IODP Expedition 374: Ross Sea West Antarctic Ice Sheet History

Site U1521 Summary

Background and Objectives

International Ocean Discovery Program (IODP) Site U1521 (proposed Site EBOCS-01D) is located in the Pennell Trough at 75°41.04′S and 179°40.31′W in 562 m of water. The site is on the mid- to outer continental shelf near a northeast to southwest oriented Miocene paleotrough identified by mapping regional unconformities in seismic profiles. The primary objective of Site U1521 was to sample and date strata above and below the Ross Sea unconformity RSU4, which was previously identified in seismic stratigraphic studies (Hinz and Block, 1983; Anderson and Bartek, 1992; Cooper, Barker and Brancolini, 1995). RSU4 has been mapped over most of the Ross Sea, and is interpreted to represent a cross-shelf expansion of the East Antarctic Ice Sheet in the central regions of the Ross Sea (Brancolini et al., 1995; De Santis et al., 1995). Strata below RSU4 are interpreted as a Middle Miocene Climatic Optimum record (~17–15 Ma) deposited on the Ross Sea continental shelf. Coring through the RSU4 should improve on the broad age constraints provided for RSU4 by DSDP Sites 272 and 273 (Bart, 2003).

Records from this site will directly address all five primary Expedition 374 objectives. The record of ice advance and retreat from Site U1521, when integrated with seismic stratigraphy, provenance studies, and numerical modeling, will allow for a fuller assessment of Antarctic contributions to numerous inferred (~30 m amplitude) variations in far-field Miocene sea level (Objective 1) (Miller et al., 2005; John et al., 2011). The magnitude of polar amplification during the Middle Miocene Climatic Optimum will be assessed through proxies for atmospheric and marine temperatures derived from both the in situ marine organic matter and terrestrial organic matter transported off shore by meltwater (e.g., micropaleontology and lipid biomarker remains) (Objective 2). Insights into the oceanic drivers for retreat of middle Miocene marine terminating ice sheets, and subsequent re-advances in the late Miocene, can be achieved by detailed lithofacies analysis to reconstruct physical changes in the paleoenvironment, whereas paleontological and geochemical proxies can identify the magnitude of the oceanic change through these intervals (Objective 3). Similarly, these methods will identify the sensitivity of middle Miocene ice sheets to orbital variability based on the presence of cyclicity in the open marine, glaciomarine, and glacial proximal sediments when combined with downhole logging results to complete the stratigraphy (Objective 4). Finally, a “backstripped” paleobathymetry through accurate dating and depth estimates of the RSU4 surface and other unconformities at Site U1521, in combination with previous drilling constraints from other locations in the Ross Sea, will allow for a fuller assessment of bathymetric controls on Antarctic Ice Sheet (AIS) evolution.

Operations

After a 2014 nmi transit from Lyttelton, New Zealand, the vessel stabilized over Site U1521 (proposed Site EBOCS-01D) at 0954 h (all times local ship time; UTC + 13 h) on 16 January 2018. The drill floor was cleared for operations at 0957 h after the thrusters were lowered and secured. The original operations plan for Site U1521 called for a single rotary core barrel (RCB) hole to 950 m drilling depth below seafloor (DSF-A) and downhole logging with the triple combo, Formation MicroScanner (FMS)-sonic, and Versatile Seismic Imager (VSI) tool strings. We ultimately cored Hole U1521A to 650.1 m DSF and logged the hole with all three tool strings.

After assembling the RCB bottom-hole assembly (BHA) and preparing a nonmagnetic core barrel, the drill string was lowered towards the seafloor. The drill pipe was drifted (checked to ensure that the interior was clear) and strapped (measured) while it was lowered. We picked up the top drive and pumped a clean out "pig" to ensure that the interior of the drill string was free of debris prior to coring. A core barrel was deployed and Hole U1521A was started at 1845 h on 16 January. The bit tagged the seafloor at 562 m below sea level (mbsl). Coring proceeded without incident to Core 37R (0–352.5 m DSF); however, after poor recovery in Cores 32R to 37R (14.49 m; 25%) due to jamming of the core barrel with clasts, we switched to cutting half-length cores to improve core recovery. Cores 38R to 43R (352.5–381.3 m DSF) were collected using a 4.8 m advance (instead of 9.6 m) and recovery improved significantly (80%). We switched back to 9.6 m advances after the formation became less indurated and continued to RCB core from Core 44R to 71R (381.3–650.1 m DSF). We terminated coring at that depth after meeting the primary scientific objectives. We recovered 411.50 m of core over 650.1 m of coring (63%) in Hole U1521A.

