IODP Expedition 401: Mediterranean–Atlantic Gateway Exchange

Site U1609 Summary

Background and Objectives

International Ocean Discovery Program (IODP) Site U1609 (37°22.6159′N, 9°35.9119′W) is located at 1659.5 meters below sea level (mbsl) on the continental slope of the Portuguese margin. The primary scientific objective of Site U1609 was to recover a distal record of the Late Miocene–Pliocene Mediterranean overflow plume. The aim was to capture the evolution of the plume's equilibrium depth through time, from the earliest evidence of overflow through the Rifian Corridor in present-day Morocco, through the Mediterranean's Messinian Salinity Crisis (5.97–5.33 Ma), to the early Pliocene (~4 Ma). This interval of major gateway and Mediterranean environmental change is likely to have substantially influenced both the density and the chemistry of the overflow on subprecessional to million-year timescales.

Site U1609 is 17 km to the west and downslope from Site U1391, drilled during Expedition 339, which comprised Pliocene–Quaternary muddy contourites with interbedded sands, hemipelagites, and several layers of mass movement deposits. On the seismic profile linking Site U1391 with Site U1609, packages of the contouritic drift migrate landward with time. IODP Site U1609 takes advantage of this landward migration and surface erosion, also visible in the seismic profiles, to access the target Miocene–Pliocene strata at relatively shallow depths. The seismic data also suggests that the Late Miocene succession at Site U1609 is more likely to provide a more complete record of the Mediterranean overflow plume than Site U1610 (proposed Site GUB-02A) in the Gulf of Cádiz, which is closer to the source of the plume.

Site U1609's distal location ensures that a less clastic, more hemipelagic succession is recovered, providing a suitable record for high-resolution astrochronological tuning, and a strong age framework for subprecessional investigation of the driving mechanisms causing changes in the plume. This record of the Miocene Mediterranean overflow plume also provides an important constraint on the upper part of the northeast Atlantic water mass structure in the Late Miocene. This record will be correlated with a deeper water site to the north, Site U1385 (which will be drilled in Expedition 401), and the Miocene successions recovered along the Expedition 397 depth transect.

In combination with other Expedition 401 Atlantic sites, the record from Site U1609 also allows us to investigate more specific objectives including:

- Establish the age of the earliest contourites formed as a result of Mediterranean overflow. Evaluate the impact of extreme environmental fluctuations in the Mediterranean on its overflow plume and the structure of the Atlantic water masses.
- Provide quantitative constraints on the mixing behavior of dense overflows by reconstructing the strength and attenuation rate of the Atlantic–Mediterranean exchange signal beyond the gateway.

Operations

Site U1609 consists of two holes and collected 983.0 m of sediment over a 1046.1 m cored interval. Hole U1609A penetrated 610.0 m with a sedimentary recovered length of 572.4 m (93% recovery). Hole U1609B cored 436.1 m with a sedimentary recovered length of 410.8 m (94% recovery).

Hole U1609A

The ship arrived at Site U1609 (proposed site ALM-03B) at 1655 h on 17 December 2023 after completing the 1220 nmi voyage from Amsterdam in 4.5 d. All thrusters were down and secure at 1712 h, and the ship switched to full auto dynamic positioning (DP) mode at 1720 h, marking the start of operations at Site U1609. Operations started on the rig floor with assembly of the bottom-hole assembly (BHA). For Site U1609A we used a polycrystalline diamond compact (PDC) drill bit, and for the extended core barrel (XCB) cores we used a PDC cutting shoe. This combination had been found on recent IODP expeditions, including during Expedition 397 in the same area, to yield very good recovery of XCB cores.

