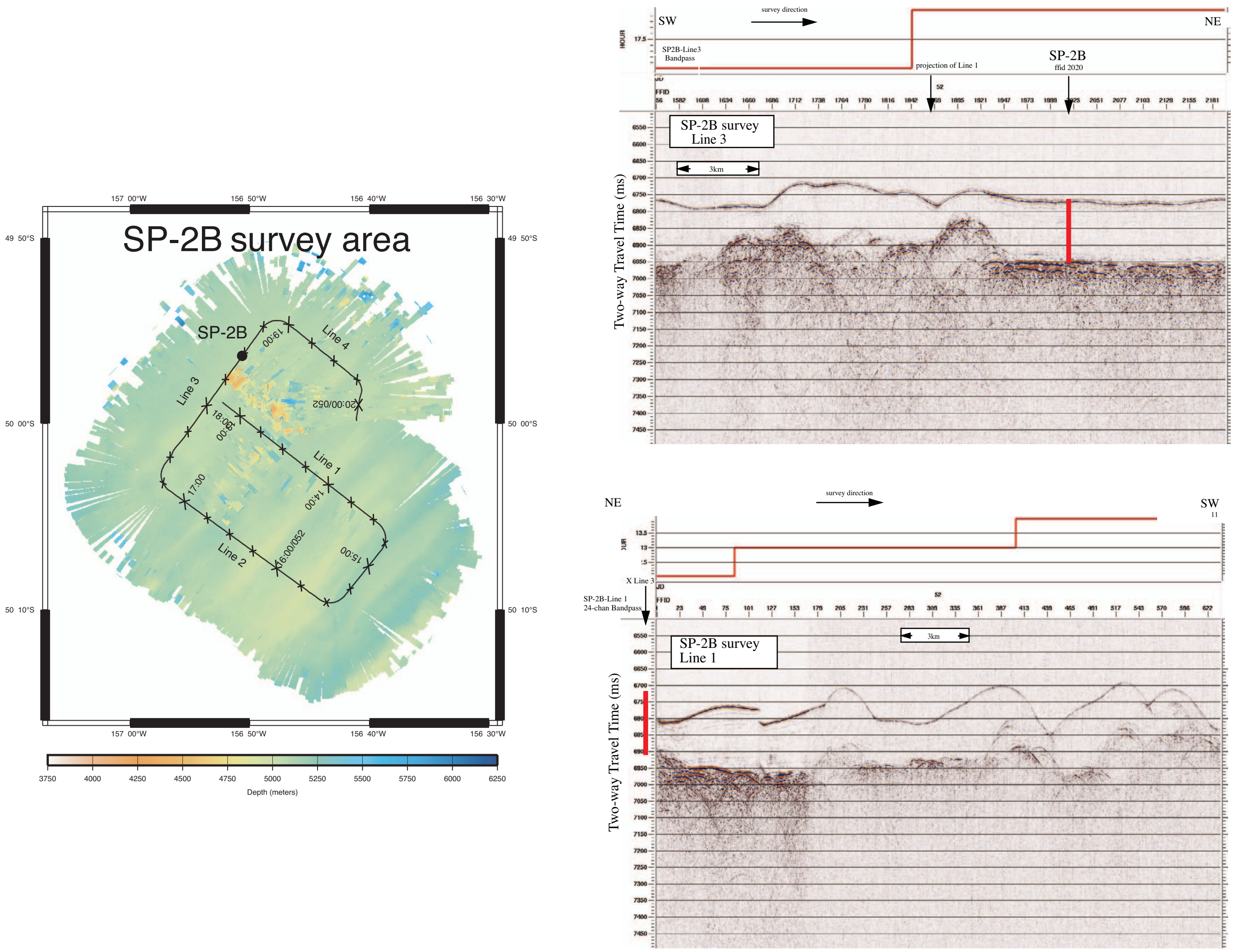


Figure AF4. Track map and seismic profiles from FFID 4340 on crossing TUIM-03 SP13A Line 9 and crossing TUIM-03 SP13A Line 11 for proposed Site SP-13A. Red bars = proposed site location based on seismic reflectors.