We prepared for logging by releasing the drill bit into the bottom of the hole, and then filling the hole with 217 barrels of heavy (10.5 lb/gal) mud. The end of the pipe was placed at 54.4 m DSF for downhole logging. We deployed three tool strings, all of which reached to within ~1 m of the bottom of the hole. The triple combo included tools to measure natural gamma radiation (NGR), density, porosity, resistivity, magnetic susceptibility (MS), and borehole diameter. The triple combo was deployed at 2325 h on 20 January and reached a total depth of 649 m wireline depth below seafloor (WSF). The end of the pipe was raised to 38.2 m DSF at the end of the run to collect data over the upper part of the borehole. The FMS-sonic tool string collected NGR, sonic velocity, and resistivity images of the borehole wall. The FMS-sonic was deployed at 0620 h on 21 January. After reaching the bottom of the hole (649 m WSF), two upward passes were conducted with the end of the pipe raised to 38 m DSF prior to completing the second run. The third tool string was the VSI to conduct a vertical seismic profile (VSP) experiment. Observation for protected species began at 1300 h on 21 January, the VSI tool string was lowered into the hole at 1330 h, and the seismic source (two 250 inch^3 Sercel G guns in parallel array) was deployed at 1400 h. A total of 18 stations were attempted with an average spacing of 33 m, and 16 of the stations were successful. The last shot was fired at 1745 h and the VSI was returned to the vessel at 1800 h. After rigging down the logging equipment, we pulled the pipe back to the rig floor at 2105 h. The acoustic beacon was recovered during the pipe trip. After disassembling and inspecting the BHA and outer core barrel, the rig floor was secured for transit at 2245 h on 21 January, ending Site U1521. A total of 132.75 h (5.5 d) were spent on Site U1521.

Principal Results

The 648 m succession of lower Miocene to recent sediment recovered at Site U1521 is divided into seven lithostratigraphic units (I [youngest] to VII [oldest]). Unit VI is further divided into Subunits VIA–VIC. Contacts between lithostratigraphic units at Site U1521 range from sharp to gradational. Diatomite, mudstone, and diamictite account for ~90% of the core recovered, whereas minor lithofacies that are less volumetrically significant include chert and conglomerate. The assemblage of facies reflects open marine to subglacial depositional environments at this location in the central Ross Sea basin since at least the early Miocene.

Lithostratigraphic Unit I (0–7.4 m CSF-A) consists of a sequence of unconsolidated olive to light olive gray diatom ooze, dark grayish brown diatom-rich mud with dispersed clasts, and gray sandy mud. Unit II is ~80 m thick and consists of dark gray massive clast-poor muddy diamictite interbedded with heavily bioturbated diatomite and diatom-rich/bearing mudstone with dispersed clasts. There are several intervals of physically intermixed diatomite/mudstone and diamictite, with microfaulting and soft-sediment deformation features. Unit III (~124 m thick) consists of bioturbated olive gray to greenish gray diatomite and diatom-rich/bearing mudstone. Some intervals are faintly laminated, and whole bivalve shells and shell fragments are present throughout. Unit IV consists of ~70 m of dark gray massive diatom-bearing clast-rich sandy diamictite with clasts of basalt and granodiorite. Mudstone and diamictite are interbedded at the top and bottom of the unit and a conglomerate composed of elongated mudstone intraclasts is observed at the base of the unit. Unit V is a 40 m interval of poorly recovered chert nodules interbedded with silica cemented mudstone. Unit VI (~245 m thick) is characterized by interbedded mudstone and diamictite that is divided into three subunits based on the style of interbedding. Subunit VIA (~56 m thick) consists of interbedded dark gray massive diamictite with silica cemented intervals and mudstone, whereas Subunit VIB (~60 m thick) consists of massive to stratified dark gray sandy diamictite with three intervals of clast-supported conglomerate. Subunit VIC (~128 m thick) is a sequence of interbedded mudstone with dispersed clasts and sandy diamictite with carbonate concretions and shell fragments. Unit VII consists of ~70 m of interbedded massive to stratified sandy diamictite.

