IODP Expedition 383: Dynamics of the Pacific Antarctic Circumpolar Current (DYNAPACC)

Site U1540 Summary

Background and Objectives

International Ocean Discovery Program (IODP) Site U1540 (proposed Site CSP-7A) is located in the central South Pacific at 55°8.467′S, 114°50.515′W, ~1600 nmi west of the Magellan Strait at 3580 m water depth. The site sits at the eastern flank of the southernmost East Pacific Rise (EPR) within the Eltanin Fracture Zone, ~130 nmi from the modern seafloor spreading axis, and is underlain by oceanic crust formed at the EPR about 6–8 Ma ago. Assuming overall constant seafloor half spreading rates of ~4.5 cm/ky, the plate tectonic backtrack path of Site U1540 moves the site westward, to an early Pliocene position ~100 nmi closer to the crest of the EPR at a water depth shallower by several hundred meters. At a smaller scale, the site is located at the northeast end of a ridge that parallels the orientation of the EPR.

Site U1540 is crossed by a sediment echosound (Parasound) profile that is oriented northwest–southeast. The Parasound profile documents excellent penetration (>150 m) with distinct layering, suggesting a succession of fine-grained soft sediments with varying lithological composition. The site is also located ~2 nmi northwest of site survey core PS75/56.

Site U1540 lies in the pathway of the Subantarctic Pacific Antarctic Circumpolar Current (ACC), ~170 nmi north of the modern mean position of the Subantarctic Front (SAF) in a zonal transition zone of the ACC. To the west of the site, the ACC and the associated fronts are strongly steered by the topography of seafloor spreading systems (Udintsev and Eltanin-Tharp Fracture Zone systems), whereas to the east the vast Amundsen Sea basin does not influence the position of the ACC strongly.

Sea surface temperatures (SSTs) seasonally vary between ~2.5°C (July to September) and ~7°C (January to March). The area is located west from the main Antarctic Intermediate and Mode Water formation regions in the Southeast Pacific. The water depth of 3580 m places Site U1540 within Lower Circumpolar Deep Water (LCDW). This hydrographic setting makes it ideal to evaluate past changes in frontal position, associated export production, ACC current speed and position, as well as aeolian dust and ice-rafted debris (IRD) input during the Pleistocene and Pliocene.

The main objectives at Site U1540 were:

- Recover a moderate to high resolution Subantarctic Pliocene–Quaternary sediment record close to the SAF;
- Investigate the sequencing of siliceous and calcareous oozes, allowing for a wide range of paleoceanographic reconstructions;
- Reconstruct high amplitude Subantarctic SSTs and sea-ice variations;

- Provide a record of lowermost Circumpolar Deep Water (CDW) and glacial Antarctic Bottom Water (AABW);
- Reconstruct export production (opal versus carbonate), nutrient distribution, and dust-productivity coupling
- Recover a potential far-field record of West Antarctic Ice Sheet (WAIS) variability.

Operations

The sea voyage to Site U1540 began at 0224 h on 7 June 2019. It was a short 61 nmi transit that was completed in only 6.1 h, arriving on site at 0830 h. The thrusters were lowered and the vessel was in full dynamic positioning mode over the site coordinates by 0929 h. The drill crew made up an advanced piston corer/extended core barrel (APC/XCB) bottom-hole assembly and lowered the drill string to the seafloor, placing the bit at 2171 m below the rig floor (mbrf) by 1645 h. The vessel began experiencing heave above 7 m with a roll of ~5° at that time, and it was decided to wait for the seas to calm before continuing operations.

By 0415 h on 8 June, the seas had calmed sufficiently to continue operations. With an estimated depth of 3600.6 mbrf (calculated by the precision depth recorder [PDR]), the bit was lowered to 3595.0 mbrf to spud Hole U1540A. Core U1540A-1H recovered 9.0 m of sediment. This determined a seafloor depth of 3584.6 m below sea level (mbsl). Hole U1540A was deepened to 150 m below the seafloor (mbsf), with Cores 1H to 16H recovering 155.1 m (103%) by 0815 h on 9 June. The top drive was set back and the bit pulled to 3561 mbrf, clearing the seafloor at 0900 h on 9 June, and ending Hole U1540A. Formation temperature measurements were taken with the advanced piston corer temperature tool (APCT-3) on Cores 4H, 7H, 10H, 13H, and 16H, and orientation measurements were taken on all cores. Misfires were recorded on Cores 1H, 7H, and 16H. A misfire on Core 7H caused an unreliable temperature reading.