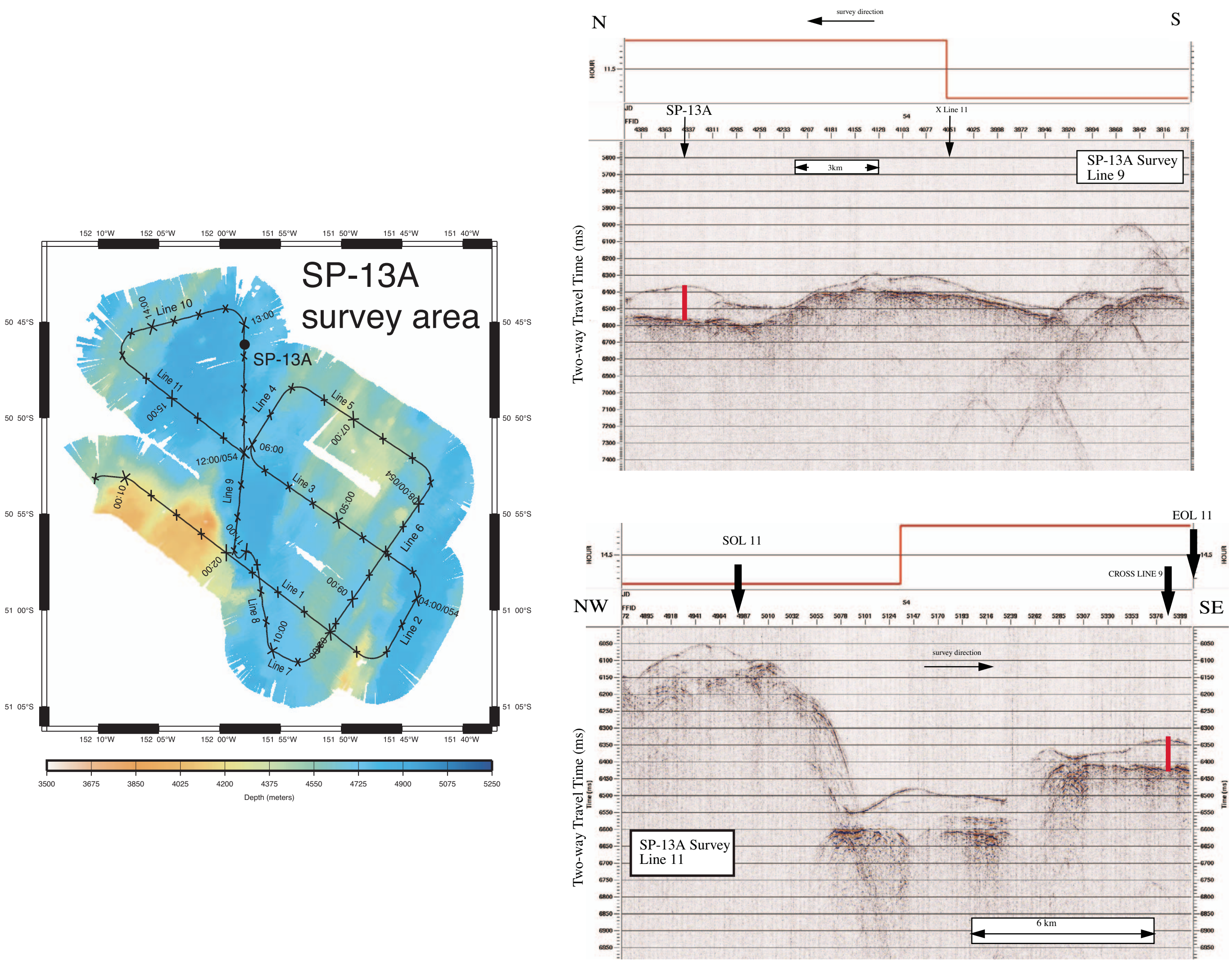
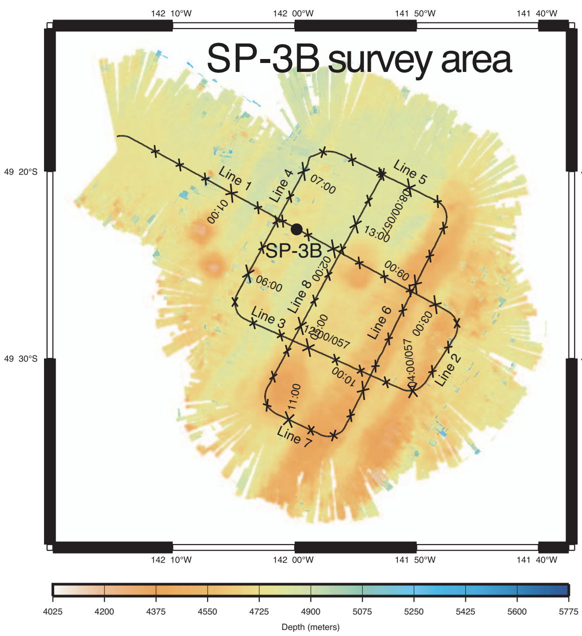