Micropaleontological investigation at Site U1521 included examination of core catcher samples and additional samples from split core sections for diatoms, radiolarians, foraminifers, calcareous nannofossils, and palynomorphs (including dinoflagellate cysts [dinocysts], pollen, and spores) to obtain biostratigraphic ages and preliminary paleoenvironmental information. The presence and abundances of the microfossil groups vary significantly throughout the recovered sediment column. Rich assemblages of diatoms, silicoflagellates, and ebridians are present in the upper

~280 m CSF-A. Below that depth, diatoms are altered to opal-CT or are poorly preserved and offer minimal biostratigraphic constraint. Radiolarians are rare in the upper ~30 m CSF-A and their abundance decreases significantly downhole. Foraminifers and palynomorphs are generally sparse throughout the hole, and calcareous nannofossils are only present in trace numbers below ~525 m CSF-A. All microfossil group assemblages represent a combination of in situ and reworked taxa of different ages.

Although all investigated microfossil groups provide valuable age and/or paleoenvironmental information, diatoms provide the best age constraint, particularly in the upper ~280 m CSF-A. Above 75 m CSF-A, age assignment is difficult due to reworking; however, diatom and radiolarian assemblages suggest a Pliocene to Pleistocene/recent age for the uppermost 25 m. An unconformity at ~25 m CSF-A separates Pliocene sediment from middle Miocene sediment. Age diagnostic diatoms are present between ~75 and 280 m CSF-A and allow assignment of that interval to the *Actinocyclus ingens* Zone and *Denticulopsis maccollumii* Zone (middle to early Miocene). Dinoflagellate cysts and other aquatic palynomorphs confirm this age. Between ~280 and 380 m CSF-A, siliceous microfossils are altered to opal-CT. From ~380 to 580 m CSF-A, diatoms are present but preservation is poor, with valves occurring as silicified casts. Despite this, the presence of *Thalassiosira* sp. cf. *T. bukryi* and absence of *T. praefraga* indicate an early Miocene age. Dinocysts are present over this interval, but the assemblage contains a mix of in situ and reworked taxa. Siliceous microfossils are absent below 580 m CSF-A, whereas dinocysts and calcareous nannofossils are present and could indicate an early Miocene age if not reworked.

Foraminifers are generally sparse and the assemblages are dominated by calcareous benthic species. The foraminifer assemblages represent distinct biofacies that generally parallel the lithofacies recovered at Site U1521. Well-preserved diatoms and dinocysts indicate a highly productive and seasonally stratified water column. All microfossils will greatly contribute to contstraining paleoceanographic and paleoproductivity changes that occurred through the early to middle Miocene in the Ross Sea.

Paleomagnetic investigations focused on measurements of archive-half core sections and oriented discrete (cube) samples. Natural remanent magnetization (NRM) measurements of archive-half core sections were conducted before and after progressive alternating field (AF) demagnetization, commonly in 5 mT increments up to 20 mT peak AF. After 20 mT peak AF demagnetization, NRM intensities usually range between ~10^{-4} and 10^{-2} A/m and vary with lithology. Selected discrete samples were also used for initial NRM measurement, followed by progressive AF demagnetization in 2 to 5 mT increments up to a peak AF of 80 mT. Principal component analysis of these measurements reveals a stable characteristic remanent magnetization component in most of the samples, yielding normal and reversed polarities based on inclination data. Steep upward or downward inclinations are present in most intervals of archive-half core data and agree with directions from discrete samples, suggesting a stable and reliable magnetic carrier that can be used for magnetostratigraphic interpretation. The inclination variations correspond to normal and reversed polarity zones that can be correlated to the geomagnetic polarity timescale, with the aid of biostratigraphic datums.