The vessel was moved 20 m east and the bit was lowered to 3575 mbrf to spud Hole U1540B. Our first attempt to take a mudline core did not retrieve any sediment. The bit then was lowered 9.5 m to 384.5 mbrf, and Hole U1540B was started at 1220 h on 9 June. Based on the recovery in Core U1540B-1H, the seafloor was calculated at 3580.0 mbsl. APC coring continued to 150 mbsf with three drilled intervals (totaling 10 m) to help obtain a good overlap with cores from Hole U1540A. A total of 16 cores were taken over a 140.8 m interval with 101% recovery. Misfires were recorded on Cores 1H, 6H, 8H, and 11H. The bit was raised, clearing the seafloor at 0958 h on 10 June, and ending Hole U1540B.

After coring Hole U1540B, permission was requested from the IODP Environmental Protection and Safety Panel to extend the allowed penetration depth at Site U1540 from 150 to 275 mbsf. The rationale behind this request was based on the successful recovery of a complete and continuous Pleistocene sedimentary record in Holes U1540A and U1540B. The increase in penetration depth would allow us to extend this record into the Pliocene, which was expected directly below the already cored maximum depth of 150 mbsf. An additional reason was based on the prevailing sea conditions, which predicted two additional days of reasonably calm seas, thus allowing for further drilling, whereas significantly worse sea conditions were forecast at our two other primary sites in the South Pacific.

Hole U1540C was spudded 20 m south of Hole U1540B at 1110 h on 10 June with the bit positioned at 3587.5 mbrf. Core U1540C-1H recovered 6.8 m, but the top of the core lacked the characteristic light brown oxidized layer that would have indicated the recovery of a good sediment/water interface. Therefore, we decided to end Hole U1540C and attempt another mudline core.

We repositioned the vessel 20 m west of Hole U1540C and started Hole U1540D with the bit at 3587.5 mbrf. Core U1540D-1H recovered 8.9 m (100%) with a noticeable light brown sediment layer at the top of the core. The amount of core recovered determined a water depth of 3577.5 mbsl. APC coring continued to 79.2 mbsf with three interspersed short drilled intervals to ensure an adequate core overlap for stratigraphic correlation between Holes U1540A, U1540B, and U1540C.

Permission to extend the penetration depth at Site U1540 to 275 mbsf was received while retrieving Core U1540D-11H from 79.2 mbsf. At that point, we drilled ahead without recovery to 131.0 mbsf before resuming coring operations. The APC coring system was redeployed and the hole was deepened until we reached APC refusal at 210.5 mbsf. Cores 21H and 22H (207.0–210.5 mbsf) recovered just 3.39 m and 0.5 m of sediment, respectively, with numerous rock fragments. We chose to deploy the XCB system for one more core in an attempt to recover more of the presumed basement material, but after coring for 45 min with only 0.5 m of advancement, the core barrel was pulled back aboard with no recovery. Then we raised the bit, which cleared the seafloor at 1710 h on 11 June, ending Hole U1540D. A total of 19 cores were taken over a 151.8 m interval with 151 m recovered (99%). Misfires were recorded on Cores 4H and 6H, and partial strokes were recorded on Cores 22H and 23H.

The vessel was offset another 20 m west of Hole U1540D, and the bit was spaced out for spudding another hole using the seafloor depth calculated from Hole U1540D. Hole U1540E was spudded at 1840 h on 11 June and drilled ahead without recovery to 135.0 mbsf. At that point, we deployed the APC system and cored continuously until APC refusal at 213.3 mbsf (Cores U1540E-2H to 10H). The pipe was recovered aboard, and the bit cleared the rotary table at 1900 h on 12 June. The rig was secured and readied for transit by 1905 h. A total of eight cores were taken in Hole U1540E with the APC system over a 76.0 m interval with 78.9 m recovered (104%). Core 10H experienced a partial stroke. There were two drilled intervals that advanced 137.0 m.

With the seas too high to raise the thrusters, the vessel waited on weather until the seas calmed down at 1545 h on 13 June. The thrusters then were raised and the vessel began the transit to Site U1541 (proposed Site CSP-1A).