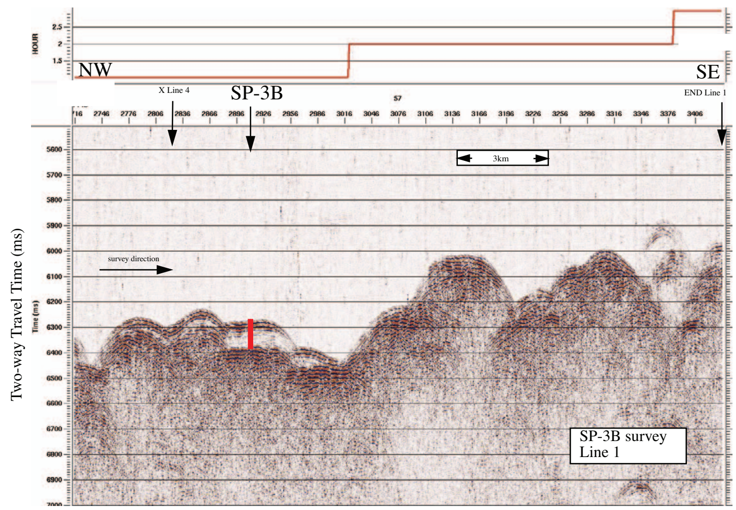