At 0430 h on 18 December, after one missed mudline, we were successful in starting Hole U1609A (37°22.6259′N, 9°35.9120′W), with the seafloor calculated at 1659.5 mbsl based on the core recovery and mudline depth in Core U1609A-1H. Cores U1609A-1H to 25H penetrated from the seafloor to 224.7 meters below seafloor (mbsf) and recovered 224.7 m (85%). Advanced piston corer temperature (APCT-3) tool temperature measurements were made during Cores 4H, 7H, 10H, and 13H, and all recorded smooth 10 min long temperature equilibration curves. At 0300 h on 19 December, we switched to the half-length advanced piston corer (HLAPC). Cores U1609A-26F to 37F penetrated from 224.7 to 269.7 mbsf and recovered 45 m (102%). At 1430 h, at 269.7 mbsf, we changed to XCB coring. Cores U1609A-38X to 73X penetrated from 269.7 to 610.0 mbsf and recovered 340.3 m (99%). Over the course of

the hole, the driller pumped eight 30 bbl sepiolite mud sweeps from 274.7 to 571.0 mbsf.

After confirming that early Tortonian sediments had been reached, and thus that we had recovered the Messinian to late Tortonian target stratigraphy, we stopped coring. The last core, Core 73X, reached 610.0 mbsf and came on deck at 2015 h on 22 December.

We prepared the hole for downhole logging by sweeping it with 30 bbl of sepiolite mud to flush out any loose sediment, displacing it with 230 bbl of barite-weighted mud to stabilize the borehole walls, and set the end of pipe to 56.4 mbsf. The triple combo downhole logging tool string was assembled by 0130 h on 23 December, but before it could be run down the pipe, the wireline heave compensator (WHC) control computer was found to be unresponsive. After troubleshooting diagnosed a probable hard drive failure, we decided to log without heave compensation. Ship heave was around 2.5 m throughout the day—higher than desirable but not atypical for logging from the ship. The triple combo logged borehole physical property data down to within 5 m of the bottom of the hole. The second tool string, the Versatile Seismic Imager (VSI), also reached close to the bottom of the hole for the check shot survey. Concurrently, we observed for protected marine species. Only two of the 13 check shot stations gave reliable first-arrival times because most of the borehole was too wide to achieve good coupling. Fortunately, those two stations were in the lower part of the hole where the data are most useful for tying borehole depth to the seismic profiles. Because of the wide borehole and the lack of heave compensation, we decided not to run the Formation MicroScanner (FMS) tool and instead to run a sonic velocity and natural gamma radiation (NGR) tool string as the third and final logging run. This tool string also reached close to the base of the hole. The logging equipment was rigged down by 2230 h on 23 December. We raised the pipe and the bit cleared the seafloor at 2235 h, ending Hole U1609A.

Hole U1609B

The ship was offset 20 m to the south of Hole U1609A along the slope, and at 0305 h on 24 December we started Hole U1609B (37°22.6159′N, 9°35.9119′W) by drilling down without recovery. The plan was to drill down without coring to spend more time coring the Early Pliocene to Late Miocene target interval; however, in these clay-rich sediments, drilling was no faster than taking cores. At 0930 h, we retrieved the center bit and started taking advanced piston corer (APC) cores at a depth of 72.6 mbsf. Cores U1609B-2H to 4H penetrated from 72.6 to 101.4 mbsf and recovered 28.5 m (95%), but after Core U1609B-4H had partial recovery and required 20,000 lb overpull to retrieve, we switched to coring with HLAPC at 101.1 mbsf. Cores U1609B-5F to 32F penetrated from 101.4 to 234.1 mbsf and recovered 133.0 m (101%). We ran the Sediment

Temperature 2 (SET2) tool after Core 32F at 234.1 mbsf, to measure formation temperature deeper than had been possible with the APCT-3 tool in Hole U1609A.

At 1630 h on 25 December, we switched to the XCB coring system. At 1600 h on 26 December, after taking Core 48X at 389.3 mbsf, we ran the SET2 tool a second time. XCB coring proceeded until cores reached the age of 8.4 Ma, old enough to cover the main events in the history of the Mediterranean–Atlantic gateways. Cores U1609B-33X to 61X penetrated from 234.1 to 508.7 mbsf and recovered 264.9 m (91%). At 1700 h on 27 December, we set back the top drive and started to pull up the drill pipe. The bit cleared the seafloor at 1905 h, and the BHA was on deck by 2345 h. The thrusters were raised and we started the transit to proposed Site GUB-02A (Site U1610) at 2354 h, ending Site U1609.

