IODP Expedition 395: Reykjanes Mantle Convection and Climate

Site U1602 Summary

Background and Objectives

International Ocean Discovery Program (IODP) Site U1602 (proposed Site REYK-14B) is located on the eastern margin of Greenland in the North Atlantic Ocean, coinciding with the elongate sedimentary body known as Eirik drift. Site U1602 is located on a V-shaped ridge, tentatively identified in free-air gravity anomaly data, that is one of the V-shaped structures that straddle the Reykjanes Ridge flanks and whose origin in relation to the Iceland hotspot is debated. The site sits on ocean crust with an age of 49.8 Ma, estimated from magnetic anomalies and plate reconstruction models.

The Reykjanes Ridge flanks are the site of major contourite drift deposits, Björn and Gardar drifts on the eastern flank of the ridge. In contrast, Eirik drift consists of an elongate, mounded contourite deposit that is plastered along the East Greenland margin. These rapidly accumulated contourite drift sediments have the potential to record variations in past climate and ocean circulation on millennial timescales. The sedimentation rate of the drifts can serve as a proxy for deepwater current strength, providing information on oceanic gateways to the Norwegian Sea and their potential ties to Iceland mantle plume behavior. The sedimentary section of Eirik drift at Site U1602 has the potential to preserve detailed records of the evolution of the Greenland and Iceland Ice Sheets and of variations in the Western Boundary Undercurrent. Site U1602 not only complements the sites on the eastern side of the Reykjanes Ridge and the drilling of Björn and Gardar contourite drifts, but also makes it possible to recover much older sediment providing insights into the North Atlantic Ocean circulation and sedimentation deep into the Cenozoic. Site U1602 is located on seismic line JC50-1, obtained in 2010 during RRS *James Cook* Cruise JC50. Sediment thickness at Site U1602 is ~1376 m based on seismic imagery.

The main target for Site U1602 was to obtain a continuous sedimentary record of Eirik drift. Another target was to obtain a sedimentary record throughout the middle Miocene warm period. A final target, time permitting, was to core into basement. This final objective was not achieved due to time constraints. Cores and data from this site will address the primary science objectives related to mantle behavior, ocean circulation, gateways, and sedimentation.

Operations

Site U1602 (61°11.7138′N, 38°10.8186′W) consists of five holes, ranging in depth from 8.8 to 1365.2 m drilled depth below seafloor (DSF). A total of 230 cores were obtained at Site U1602. These cores collected 1444.65 m of sediment over a 1903.8 m cored interval (76% recovery). Two drilled intervals were recorded over a 531.3 m interval. Downhole wireline logging operations were attempted at Hole U1602E and were partially successful. The total time spent at Site U1602 was 19.5 d.

Hole U1602A

The ship completed the 350 nmi transit, averaging 11.0 kt, from Site U1562 to proposed Site REYK-14B at 1701 h on 4 July 2023. The thrusters were lowered, and the ship was in dynamic positioning (DP) mode at 1718 h, marking the start of Site U1602. The bit was spaced out to initiate Hole U1602A (61°11.7138′N, 38°10.8186′W), which was spudded at 0425 h on 5 July. Core U1602A-1H recovered 8.8 m of core, establishing a seafloor depth of 2708.6 meters below sea level (mbsl). However, Core 1H also recovered part of the "pig," a foam device with metal bristles used to clean rust from the inside of the drill pipe, which disturbed the mudline interval. Hole U1602A was terminated to recover an undisturbed mudline. A total of 8.81 m of core was recovered over an 8.8 m interval (100% core recovery).

Hole U1602B

Hole U1602B (61°11.7144′N, 38°10.8184′W; 2709.2 mbsl) was spudded at 0535 h on 5 July from the same ship position and Core U1602B-1H recovered 5.15 m of core with a good mudline. Coring continued with Cores 2H to 16H (5.2–147.7 m DSF). The half-length advanced piston corer (HLAPC) was deployed for Cores 17F to 38F (147.7–251.1 m DSF). Piston coring refusal was reached at Core 38F, which required 80,000 lb of overpull to free the barrel from the formation. The drill string was pulled from the hole, with the bit clearing the seafloor at 1600 h on 6 July, marking the end of Hole U1602B.

A total of 38 cores were collected from Hole U1602B using the advanced piston corer (APC) and HLAPC, with 262.37 m of core recovered over a 251.1 m interval (104%). Temperature measurements using the third-generation advanced piston corer temperature (APCT-3) tool were collected on Cores U1602B-4H, 7H, 10H, and 13H.

Hole U1602C

Following Hole U1602B, the vessel was offset 20 m to the north. Hole U1602C (61°11.7253′N, 38°10.8193′W) was spudded at 1920 h on 6 July. Core U1602C-1H recovered 7.07 m of core, placing the seafloor at 2710.0 mbsl. Cores U1602C-1H to 20H (0–180.0 m DSF) were recovered. Within this cored interval, an interval of 2 m was drilled without recovery (64.0–66.0 m DSF; Core U1602C-8-1) to offset coring gaps for stratigraphic correlation. The HLAPC was deployed for Cores U1602C-21F to 39F (180.0–269.3 m DSF). Piston coring refusal was reached at 269.2 m DSF and the hole was ended. The drill pipe was pulled out of the hole and the bit cleared the seafloor at 0525 h on 8 July, ending Hole U1602C. A total of 38 cores were recovered from Hole U1602C, with 272.63 m of sediment recovered from a 267.3 m cored interval (102% recovery).