Principal Results

A ~213 m thick continuous sequence of Holocene to early Pliocene sediment was recovered at Site U1540. A bottom-hole age of ~4.8 Ma and a mean sedimentation rate of ~4.5 cm/ky were determined. The deepest cored sediments were recovered in Hole U1540E. A spliced sedimentary sequence of ~227 m in length was constructed from Holes U1540A–U1540E. Five primary lithofacies were identified at this site. The numbering of facies is based on all facies documented for Expedition 383 so far. The sequence is dominated by light greenish gray to gray carbonate-bearing to carbonate-rich diatom oozes (lithofacies 2). These are frequently interbedded with light gray or light greenish gray diatom-bearing to diatom-rich nannofossil or calcareous oozes (lithofacies 3). Less abundant are white to very light gray nannofossil oozes of heavily bioturbated, massive appearance (lithofacies 4) and greenish gray to gray clay-bearing to clay-rich biogenic oozes (lithofacies 6 and 7). Based on the distribution and co-occurrence of the defined lithofacies, we have divided the Site U1540 sedimentary sequence into two lithostratigraphic units with the upper Unit I subdivided into two subunits: Unit IA and IB. Unit IA extends down to ~58 mbsf (~62 m core composite depth below seafloor [CCSF-A]) and is dominated by lithofacies 2 and thin intercalated beds of lithofacies 4. It is therefore broadly equivalent to Subunit IA at Site U1539. Subunit IB spans from ~58 to ~156 mbsf (~62 to 178 m CCSF-A) and shows an increased occurrence of lithofacies 3 and a decreased contribution of lithofacies 2. Lithofacies 1, 4, and 6 are virtually missing in this subunit. Unit II extends from 178 m to the base of the record at 227.1 m CCSF-A (165.83–210.50 m CSF-A in Hole U1540D and 165.33–213.3 m CSF-A in Hole U1540E). This unit is marked by a significant increase in the proportion of calcareous lithofacies 3 and 4 and the appearance of the clay-bearing to clay-rich lithofacies 6 in the lowermost ~40 m of the unit. Lithofacies 7 occupies parts of the lowermost ~8 m of Unit II, is pale yellowish brown to dark reddish brown, and is visually enriched in Fe (hydr)oxides. The last two sections of Core U1540D-21H and the core catcher of U1540D-22H contained altered volcanic glass.

Biostratigraphic age assignments are overall consistent with each other and are mainly derived from diatom, radiolarian, and calcareous nannofossil datums, as well as planktonic foraminifer biozonations. None of the different biozonations record any major hiatuses, indicating that a continuous sediment sequence from the early Pliocene through the Holocene was recovered at this site. The core catcher sample of the deepest core in Hole U1540E (Core 10H) contained a few reworked taxa from the Miocene. However, the in situ microfossils present in this interval indicate a maximum early Pliocene age at the base of Site U1540.

Paleomagnetic measurements indicate a number of polarity changes, which are best illustrated by downhole changes in inclination. The boundaries that define each polarity reversal are overall reasonably distinct. Prior to demagnetization, inclinations in the top 40 m CCSF-A are dominantly positive, opposite to the expected inclination during the normal polarity Brunhes Chron. After demagnetization, inclinations become steeply negative and largely consistent with values expected for a geocentric axial dipole for the site’s location. Positive inclinations associated with reversed polarity of the Matuyama Chron are observed in Holes U1540A, U1540B, and U1540D. However, the Matuyama/Brunhes polarity transition is not definitively captured within any core other than possibly at the base of Core U1540B-5H. Three normal polarity Subchrons within the Matuyama Chron are observed. The upper polarity transition of the Jaramillo Subchron is observed at the base of Core U1540D-8H and somewhat more noisily within Core U1540A-6H, while the lower Jaramillo polarity transition from the Matuyama Chron can be observed in Cores U1540B-10H and U1540D-10H. The upper polarity transition from the Olduvai Subchron (C2n) is observed within Core U1540B-17H and somewhat more noisily within Core U1540A-12H. The lower polarity transition from the Matuyama Chron is observed within Core U1540B-16H and possibly the upper part of Core U1540A-13H. The normal polarity Reunion Subchron is recognized in all cored holes with varying fidelity. Below ~180 m CCSF-A, polarity becomes more difficult to interpret as well-defined intervals of both polarities are observed on a decimeter scale.

