IODP Expedition 401: Mediterranean–Atlantic Gateway Exchange

Site U1610 Summary

Background and Objectives

Site U1610 is the closest of the expedition's Atlantic sites to the Gibraltar Strait and, by extension, to the Mediterranean–Atlantic gateway during the late Miocene. It is located at 556.3 m below sea level (mbsl) in the Gulf of Cádiz (36°41.9812′N, 7°25.8844′W). The aim of drilling at Site U1610 was to provide a proximal record for the proximal–distal transect along the path of the Mediterranean Overflow plume during the late Miocene and early Pliocene.

There is considerable uncertainty about the late Miocene timing of opening and closure of the three different Mediterranean–Atlantic gateways (the Betic corridor through southern Spain, the Strait of Gibraltar, and the Rifian corridor through Morocco) (Krijgsman et al., 2018), and establishing this history is one of the main objectives of the expedition. Site U1610 was positioned in a location that would capture a record of the Mediterranean overflow plume, whichever possible gateway it was coming from, throughout the 8–4 Ma interval of interest. The Miocene target interval also needed to be sufficiently shallowly buried (<1700 m below seafloor [mbsf]) and in deep enough water to be accessible to *JOIDES Resolution* drilling capability. However, the Pliocene–Pleistocene succession in the Gulf of Cádiz derives both from more recent Mediterranean overflow and substantial clastic deposition from mainland Spain and Portugal, so in many places it is too deeply buried. Additionally, all potential IODP sites need to be in locations where hydrocarbon accumulations are demonstrably absent, which was also challenging for the Gulf of Cádiz. Within these constraints, there really was very little choice about the location of Site U1610, and even then, the target depth of 1460 mbsf was very deep for IODP drilling.

The two-way traveltime (TWT) to depth conversion used for the Pliocene–Pleistocene succession at Site U1610 was derived from adjacent Expedition 339 Sites U1386 and U1387 (Stow et al., 2013), which lie ~20 km to the northwest. This indicated that the Pliocene–Pleistocene succession at Site U1610 was ~750 m thick. Our drilling strategy was to drill ahead without coring the Pleistocene and the top of the Pliocene, casing the hole down to 550 mbsf, in order to increase the chances of recovering the target interval.

Site U1610 is located in the Deep Algarve Basin of the Gulf of Cádiz (Ng et al., 2022). Based on regional correlations to Expedition 339 sites and industry wells, the late Miocene seismic stratigraphic sequence at the site location was divided into four distinct stages, charting the progradation of a submarine fan (channel-levee-lobes system) influenced by bottom currents. The seismic packages transition upward from distal submarine lobes (a low-amplitude reflection unit below 2 s TWT) to more proximal, coarser-grained (higher amplitude) submarine lobes, overlain by a transparent unit (MTU) thought to reflect hemipelagic deposition, and then a Pliocene–Pleistocene Mediterranean-overflow-derived contouritic drift.

Expedition 339 drilled the top of the MTU at Site U1387 and recovered hemipelagic sediments (Stow et al., 2013). Beneath this we anticipated a migrating channel fill succession, below which is an unconformity and a succession of dipping bright reflectors (Ng et al., 2022). Beneath this is a package of parallel-bedded, lower amplitude reflectors which is thought to be of Tortonian age. At around 2.1 s (TWT) is a wedge-shaped unit that is interpreted to be the toe of a seismic unit with irregular internal reflections that thickens to the southeast and is thought to be an olistostrome, equivalent to the olisostrome seen in the outcrop in southern Spain. The 8 Ma target age was anticipated to lie just below this chaotic interval.

Operations

Site U1610 consists of one hole, Hole U1610A, and 751.2 m of sediment was collected from over a 933.5 m cored interval (81% recovery). The upper 501.9 m of the hole was cased to prevent caving and to make it easier to flush cuttings out of the borehole, with the aim of increasing the chances of coring and logging successfully to the target depth of 1460 mbsf. The Pleistocene and late Pliocene stratigraphy, which was not recovered in the top 501 m at Site U1610, is already known from nearby Expedition 339 Site U1387, located ~27 km to the northwest.

