IODP Expedition 401: Mediterranean–Atlantic Gateway Exchange

Site U1611 Summary

Background and Objectives

Site U1611 is located in the Alborán Sea just to the east of the Strait of Gibraltar in the Mediterranean. It marks the eastern end of Expedition 401's transect of sites that track Mediterranean outflow water from its source, through the Atlantic–Mediterranean gateway into the Gulf of Cádiz (Site U1610) and around to the west of the Iberian margin (Sites U1609 and U1385). Today, the Alborán Basin is a relatively narrow (150 km wide, north to south), elongate (350 km long, east to west), and shallow (maximum water depth ~1950 m) area that links the deeper parts of the Mediterranean Sea to the Atlantic. Atlantic water flows into the Mediterranean through the Strait of Gibraltar at the surface as a coherent layer of warm and relatively fresh marine water, while deeper, cooler, and more saline water generated in the Mediterranean flows through the Alborán Sea and out into the Atlantic at depth. The stratified water mass structure in the Alborán Sea reflects this exchange as well as the densities of the different water masses generated within the Mediterranean, principally the Levantine Intermediate Water (LIW) and the Western Mediterranean Deep Water (WMDW; Ercilla et al., 2016). Site U1611 is located on the north side of the basin on the Spanish continental slope at a water depth of 810 m. Today, this area is bathed in WMDW with a temperature of ~12.9°C and a salinity of ~38.45 (Ercilla et al., 2016). Deposition at the site is directly impacted by both westward flowing bottom currents that produce contourite deposition along the Spanish margin and input of gravity deposits from the upslope margin (Ercilla et al., 2016).

Exchange through a single gateway at Gibraltar is a relatively recent (Pliocene–Pleistocene) phenomenon (e.g., Flecker et al., 2015). As a result of Africa-Eurasia convergence, westward docking of the Alborán plate, and simultaneous slab retreat (e.g., van Hinsbergen et al., 2014), the Atlantic–Mediterranean connection evolved from a single, wide-open seaway in the Tortonian to two narrow corridors in the early Messianian: one in northern Morocco and the other in southern Spain (Martín et al., 2014).

Ongoing restriction of the marine corridors permitted Mediterranean salinity to rise, and a distinct, dense water mass formed. Ultimately, the narrowing and closure of these connections resulted in extreme salinity fluctuations in the Mediterranean, leading to the precipitation of more than 1 million km^3 of salt, equivalent to ~6% of the total dissolved oceanic NaCl (Blanc, 2006; Ryan and Hsü, 1973) in the latest Miocene. This event is known as the Messinian Salinity Crisis (MSC; Hsü et al., 1973). Progressive tectonic convergence coupled with isostatic rebound related to lithospheric mantle dynamics not only severed these earlier marine connections but also uplifted and exposed them on land (Capella et al., 2017). In the early Pliocene, two-way exchange was established through a single conduit, the Strait of Gibraltar. This reconnection event is known as the Zanclean deluge. Many authors suggest that catastrophic failure of the Atlantic–Mediterranean occurred at Gibraltar resulting in rapid refilling of the Mediterranean and major erosion in the Alborán Basin (e.g., Estrada et al., 2011, Garcia-Castellanos et al., 2020).

Objectives

Site U1611 targets one of the few thick late Messinian sedimentary successions in the Alborán Basin. The record recovered from this location provides key constraints on the chemistry and physical properties of Mediterranean outflow during the late Miocene. The major objective for Site U1611 was to recover an 8–4 Ma succession that records the evolution of the Alborán Sea before, during, and after the MSC. This information will then be used to test the following hypotheses:

- The Alborán Basin was an intermediate marine system influenced by the Atlantic and separated from the Mediterranean by the Alborán volcanic arc during the MSC.
- Mediterranean–Atlantic exchange occurred through the Strait of Gibraltar before the start of the MSC.
- Extreme environmental fluctuations in the Mediterranean are mirrored both by environmental conditions in the Alborán Sea and by visible perturbations down the Mediterranean overflow plume in the Atlantic.