Discrete samples were also used to measure the anisotropy of magnetic susceptibility (AMS) and mean bulk MS. The AMS agrees well with variability in the lithological units. For instance, AMS shows oblate fabric in the diatom-rich to diatom-bearing mudstone of lithostratigraphic Unit III.

Physical property measurements were conducted on whole-round cores, split core sections, and discrete samples. In general, the whole-round core gamma ray attenuation (GRA) bulk density and MS measurements are in good agreement with discrete moisture and density (MAD) samples and point measurements of MS on the section halves. The latter provide more accurate results since the whole-round measurements are dependent on the volume filling the core liner, which is less from RCB cores. A downhole increase in *P*-wave caliper (PWC) values generally coincides with an increase in bulk density and a decrease in porosity. Downhole variations in NGR also correlate well to changes in bulk density. Downhole changes in physical property characteristics are in good overall agreement with the lithostratigraphic units that are defined based on sedimentologic characteristics. In general, diatom ooze, diatom-rich mud/mudstone, and mudstone lithofacies (lithostratigraphic Units I, III, and V) correspond with low MS, NGR, thermal conductivity (<1 W/[m·K]), and bulk density, and high porosity. The lowest grain densities and highest porosities correspond with diatom-rich/bearing mudstone that is the dominant facies within lithostratigraphic Unit III. In contrast, intervals that are predominantly diamictite (lithostratigraphic Units II, IV, VI, and VII) are characterized by increased NGR, high bulk density, *P*-wave velocity, and thermal conductivity, moderate to high MS, and low to moderate porosity. Variations in MS for clast-poor diamictite (low to moderate) and clast-rich diamictite (variable and generally high) suggests that MS is an indicator of the abundance of glacially transported clasts in the sediment.

Headspace gas analyses show low methane and ethane concentrations in the upper 40 m CSF-A of the hole, increasing downhole up to 67,000 ppmv for methane and 264 ppmv for ethane. Interstitial water analyses on 15 samples from the uppermost 360 m CSF-A show a typical diagenetic profile with sulfate reduction and increasing ammonium concentrations in the uppermost 75 m CSF-A. Alkalinity follows a similar profile to ammonium, whereas iron and manganese concentrations in the interstitial waters were below detection limit. A range of major and trace elements show smooth downhole profiles with changes that are generally well correlated with lithostratigraphic units. Total organic carbon (TOC), total nitrogen (TN), and carbonate ($CaCO_3$) contents in Site U1521 sediments are generally low (<1.2 wt%, ≤0.1 wt%, and <6 wt%, respectively). The TOC content is slightly higher in the mudstone facies in the upper 300 m CSF-A, and decreases in the diamictite between ~330 and 640 m CSF-A. The TOC/TN ratio suggests mixed input of terrestrial and marine-derived organic matter with no clear downhole trend. Elevated $CaCO_3$ content is only observed in the sandy diamictite of lithostratigraphic Unit IV, Subunit VIA, and Unit VII, which also show higher MS. Elemental ratios obtained by handheld X-ray fluorescence (XRF) scans show good agreement with major lithostratigraphic units, but also suggest some deviations between chemical and lithological boundaries.

Downhole logging of Hole U1521A consisted of three separate tool runs (triple combo, FMS-sonic, and VSI), all of which reached to the bottom of the hole and proceeded without issue due to favorable borehole conditions. The triple combo measured NGR, density, porosity, resistivity, MS, and borehole diameter. The caliper data show that the borehole was in excellent condition, with only one washed out interval between 221 and 226 m WMSF. The NGR, bulk density, and porosity data match well with core measurements, whereas the MS data do not correlate as well, possibly due to temperature drift or other issues with the magnetic susceptibility sonde. The second logging run consisted of the FMS-sonic tool string to measure resistivity borehole images and acoustic velocity. The latter shows good correlation to the data measured with the *P*-wave caliper, especially above ~300 m CSF-A. The FMS images are extremely well resolved and clearly show clasts in the diamictite intervals, as well as a poorly recovered layered interval of chert and mudstone. The third logging run was the VSI tool (geophone) to conduct a VSP experiment. Raw checkshot data were used in preliminary velocity models for an initial seismic-core-log correlation.

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