Hole U1610A

The ship completed the 122 nmi voyage to Site U1610 (proposed Site GUB-02A) at a speed of 11.5 kt, arriving at 1010 h on 28 December 2023. The hydraulic release tool (HRT) and casing was prepared, consisting of the HRT assembly, the HRT base, and 498 m of 10¾ inch casing. The rig team then made up the bottom-hole assembly (BHA), including the bit, underreamer bit, and mud motor. The BHA and drill pipe were lowered down through the casing until the bit and underreamer extended below the casing by 3 m. The HRT running tool was attached to the casing and the funnel was welded on; then the entire casing system was lowered down through the moonpool and the ship was positioned over the hole coordinates.

Hole U1610A started at 1200 h when the seafloor was tagged at 561.7 mbsl. The funnel's base landed on the seafloor with the casing shoe at 501.9 mbsf. After the casing was released, the bit was raised, clearing the seafloor at 2215 h on 30 December and clearing the rotary table at 0302 h on 31 December, completing casing operations.

We elected to start coring in Hole U1610A with the extended core barrel (XCB) coring system because it had recovered good quality cores at equivalent depths in Hole U1609A. The nonmagnetic drill collar was left out of the assembly to improve the robustness of the BHA, and a lockable float valve was included for potential downhole logging.

Hole U1610A was reentered at 0940 h on 31 December, and during this process the depth to seafloor was found to be 556.3 mbsl, identical to the precision depth recorder reading, but shallower than the previous estimate of 561.7 mbsl. The bit was lowered to the base of the hole, 505.2 mbsf, and the first science activity at the site was to run the Sediment Temperature 2 (SET2) tool. At 1430 h, we started coring Core U1610A-2X and continued into the new year.

At 0340 h on 4 January 2024, we started a more rigorous headspace gas sampling protocol for the depth interval 754 to 960 mbsf at this site, following the recommendation by the IODP Environmental Protection and Safety Panel and the Texas A&M University Safety Panel. Beginning with Core U1610A-27X at 747.7 mbsf, the headspace gas results from each core were analyzed before advancing the bit to collect the next core. This protocol was in effect because a detailed preexpedition analysis of 3-D seismic data showed that there is a nonzero, but very low, risk of finding gas at the Site U1610 location. Headspace gas results from all XCB cores were found to be in the normal (safe) range of methane/ethane ratios and absolute methane values. Cores U1610A-2X to 36X penetrated from 505.2 to 827.8 mbsf and recovered 322.6 m (93%).

At 0700 h on 4 January there was a failure in the top drive brake system, causing the brake to engage and overheat. We stopped coring and pulled up Core 36X, which had advanced 3 m. The bit was raised to 793.5 mbsf, the top drive was racked to allow repair, and the bit was raised to 495.2 mbsf just inside the casing. The first interval of top drive inspections and repair ran from 0945 to 1330 h. The cause for the failure appeared to be the exhaust valve on the brake. A portion of the diaphragm in the exhaust valve had broken off, lodged in the valve, and kept air pressure to the energizing bladder behind the brake bands. This kept the brake engaged. There was significant damage to the brake and bladder assembly from the resultant overheating, and the entire brake assembly needed to be replaced with the spare unit from the warehouse.

Meanwhile, we decided to change the coring system from XCB to rotary core barrel (RCB) for the remainder of the hole. We raised the bit to the ship, clearing the seafloor at 1423 h and the rig floor at 1630 h. Repairs to the top drive continued and were complete by 0215 h on 5 January. The rig floor team then assembled the RCB BHA with a new 9⅞ inch polycrystalline diamond compact bit and Hole U1610A was reentered at 0548 h. Core 50R marked the end of the special headspace gas protocol, and results were within the normal range for the interval where the enhanced gas safety protocol was in effect. The procedure resulted in a delay of ~45 min per core across 23 cores.

Coring continued with very good recovery until Core 95R, which recovered just 15 cm of hard dolostone rock pieces. Core 96R was empty, so we ran the bit deplugger to remove any potential obstructing rock lodged in the bit. Although the drilling rate indicated that we were drilling recoverable sediments and had passed below the hard lithified sediments that had been partly recovered in Core 95R, no sediments were recovered, so we stopped coring at 0515 h on 11 January with Core 100R. Cores 37R to 100R penetrated from 827.8 to 1438.7 mbsf and recovered 610.9 m (74%).