Figure AF5. Track map and seismic profiles from crossing TUIM-03 SP3B Lines 1 and 4 for proposed Site SP-3B. Red bar = proposed site location based on seismic reflectors.





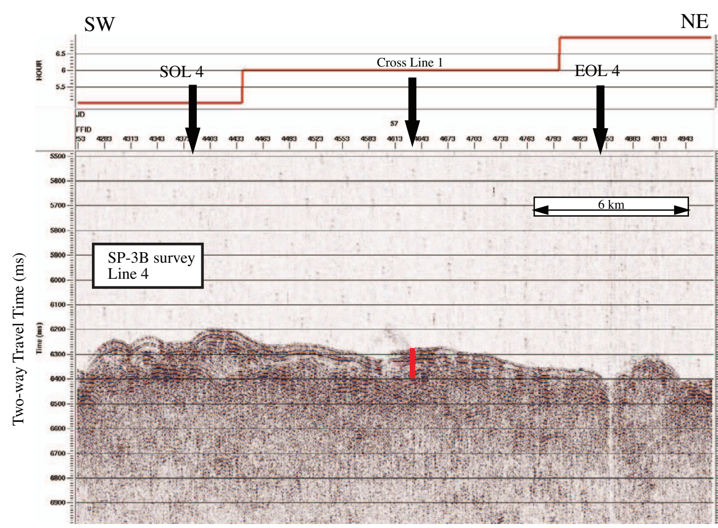
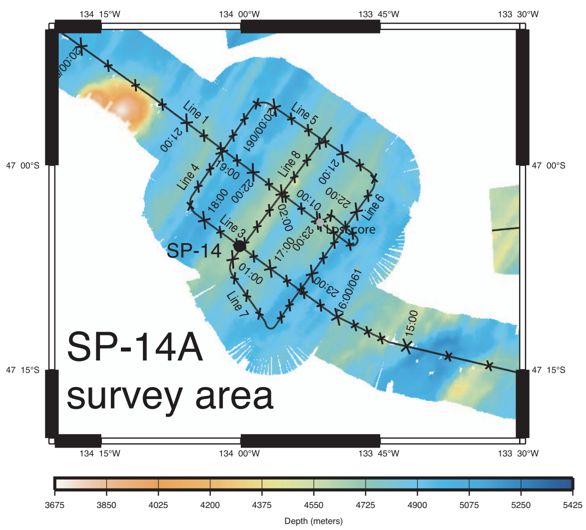
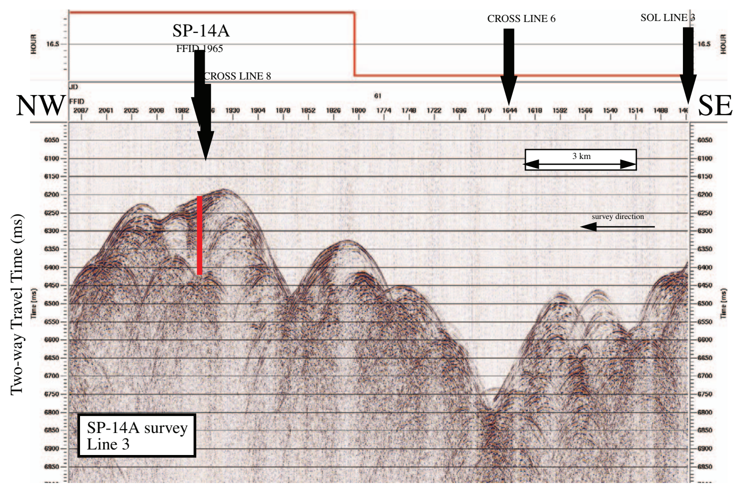


Figure AF6. Track map and seismic profiles from crossing TUIM-03 SP14A Lines 3 and 8 for proposed Site SP-14A. Red bars = proposed site location based on seismic reflectors.





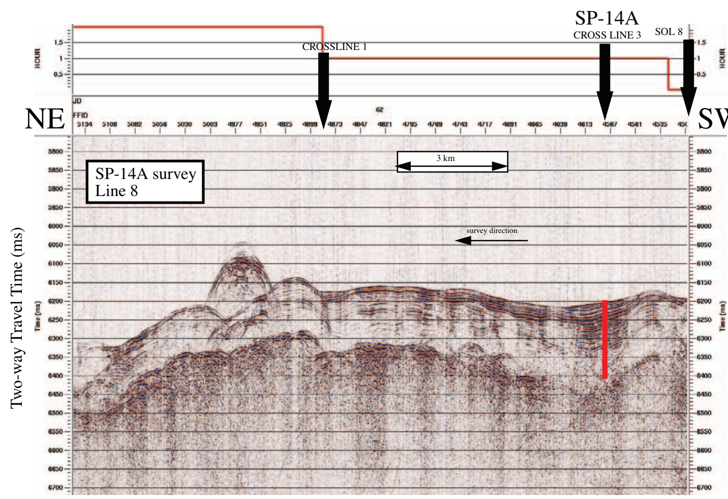


Figure AF7. Track map and seismic profile from the crossing TUIM-03 SP15A Lines 1 and 4 for proposed Site SP-15A. Red bar = proposed site location based on seismic reflectors.