Operations

On the morning of 19 January 2014, the *JOIDES Resolution* sailed through the Strait of Gibraltar, one of the Mediterranean–Atlantic Gateways in the title of Expedition 401. The 333 nmi transit from Site U1385 to Site U1611 (proposed Site WAB-03A) in the Alborán Basin of the Mediterranean Sea took 29.8 h at an average speed of 11.2 kt. We arrived on site at 1315 h on 19 January, lowered the thrusters, and started to unstow the bottom-hole assembly (BHA). At 1745 h, high winds made it unsafe for the derrickman to work at the monkey board in the derrick, so we waited until 2015 h for the wind to drop before resuming operations (a 2.5 h delay).

The rig floor team assembled ~650 m of 10¾ inch casing and hung it below the ship, and made up the casing stinger 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 hydraulic release tool (HRT) running tool was attached to the casing and the funnel was welded on. The funnel was lowered through the moonpool at 1540 h on 20 January, and the whole casing system was lowered down to 792.1 meters below sea level (mbsl) before installing the top drive. Hole U1611A was started at 1730 h, and we continued to drill the casing into Hole U1611A until the reentry cone base landed on the seafloor at 810.1 mbsl with the bit at 654.6 meters below seafloor (mbsf) and the casing shoe at 652.6 mbsf. The subsea camera was deployed to observe the release of the casing, and at 0405 h on 22 January the casing assembly was released from the pipe and BHA. The bit was raised back to the ship, clearing the rig floor at 1103 h, and completing the casing portion of operations at Hole U1611A. The rotary core barrel (RCB) BHA was assembled with a polycrystalline diamond compact (PDC) bit and was lowered to 584.9 mbsl, and the subsea camera was deployed to guide reentry into the hole.

Hole U1611A was reentered at 1832 h, and the top of the cone was confirmed to be at 807.3 mbsl and the seafloor at 810.1 mbsl, very close to the precision depth recorder (PDR) estimate of seafloor depth at 810.2 mbsl. The bit was lowered down the casing to 613 mbsf, where it took weight, probably because it met sediments that had come up into the casing. The top drive was installed and the bit was washed down to 656.3 mbsf, followed by a 30 bbl mud sweep to clear any remaining loose sediment from the casing. At 0000 h on 23 January, the core line winch electrical controller failed, specifically the Veeder-Root counter in the controller. It was replaced and the winch was back online by 0545 h. The first run on the core line was the Sediment Temperature 2 tool (SET2). The Icefield MI-5 core orientation tool, usually run to orient advanced piston corer (APC) cores, was run by piggybacking on the SET2 tool deployment to estimate any deviation of the casing from vertical. It showed a small angle at the top of casing, deviating to 10° at the base of casing. This result was subsequently confirmed by downhole logging inclinometer data. Coring started at 0815 h with Core U1611A-2R, but it recovered only 3 cm of sediment, so we ran the bit deplugger. Recovery improved for subsequent cores. Cores U1611A-2R to 24R penetrated from 656.3 to 879.4 mbsf and recovered 223.1 m (74%). Cores 25R and 26R returned nearly empty, probably because coarse-grained sediments in the formation entered the base of the pipe. The bit deplugger was deployed again. We made five 30 bbl mud sweeps per day to flush cuttings and loose sediment out of the borehole, and coring continued with moderate to good recovery. At 0815 h on 26 January, following Core 44R, we switched to half-core advances, which improved core recovery. (On 26 January, full-core advances yielded 69% recovery and half-core advances yielded 87%.)