We prepared for downhole logging by releasing the bit at the bottom of the hole, filling the hole with 354.3 bbl of heavy (10.5 lb/gal) barite mud, and raising the pipe. When the end of the pipe reached 779.4 mbsf, the drill pipe became stuck. After an overpull of 60,000 lb would not free the pipe, the circulating head was attached so that fluid could be pumped, and the top drive was picked up so that the pipe could be rotated. After several attempts, the pipe came free at 1215 h on 11 January with 90,000 lb overpull and a pump pressure of 600 psi. The end of pipe was set at 516.6 mbsf for logging, 14.7 m below the casing shoe.

At 1415 h, we started to assemble the quad combo tool string, including natural gamma radiation (NGR), density, resistivity, and sonic velocity tools. The tool string was lowered down the hole, passing out of the casing into the open hole at 1640 h. At ~726 mbsf, the tool string encountered an obstruction and, after eight attempts, could not pass any further down the hole. This is the same depth interval at which the drill pipe was stuck earlier in the day. However, useful log data were acquired from the ~208 m open hole logged interval.

The inclinometer in the cable head of the quad combo logging tool string showed that Hole U1610A was inclined between 13° and 15° from vertical in the logged interval. The hole had been suspected to deviate from vertical from observations of inclined beds in the cores.

The downhole logging equipment was rigged down by 0045 h on 12 January and the pipe was raised, clearing the seafloor at 0130 h and the rig floor at 0300 h. The rig floor was secured for transit, we raised the thrusters at 0336 h, and we started the sea passage to Site U1385 at 0348 h, ending Site U1610.

Principal Results

Lithostratigraphy

Seven primary lithologies were described in Hole U1610: calcareous clay, calcareous mud, calcareous silty mud, calcareous (sandy) silt(stone), calcareous (silty) sand(stone), clayey calcareous ooze, and dolostone. Minor coarser-grained lithologies were also observed. Based on these lithological descriptions, Site U1610 is divided into five stratigraphic units. Contacts between lithologies are predominantly gradual, with subtle color and grain size changes; however, some contacts are sharp to erosive.

Unit I ranges from 505.2 to 699.4 mbsf and is composed of alternating calcareous mud and calcareous silty mud, with minor coarser, sandy intervals. Unit II ranges from 699.2 to 831.7 mbsf and consists of calcareous mud and calcareous clay. Unit III ranges from 837.5 to 934.8 mbsf and consists of interbedded calcareous mud and clayey calcareous ooze to calcareous silty mud, with minor coarser, sandy intervals. Unit IV ranges from 934.8 to 1388.8 mbsf and is divided into three subunits. Subunit IVa consists of alternating calcareous silty mud, calcareous sandy silt, calcareous mud, and coarser-grained sand and silty sand intervals, with minor clayey calcareous ooze to calcareous clay (934.8–1112.7 mbsf). Subunit IVb consists of calcareous mud, calcareous silty mud, calcareous sandy silt, and calcareous sand (very fine, fine, and medium), with some clayey calcareous ooze to calcareous clay, and minor lithified siltstone, sandstone (fine to medium), and conglomerate (1112.7–1220.3 mbsf). Subunit IVc consists of alternating calcareous mud, calcareous silty mud, calcareous sandy silty, and coarser-grained sand and silty sand intervals, with minor clayey calcareous ooze to calcareous clay and calcareous clay (1220.3–1388.8 mbsf). Unit V ranges from 1388.6 to 1388.8 mbsf and consists entirely of dolostone. Cores U1610A-96R through 100R (1388.6–1438.7 mbsf) had 0% recovered sediments and are not included in the unit definition.

General Sedimentary Model

Site U1610A is located in the southern part of the Deep Algarve Sedimentary Basin, within the Gulf of Cádiz. During deposition of Unit IV in the early to late Messinian (<6.9–7.1 Ma to around 5.78 Ma), there was an interplay of gravity processes, (contouritic) bottom currents and pelagic/hemipelagic deposition that determined the evolution of a mixed (turbidite-contourite) depositional system, where turbiditic deposits were reworked by bottom currents. The bottom current processes are associated with an intermediate water mass flowing along the middle slope of the margin. This mixed depositional system underwent a long-term evolution from Subunit IVc to IVa, with a wide spectrum of features and deposits formed under synchronous and asynchronous interactions of gravity and contouritic processes. Turbidite deposits have been described in both the Guadalquivir Basin and the Deep Algarve Basin during the Messinian, and are associated with continental margin progradation, tectonic instability, and relative sea level variations.