We analyzed samples for headspace gas, interstitial water chemistry, and bulk sediment chemistry at a resolution of one 5 cm^3 sample per core at Holes U1540A (Cores 1H–16H), U1540B (Core 2H), and U1540D (Cores 15H–21H). Methane concentrations were low at this site overall. Methane concentrations gradually increased downhole, averaging 12.3 ppmv and never exceeding 18.4 ppmv. Ethane and propane remained below detection limit throughout the entire hole.

Above ~134 mbsf alkalinity and pH show no obvious trends, varying around averages of 3.4 ± 0.5 mM and 7.96 ± 0.07, respectively. Below this depth, alkalinity and pH exhibit almost identical behavior, first increasing to a local peak at ~157 mbsf, and then decreasing steadily to the bottom of the core.

The composite carbonate record of Site U1540 shows a downhole variability ranging from 6 to 93.5 wt%, and a strong correlation with RGB Blue, reflectance L*, and gamma ray attenuation (GRA) bulk density measurements. Total organic carbon (TOC) content has a mean value of 0.39 wt% and a standard deviation of ±0.12 across the entire cored interval. In the upper portion of the core, TOC values increase from 0.23 to 0.75 wt% between 15.69 and 28.7 m CCSF-A, respectively, and return to a lower value of 0.26 wt% at 75.42 m CCSF-A. The TOC record shows no correlation to the $CaCO_3$ record ($r^2 = 0.004$) downhole.

Physical properties measurements at Site U1540 comprised nondestructive whole-round measurements of GRA bulk density, magnetic susceptibility (MS), Whole-Round Multisensor Logger (WRMSL) *P*-wave velocity, and natural gamma radiation (NGR) on core sections from Holes U1540A to U1540E. Additional physical properties collected include thermal conductivity on whole-round core from all holes. Data acquired from whole-round measurements are generally in good agreement with those from split-core measurements and discrete samples. In particular, discrete MAD and GRA derived densities correlate well, and GRA density is also well correlated to discrete carbonate measurements from the different holes. Major bulk density peaks, corresponding to the lowest *P*-wave velocities, correlate with high carbonate nannofossil content, while smaller GRA, NGR, and MS peaks observed simultaneously are partly linked to IRD content. Low GRA densities reflect the more biosiliceous facies and correspond to higher *P*-wave velocity and high porosity. The older part of the record at the site, from 185 m CCSF to the bottom, shows a clear inverse correlation of MS and GRA densities, indicating that the oldest sediments are mainly composed of only two components, carbonate nannofossils and clay. NGR data also imply that total counts and the derived K content can be used as a semiquantitative proxy for the abundance of terrigenous material delivered by dust or sea ice and iceberg transport. Downhole changes in physical properties characteristics overall are thus in good agreement with the identified lithostratigraphic units based on sedimentologic characteristics. Comparison of the different physical properties allows the discrimination of intervals consisting of mainly two components from intervals consisting of three or more components, and could help provide a more quantitative determination of the sediment composition.

Correlations between holes were accomplished using the Correlator software (version 3.0). Tie points were established mostly using the RGB Blue channel extracted from the Section Half Imaging Logger (SHIL) digital images, but in many cases a combination of measurements was used. We constructed a splice from 0 to 222.95 m CCSF-A using four holes (U1540A, U1540B, U1540D, and U1540E). However, due to some misfired cores that were disturbed and could not be used, the splice contains two gaps. The deepest cores of Holes U1540D and U1540E (U1540D-22H, U1540D-22X, and U1540E-10H) were excluded from the spliced interval due to poor recovery and high levels of drilling disturbance.

We constructed a preliminary age model based on biostratigraphic and paleomagnetic age markers. These data suggest that the sedimentary sequence recovered at Site U1540 covers the past ~4.8 Ma. Though substantially lower than at Site U1539, sedimentation rates at Site U1540 are remarkably high for a pelagic setting. Below a condensed shallow section down to ~0.3 Ma, sedimentation rates average 7.5 cm/ky down to ~2.7 Ma and decrease to ~1.5 cm/ky during most of the Pliocene (2.7–4.8 Ma). This age model is generally consistent with preliminary stratigraphic tuning performed aboard, based on physical properties data such as color measurements (RGB Blue) and GRA bulk density.

The combination of nearly continuous recovery, very high sedimentation rates driven by high diatom productivity during glacial periods and potential sediment focusing, clear patterns in physical properties and sediment color, and a rich array of well-preserved diatoms combined with calcareous microfossils will provide unprecedented opportunities for improving our understanding of the dynamics of the ACC and its link to global carbon cycle changes at orbital and suborbital timescales.