We switched from half-length to full-length RCB core advances with Core 77R. Core 79R returned empty, so we ran the bit deplugger again and switched back to half-length advances for Cores 80R to 83R, each of which recovered less than 10 cm. Because hole conditions were difficult, at 1945 h we started a wiper trip to clear bridges in the hole prior to further coring and downhole logging. Overpulls of 20,000 to 30,000 lb were observed at 1104.9, 949.4, 881.7, and 872.0 mbsf before the bit could be raised to the casing shoe at 652.6 mbsf. On washing down, 12 tight spots were encountered and 6 m of fill was found at the base of the hole. From 0730 to 1030 h on 29 January we washed out the fill and swept the hole with 30 bbl sepiolite mud in preparation for coring. Cores U1611A-84R to 86R penetrated to 1281.9 mbsf, the final depth of the hole, and recovered 13.2 m (68%). Cores U1611A-2R to 86R penetrated from 656.3 to 1281.9 mbsf and recovered 625.6 m of core (69%).

At 1545 h we started to prepare the hole for downhole logging. The bit was released at the base of the hole, the hole was displaced with barite-weighted mud, and the end of the pipe was raised to 672.7 mbsf. The rig floor team assembled the triple combo logging tool string, without the source, and started lowering it down the pipe at 2145 h. The tool string reached an impassable obstruction at 909.6 mbsf, and made a repeat and main pass, which together cover the open hole interval from 672.7 to 909.6 mbsf. Borehole diameter varied between narrower than 6 inch to wider than the maximum extent of the caliper measurement, 17 inch, and the logged interval of the borehole was inclined from the vertical by between 10° and 15°. The triple combo tool string was back on deck at 0410 h on 30 January and a sonic-inclinometry tool string was assembled for the second logging run. This tool string was lowered into the borehole but could not pass below 743.6 mbsf. It recorded data for the short interval up to the bit, it was back on deck by 0910 h, and the logging equipment was disassembled by 1100 h. The BHA was raised back to the ship, clearing the rotary table at 1400 h, and ending Hole U1611A. A new mechanical bit release (MBR) and PDC RCB bit were added to the BHA and were lowered back down close to the seafloor.

The ship was offset 1316 m to the northwest and Hole U1611B was started at 1725 h on 30 January at a water depth of 784 mbsl. The relatively large offset was made in order to core part of the seismic profile where reflectors had greater horizontal continuity than at Hole U1611A. We drilled ahead from 211.6 to 744.9 mbsf and pumped 30 bbl sepiolite mud sweeps after adding every two stands of pipe to keep the hole clear. When the center bit was retrieved, 1.7 m of sediment was found behind it in the core barrel, which was curated as a wash core, Core U1611B-2W. Coring started at 1830 h on 31 January. Cores U1611B-3R to 4R had 91% recovery, but the following two cores, Cores 5R and 6R, returned nearly empty, so we ran the bit deplugger and then switched to half-core RCB advances. Coring proceeded with half-core advances for the next three days, until operations needed to stop to begin preparing for the transit to Napoli, Italy. Core U1611B-66R arrived on the catwalk at 2330 h on 4 February and was the last core of the site and the expedition. Cores U1611B-3R to 66R penetrated from 744.9 to 1069.9 mbsf and recovered 77.3 m (89%).

Science Results

Lithostratigraphy

Four main lithologies were described in Site U1611: (calcareous) mud, (calcareous) silty mud, sandy silt, and silty sand. Minor lithologies include sandy mud, conglomerate, breccia, and cemented carbonate (e.g., dolostone, limestone). Holes U1611A and U1611B are divided into three lithostratigraphic units. Contacts between these units and the lithologies within them are mainly gradational in Unit I (early Pliocene), characterized by subtle changes in color and grain size, and are more commonly sharp in Units II and III (Messinian), with distinct color changes and frequent laminations. The coarser silts and sandier beds typically have sharp to erosive basal contacts.