During deposition of Unit III and Unit II in the latest Messinian–early Pliocene (5.78–>4.52 Ma), an important change in the depositional style with respect to Unit IV took place, with the development of hemipelagic deposits, and with very occasional, very fine grained turbidites not affected by bottom currents. This result agrees with the previous interpretation for the upper part of the Messinian in the Gulf of Cádiz that proposed hemipelagic sedimentation during the late Messinian and no significant MOW influx during the earliest Pliocene (e.g. Stow et al., 2013; Hernandez-Molina et al., 2016, Van der Schee et al., 2016), but at Site U1610 it appears that this change happened earlier than previously documented based on seismic data on the same area (Ng et al., 2022). However, this hypothesis for the lack of bottom water current reworking and contourite deposition is contrary to other authors who consider a MOW influence since the Miocene/Pliocene boundary (e.g., Nelson et al., 1999).

During deposition of Unit I, later in the Pliocene (4.6–3.57 Ma), bottom water current (contouritic) and pelagic/hemipelagic sediments dominate the succession. Similar Pliocene sequences observed elsewhere in the Gulf of Cádiz are considered to result mainly from MOW bottom currents (e.g., Nelson et al., 1999; Rodrigues et al., 2020).

Biostratigraphy

Based on the calcareous nannoplankton and foraminifer assemblage, an age between 3.61 and 3.57 Ma is estimated for the top of the recovered sequence (510.3 mbsf). Below this, a continuous series of calcareous nannoplankton and planktonic foraminifer events were recorded. The presence of *Globorotalia miotumida* and *Reticulofenestra rotaria* at the bottom of the hole constrains the age to between 6.38 and ~7.2 Ma. The Miocene/Pliocene boundary is placed at ~800 mbsf (the subunit IIb/c transition), based on the highest occurrence (HO) of *Orthorhabdus rugosus* and the highest common occurrence of *Neogloboquadrina incompta* (sinistral).

During the Pliocene, sedimentation rates determined from biostratigraphy are on the order of ~160 m/Ma, and were higher during the Miocene, reaching up to 240 m/Ma.

The preservation of microfossils is generally good with abundant calcareous nannofossils and planktonic foraminifers, but the concentration and preservation of planktonic foraminifers decreases with depth in the late Miocene samples. The benthic/planktic ratio is indicative of intermediate water depths during the Miocene and Pliocene. There is evidence of sediment reworking, so some of the calcareous nannofossil bioevents, specifically the HO events, may have been redeposited in younger strata.

Paleomagnetism

The paleomagnetists measured the natural remanent magnetization (NRM) of all the archive half-core sections from Hole U1610A on the superconducting rock magnetometer (SRM). Alternating field (AF) demagnetization was performed at 5, 10, 15, and 20 mT, with measurement of the remaining NRM being taken at 2 cm resolution after each step. A drilling overprint was mostly removed by 10 mT demagnetization.

In addition, we measured the NRM of 134 cube samples on the JR-6A AGICO spinner magnetometer, then the samples were AF demagnetized. The NRM of discrete samples is significantly stronger than at Site U1609, with an average of 10×10^{-4} A/m. In general, steps of 5, 10, 15, 20, 30, 40, 50, and 60 mT, and in some cases up to 100 mT, were added to fully demagnetize the characteristic magnetic component.

Results from 501 to 540 mbsf clearly show normal inclinations in both SRM and JR-6A records. Between 540 and 1010 mbsf, reversed directions are dominant and many SRM inclination values approach the expected antipodal geocentric axial dipole (GAD) inclination at the site (57°). Some short (<20 m) normal polarity depth intervals are present, but they are not clear, and only a few show successive inclinations with the expected GAD value. Normal polarities dominate from 1010 to 1390 mbsf. Correlations to the geomagnetic polarity timescale are tentative, but the lack of reversals in the lower 1010 to 1390 mbsf are consistent with the high sedimentation rates observed by biostratigraphy.