Overall, we spent 10.2 d at Site U1609, about two days shorter than in the original operations plan, because the age targets were shallower than had been anticipated. For this reason, we were also able to recover two cored records of the target interval rather than the single core record that originally had been planned in the expedition *Scientific Prospectus*.

Principal Results

Lithostratigraphy

Three main lithologies are described in Site U1609: calcareous mud, calcareous silty mud, and clayey calcareous ooze. Minor coarser-grained deposits (e.g., calcareous silt, sandy silt, and calcareous sand) are also observed. On the basis of subtle lithological changes, Holes U1609A and U1609B are divided into four stratigraphic units. Contacts between these units, and the lithologies within them, are mainly gradational, characterized by subtle changes in color and grain size. Only the coarser silts and sandier beds are characterized by sharp to erosive basal contacts. In Hole U1609A, Unit I ranges from 0 to 344 mbsf and is characterized by alternating calcareous mud and calcareous silty mud. Unit II ranges from 344 to 457 mbsf and consists of alternating calcareous mud and clayey calcareous ooze. Unit III ranges from 457.7 to 531.5 mbsf and contains triplets of calcareous mud of two different shades (lighter/darker) and clayey calcareous ooze, repeating on a meter scale. Unit IV ranges from 531.5 to 609.3 mbsf and contains two distinct types of calcareous muds and clayey calcareous ooze, with brown calcareous muds the dominant lithology. In this unit, bed thickness is usually <1 m and the beds occur rhythmically. Coarser sandy and silty deposits, at ~10 cm scale, are observed primarily in Units II and III.

Biostratigraphy

The sedimentary record recovered at Site U1609 is mostly continuous, although minor discontinuities cannot be totally excluded based on the low resolution of the biostratigraphic sampling on board. Preservation of microfossils is generally good with abundant calcareous nannofossils and planktonic foraminifers; benthic foraminifers are rare.

Based on the calcareous nannoplankton assemblage, the top of the sequence recovered in Hole U1609A is estimated to be >0.24 Ma, indicating that a significant proportion of the Pleistocene sequence has been eroded at this location. A continuous series of calcareous nannoplankton and planktonic foraminiferal events were recorded in this site spanning ~1.24 Ma to the earliest Tortonian. Some of the calcareous nannofossil bioevents, specifically the highest occurrence (HO) events, may have been affected by reworking and redeposition. However, the ages derived from both the nannofossils and the foraminifers suggest that this is not a major issue. Sedimentation rates for the lower part of the sequence combined with the oldest bioevent, suggest an age close to the Tortonian/Serravallian boundary for the base of Hole U1609A.

During the Pliocene, sedimentation rates range from 37 to 90 m/my, in line with those estimated from the paleomagnetic records. Miocene sedimentation rates have a lower range (39 to 71 m/my).

Paleomagnetism

Paleomagnetic investigation of cores from Holes U1609A and U1609B focused on demagnetization of the natural remanent magnetization (NRM) of archive half-core sections and discrete samples of the working half-core sections. The Icefield MI-5 tool was used to orient the uppermost 24 cores in the APC section of Hole U1609A. The NRM intensity is very weak, ranging from about 1.4×10^{-5} to 4.0×10^{-1} A/m, with an average of 2.5×10^{-3} A/m.

In Hole U1609A, NRM removed by 10 mT alternating field (AF) demagnetization is likely related to an overprint caused by core drilling. Inclination values after 20 mT AF demagnetization roughly show polarity reversals, but with a lot of values scattered between expected normal and reverse values, and with very few of the reversed values reaching the expected geomagnetic axial dipole inclination at the site (56.8°). The weak magnetization and scattered directions may be due to dissolution of most of the original magnetic minerals and precipitation of authigenic iron sulfides. However, after running a 1 m smoothing window on the inclination values, normal and reversed polarity intervals can be tentatively recognized and, constrained by the biostratigraphic framework, they were correlated to the geomagnetic polarity timescale (GPTS) from about 1.2 to 8.7 Ma.