Unit I ranges from 656.3 to 820.4 mbsf in Hole U1611A, and from 746.4 to 814.2 mbsf in Hole U1611B. In Hole U1611A Unit I comprises three subunits, consisting of alternating calcareous mud and calcareous silty mud. The interval 733.9 to 772.3 mbsf contains more occurrences of coarser lithologies including conglomerates and calcareous sandy silt. In Unit I in Hole U1611B, calcareous muds also alternate with calcareous silty muds, with the frequency of coarser lithologies increasing with depth.

Unit II ranges from 820.4 to 996.5 mbsf in Hole U1611A, and from 814.2 to 996.9 mbsf in Hole U1611B. It is characterized by the presence of laminated beds alternating with nonlaminated and sometimes coarse graded beds. Unit II consists of two subunits. Subunit IIa (820.4 to 964.3 mbsf in Hole U1611A) is composed of lithologies with variable carbonate content, including mud, calcareous mud, calcareous silty mud, sandy silt, and silty sand, with minor aragonite, cemented carbonate, breccia, and conglomerate. Subunit IIb (971.5 to 996.5 mbsf in Hole U1611A) is composed of similar lithologies as Subunit IIa, but with a lower carbonate content, with beds of calcareous muds and calcareous silty muds alternating with muds, sandy silts, and sands. In Hole U1611B, Unit II mostly consists of the same lithologies as in Hole U1611A, typically with a lower calcareous content with increasing depth. However, in Hole U1611B more silty muds were described in Subunit IIb, and in general there are more coarser beds.

Unit III ranges from 1000.6 to 1275.9 mbsf in Hole U1611A, and from 997.1 to 1069.69 mbsf in Hole U1611B. In Hole U1611A, Unit III consists of two subunits. Subunit IIIa (1000.6–1144.9 mbsf) consists of frequent alternations of silty mud and calcareous silty mud in the shallower parts, with numerous intervals of sandy silt and silty sand. The proportion of calcareous silty mud is lower in the deeper part of Subunit IIIa. There is also minor conglomerate typically associated with contorted, slump-like sediment deformation, and cemented carbonate. Subunit IIIb (1146.1 to 1275.9 mbsf in Hole U1611A) consists of similar lithologies to Subunit IIIa, except that Subunit IIIb lacks the high-frequency interbedding of calcareous silty mud and silty mud and contains more frequent occurrences of coarser-grained intervals (e.g., sandy silt and silty sand). In Hole U1611B, Unit III is similar to the upper part of Subunit IIIa in Hole U1611A, except that there is a notable thick conglomerate (1030–1038.5 mbsf) that was not recovered in Hole U1611A. Unit III is characterized by the presence of laminated beds alternating with nonlaminated and normally graded beds, but the laminations appear subtler than in Unit II.

Biostratigraphy

The site features diverse lithologies, including muds, silts, sands, conglomerates, and cemented carbonates. Notably, some intervals were poor in microfauna, particularly planktonic foraminifers. However, despite some core catchers (CC) being barren in foraminifers, they were rich in fish teeth and scales, wood fragments, and shell fragments, providing valuable understanding of the site's paleoenvironment.

Both holes were drilled down with the intent to start retrieving cores in the early Pliocene, and this age was confirmed by the calcareous nannoplankton and foraminifer assemblages recovered in the uppermost CC samples of both holes. Below Samples U1611A-18R-CC (821.2 mbsf) and U1611B-14R-CC (815.7 mbsf), close to the Lithological Unit I/II boundary, planktonic foraminifers are absent (with rare exceptions) in the fraction >150 µm, although they continue to be present in the 63–150 µm fraction. We associate this change with the Messinian/Zanclean boundary. There is also a significant change in the lithology of this interval, with almost no biogenic particles in the coarse fraction, with the exception of fish and wood fragments. The near total absence of >150 µm planktic foraminifers continues to Sample U1611A-42R-CC (1037.2 mbsf). Beneath this depth, to the bottom of Hole U1611A, the sediments typically contain some planktic foraminifers in the >150 µm fraction, but few benthic foraminifers. The presence of calcareous nannofossils *Reticulofenestra pseudoumbilicus* and *Nicklithus amplificus* in the deepest from Hole U1611A (1281.9 mbsf) constrains the age at the base of the hole to between 6.82 and 7.10 Ma.