We measured the anisotropy of magnetic susceptibility (AMS) and bulk magnetic susceptibility (MS) of all the discrete samples using the MFK2 KappaBridge instrument. Results show that all the κ_{min} axes have a tilt of ~15°–17° deviating from the vertical. Because κ_{min} is generally perpendicular to the sedimentary bedding plane, this value indicates that drilling was not vertical, but must have occurred with an angle of 15°–17°, and it is consistent with the observation of inclined beds in the visual core descriptions and the logging data. In principle, we think it should be possible to reconstruct the strike of the dipping borehole, provided the paleomagnetic signal is robust enough, which will allow AMS results to be interpreted in terms of current flow direction.

Geochemistry

At Hole U1610A the safety protocol for drilling between 740 to 960 mbsf required the methane concentration in headspace gases and methane/ethane ratios to be reported to the drilling team prior to advancing to drill the next core. In all headspace gas samples in this interval, the methane concentrations remain <12,000 ppmv (well below threshold), ethane concentrations are <12 ppmv, and the minimum ratio of these two gases (C_1/C_2) is 406. These low concentrations of methane and ethane and the dominance of methane (low C_1/C_2 ratio) present no concerns for drilling safely as they indicate a microbial rather than petrogenic source. Methane and ethane were commonly detected, while ethene, propane, isobutane, and isopropane were detected in trace amounts.

Void space was also sampled directly when gas pockets appeared in the core. In void spaces, the absolute concentrations are not meaningful as they are essentially methane pockets (measured methane is close to 100%), but we found similar trace constituent composition to that measured with the standard interstitial headspace gas protocol. In void spaces, the C_1/C_2 ratio minimum is 1930, indicative of microbial rather than petrogenic sourcing.

The inorganic geochemistry team sampled 42 interstitial water (IW) samples and two bottom water samples from Hole U1610A and measured salinity, pH, and alkalinity. One IW sample was collected from every core, except where recovery was short (<3 m core) or poor quality (abundant fractures), in which case the IW sample was not taken. Approximately 10 mL of IW was extracted initially, which decreased to ~6 mL of water during RCB coring. Sampling continued until water yields decreased below ~1 mL at Core 61R. The team also obtained an additional IW sample from Core 72R with insufficient yield for most measurements. Alkalinity ranges from 1.4 to 4.8 mM, pH varies between 7.5 and 8.0, and salinity is 32 to 35 within IW samples. Major and trace elements in the IW samples were measured by ion chromatography and inductively coupled plasma–atomic emission spectroscopy. The bottom water samples each have an elevated salinity of 36, indicating we were sampling Mediterranean overflow water.

Overall, $CaCO_3$ ranges from 25.4 to 79.8 wt%, with a mean of 35.3 wt% and a standard deviation of 7.3 wt%. Standard reproducibility was 1.12 wt% (n = 13). $CaCO_3$ is generally relatively invariant at Site U1610, with most samples falling within 28 to 40 wt% downcore. This included some selected for color variations, implying that color variations are driven by changes in components other than carbonates, likely the siliciclastic fraction.

Physical Properties and Downhole Measurements

In the upper part of the cored interval, 510–685 mbsf, ~2 m scale cycles are evident in the MS and NGR data and they have higher amplitude in the underlying interval, 685–975 mbsf. The interval of 975 to 1130 mbsf is characterized by a downhole increase in MS values by two orders of magnitude and a decrease in NGR values. From 1130 to 1295 mbsf, MS and NGR return to lower values and lower amplitude variations, with longer wavelength changes and less-evident cyclicity. Below 1295 mbsf, shorter wavelength variability is again seen in the MS and NGR datasets.

Downhole logging in Hole U1610A unfortunately did not reach deeper than 726 mbsf. Caliper logs show that the hole was alternately washed out to greater than 15 inch and closed in to narrower than the bit diameter. However, the 220 m long open hole logged interval shows cyclic variation that can be used to cover stratigraphic gaps in lithostratigraphic Unit I. The density log is strongly affected by borehole conditions, but in narrower borehole intervals, the readings are probably valid and reach a maximum of 2.0 g/cm^3. Perhaps the most important logging result is quantifying that the hole is inclined from vertical by 13°–15° in the logged interval. Hole inclination will have to be considered in calculating bed thicknesses and depths to seismic reflectors, because coring depth along the borehole overestimates true vertical depth.

The SET2 probe results gave a temperature of 24.8°C at 505.2 mbsf. Using this result and the seafloor temperature of 12°C (measured on the Conductivity-Temperature-Depth deployment), the geothermal gradient at the site is 25.3°C/km.

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