Geochemistry

The inorganic geochemistry team measured salinity, pH, alkalinity, and concentrations of major anions and cations, ammonium and phosphate, and trace elements for 66 interstitial water (IW) samples and a mudline (bottom water) sample from Hole U1609A. IW was extracted by squeezing a 5–7 cm whole-round sample, and the squeeze cake residues were then sampled for sedimentary geochemistry. One IW sample was collected in every APC and XCB core (Cores 1H to 25H, and Cores 38X to 73X) and one in every other HLAPC core (Cores 28F to 36F). Alkalinity increased from 2.4 mM at the mudline to >15 mM between 44.8–256.1 mbsf, driven primarily by sulfate reduction, and pH varied between 7.4 and 7.8. Major ion concentrations, nutrient concentrations, and alkalinity reflect a variety of subsurface diagenetic processes including sulfate reduction, carbonate mineral precipitation and dissolution, organic matter remineralization, and water uptake into clay minerals. The sulfate–methane transition zone (SMTZ) occurs around Core U1609A-6H at a depth of ~45 mbsf.

The organic geochemistry team measured weight percent (wt%) total inorganic carbon (TIC), sedimentary carbon (TC), and total nitrogen (TN) on the squeeze cake residues from the IW sampling at Hole U1609A. Headspace gas was also measured from a discrete sample taken at the top of the core section below each of the 66 IW samples. Methane and ethane were commonly detected, while ethene and propane were detected in trace amounts in <10 samples. Methane concentrations ranged from 0–42,000 ppmv, and ethane concentrations ranged from 0–3.3 ppmv, with highest abundances between 100–300 mbsf. Calcium carbonate content ($CaCO_3$ wt%) was calculated from the TIC content, assuming that all inorganic carbon is present as calcium carbonate. Total organic carbon (TOC) was determined as the difference between TC and TIC. Calcium carbonate varied between 20–75 wt%, increasing toward the bottom of Hole U1609A, while TOC and TN remained low (<1% and <0.08%, respectively) throughout.

Physical Properties and Downhole Measurements

The correlation between physical property data and sedimentary data allowed the definition of four main physical properties units at Site U1609 with boundaries at 344, 458, and 531 mbsf. The boundary at 344 mbsf matches with a sedimentological transition from calcareous muds and calcareous silty muds (Unit I) to clayey calcareous oozes and muds (Unit II). In general, there is a correlation between magnetic susceptibility (MS), NGR, and gamma ray attenuation (GRA) bulk density, all presenting a slight decrease from the top to the bottom of Unit I. The correlation is even better between NGR and MS. Unit II shows an increasing trend for both NGR and GRA toward the bottom (458 mbsf). Unit III contains several coarser sandy layers and is followed by

greater variations on physical properties that present a global decreasing trend toward the bottom (531 mbsf). Unit IV represents a decrease in all the measured physical properties. This is reflected in the sedimentological data by the transition to a less siliciclastic sequence of clayey calcareous oozes and calcareous muds. Generally, variations in physical properties are associated with color changes identified by the sedimentology team and in the red-green-blue (RGB) and reflectance data. This suggests that color changes are associated with changes in grain size and mineralogical composition.

Logging data from the downhole logging operations in Hole U1609A were processed at Lamont-Doherty Earth Observatory, Columbia University. The sonic velocity logs and check shot interval velocity values reached 2.25 km/s at the base of the logging interval, 578 mbsf. These in situ velocity data enabled the Hole U1609A stratigraphy to be more accurately tied to the seismic stratigraphy.

Six downhole temperature measurements were made, four with the APCT-3 tool in Hole U1609A and two with the SET2 tool in Hole U1609B. The seafloor temperature is 6.9°C.