Paleomagnetism

Pass-through paleomagnetic measurements were performed using the superconducting rock magnetometer (SRM) to investigate the natural remanent magnetization (NRM) of all the archive half sections of Hole U1611A and Hole U1611B. Alternating field (AF) demagnetization was performed on the SRM by applying stepwise peak fields of 5, 10, 15, and 20 mT, with measurement of the remaining magnetization taken at 2 cm resolution.

In addition, we collected discrete samples of all the working half sections of Hole U1611A. We measured the anisotropy of magnetic susceptibility (AMS) and bulk magnetic susceptibility (MS) using the MFK2 KappaBridge unit and the NRM on the JR-6A AGICO spinner magnetometer. Stepwise AF demagnetization was performed at successive peak fields of 0, 5, 10, 15, 20, 30, and up to a maximum of 60 mT. In addition, we performed stepwise thermal demagnetization up to a maximum temperature of 600°C on six samples. The paleomagnetic intensities are weak and inclinations are scattered between expected normal and reverse polarities, so we are not sure if we are measuring the primary magnetic signal or a pervasive overprint. Thermal demagnetization experiments show the presence of iron sulfides in the sediment.

The AMS results from Hole U1611A show an overall vertical direction of the κ_{min} axis with a scatter on the order of 10°, in agreement with observations of subhorizontal strata in the split cores.

Geochemistry

Headspace gas samples and interstitial waters (IW) in Hole U1611A were taken at one per recovered core or one every other half advance (~10 m). Gas contents in both holes remained within a safe range, and the downhole pattern of methane/ethane ratios and absolute methane values are similar between the holes, despite a horizontal separation of 1361 m. IW salinities reached a maximum of 70 at ~1050 mbsf and then decreased below that level. Major ion chemistry was used to interpret the origin of these saline IWs as a possible remnant of late-Messinian brine. Partly because of this observation, we consulted with onshore microbiologists and collected 5 cm whole-round samples from Hole U1611B at 20 m intervals using clean equipment, and immediately froze them at −80°C for possible future microbiological analysis.

Weight percent $CaCO_3$ varies from 5.0 to 92.0 wt% at Site U1611, with a mean of 28.3 wt%. $CaCO_3$ is generally between 30 and 60 wt% in the Pliocene Unit I. In Unit II, carbonate decreases to between 14 and 36 wt%, and in Unit III it decreases further to the range of 15 to 25 wt%. In Unit III these low carbonate concentrations are interrupted by decimeter-scale dolomitic or cemented carbonate beds with high values, typically greater than 60 wt% (seven samples).

Physical Properties and Downhole Measurements

Large-scale downhole patterns in the whole-round physical properties data of Holes U1611A and U1611B typically match well, but the same horizons are approximately 5 to 15 m shallower in Hole U1611B compared to Hole U1611A. Coarser lithologies tend to have lower NGR values. Cemented carbonate layers are distinguished by low NGR and MS values and relatively high gamma ray attenuation (GRA) density values.

Downhole logging in Hole U1611A was only partially successful, with the triple combo tool string reaching 909 mbsf, logging a 236 m open-hole interval. However, this interval includes the Messinian/Zanclean boundary at ~820 mbsf and provides stratigraphic continuity there, and also covers some poorly recovered Messinian intervals. The sonic-inclinometry tool string reached 743 mbsf before the hole became impassible. The borehole was characterized in the caliper borehole diameter log by washouts, bridges, and ledges. According to both the General Purpose Inclinometry Tool (GPIT) logs, at the end of the pipe the borehole was inclined at ~9° from vertical and the inclination increased with depth to more than 12° at 750 mbsf.

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