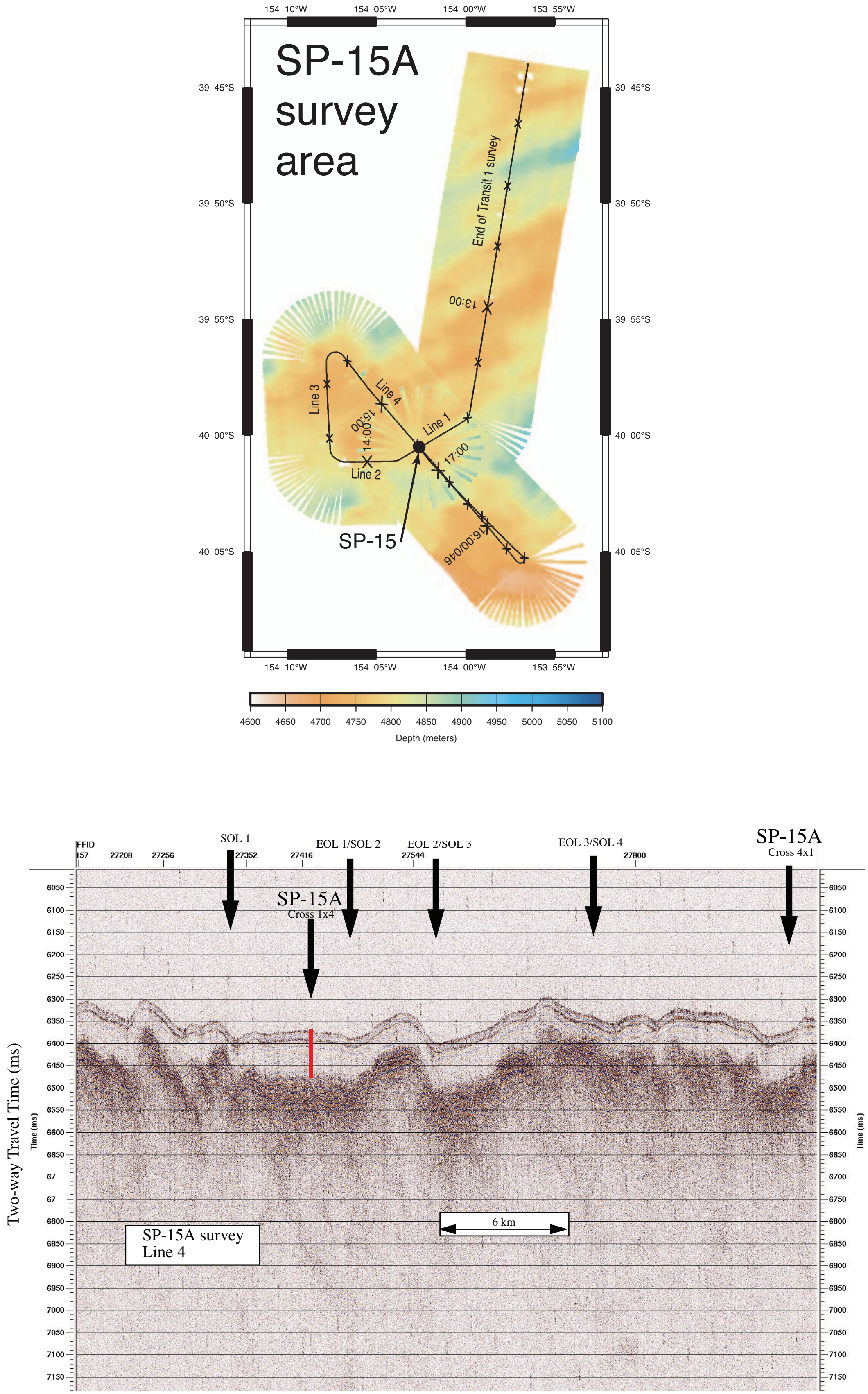


Figure AF8. Track map and seismic profiles from crossing TUIM-03 SP4B Lines 9 and 3 for proposed Site SP-4B. Red bars = proposed site location based on seismic reflectors.

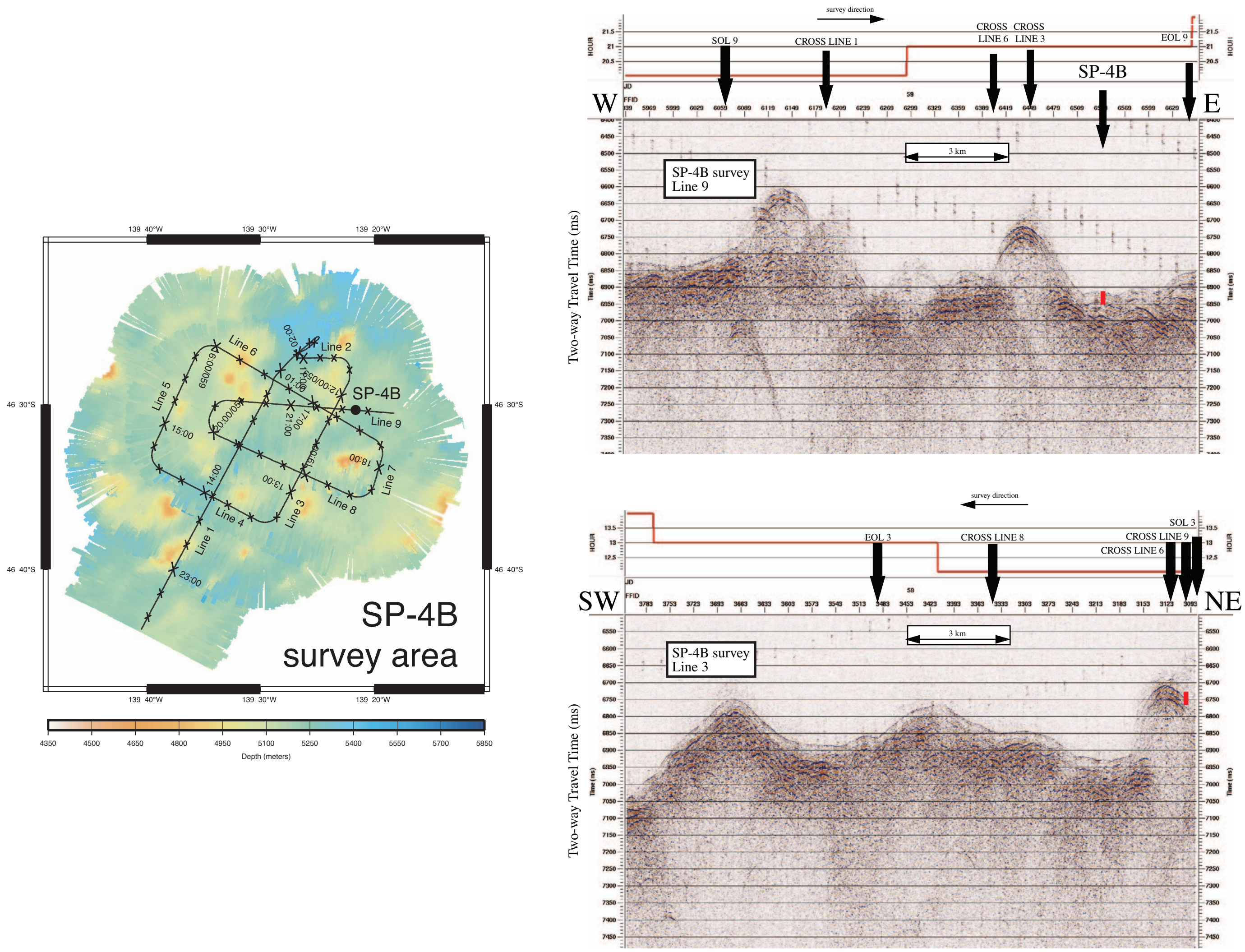


Figure AF9. Track map and seismic profiles from crossing TUIM-03 SP5B Line 1 and transit track map and transit Line 6 for proposed Site SP-5B. Red bar = proposed site location on transit line.