Hole U1602D

The vessel was offset 20 m to the east of Hole U1602C. Hole U1602D (61°11.7259′N, 38°10.7967′W; 2709.1 mbsl) was spudded at 0805 h on 8 July. Cores U1609D-1H to 19H advanced from 0 to 175.8 m DSF. APC refusal was reached at 175.8 m DSF and the HLAPC was deployed for Cores 20F to 37F and advanced to a depth of 260.4 m DSF. The extended core barrel (XCB) system was used to cut Cores 38X to 66X (260.4–540.7 m DSF). The cutting of Core 66X was very slow compared to the other XCB cores. When the core barrel was retrieved, it was immediately noticed that the XCB cutting shoe was severely damaged with large pieces missing. Coring could not continue because the location of the broken metal from the cutting shoe was not known, and therefore Hole U1602D was terminated at a depth of 540.7 m DSF. The drill string was pulled from the hole with the bit clearing the seafloor at 1130 h on 11 July. The vessel was offset 20 m south of Hole U1602D and the drill pipe and bottom-hole assembly (BHA) continued to be pulled up to the rig. At 1645 h, the bit cleared the rig floor ending Hole U1602D. A total of 450.45 m of sediment was recovered from a 540.7 m cored interval (83%).

Hole U1602E

The drill string with a rotary core barrel (RCB) BHA and C-4 drill bit was deployed to the seafloor and Hole U1602E (61°11.7150′N, 38°10.7961′W) was spudded at 0630 h on 12 July. A seafloor depth of 2709.2 mbsl was used based upon the offset of Hole U1602B, which recovered the best-preserved mudline core. The hole was advanced without recovery to a depth of 529.3 m DSF, the center bit was retrieved, and rotary coring began. Cores U1602E-2R to 88R (529.3–1365.2 m DSF) were recovered. Due to expedition time constraints, coring at Hole U1602E was terminated following the recovery of Core U1602E-88R, and the rig floor began to prepare for downhole wireline logging operations. A total of 87 RCB cores collected 450.39 m of sediment from an 835.9 m cored interval (54%) at Hole U1602E. A 529.3 m drilled interval was recorded for the hole.

The hole was cleaned with 40 barrels of high-viscosity mud. After releasing the RCB bit at the bottom of the hole, the drill pipe was pulled up to 77.8 m DSF. At 0600 h on 22 July, the triple combo was deployed, and the tools were run to a maximum depth of 1270 m wireline depth below seafloor (WSF), at which point the tool string was unable to descend farther into the hole. The calipers were opened for the first pass up the hole and the tool string immediately became stuck. The calipers were closed but the tool remained trapped in the hole. Because the Hostile Environment Litho-Density Sonde (HLDS) on the triple combo contains a ^{137}Cs radioactive source, it was necessary to recover the tool string.

After attempting to free the tool for >1 h, the wireline cable was cut at the surface and connected to the core winch line to pull on the line with more force. The tool string was briefly freed and ascended 160 m before getting stuck again. The decision was made to run the drill pipe back down the hole and to move the drill pipe over and around the stuck tool string. At 1300 h, after some complications, the end of the pipe reached the triple combo tool string at a depth of 1079 m

DSF. The drill pipe was maneuvered around the tool sting, which was then pulled into the pipe. The tools arrived at the rig floor at 1645 h. The drill string was pulled from the hole with the end of the pipe clearing the seafloor at 2135 h. At 0345 h on 24 July, the end of the pipe cleared the rig floor. The drill floor was secured for transit and the vessel was put into cruise mode at 0409 h, marking the end of Site U1602.

Principal Results

Sedimentology

The Holocene to late Eocene/early Oligocene sediments cored at Site U1602 are primarily composed of silty clay, silty clay/claystone with nannofossils, nannofossil silty clay/claystone, nannofossil chalk, and sandstone. Based on the observations of sediment composition along with attenuation patterns of natural gamma radiation (NGR), magnetic susceptibility (MS), and calcium carbonate ($CaCO_3$), Site U1602 is divided into three major lithostratigraphic Units (I–III). Unit III consists of two subunits, IIIA and IIIB. The site is dominated by terrigenous components, mainly quartz, feldspar, glass, opaque grains, pyrite, and glauconite with smaller amounts of chlorite and Fe/Mn oxides. Biogenic components are dominated by nannofossils, which generally increase downhole. Foraminifers and biosilica are common to rare in Unit I, trace to absent in Unit II, and absent in Unit III. Sediments contain a wide variety of sedimentary structures, such as laminations, graded bedding, alternating grading, cross-bedding, flaser bedding, mud drapes, and sand injections. Fractures with slickensides are also present in Units II and III. Bioturbation is generally sparse to moderate in Units I and II. In Unit III, however, bioturbation is generally abundant in the chalk, but absent to sparse in the sandstone intervals.

Micropaleontology

At Site U1602, a 1357.99 m interval of upper Eocene to lower Oligocene to upper Pleistocene material was recovered across multiple holes. Micropaleontological analyses were undertaken on sediment samples from Holes U1602B (0–251.43 m CSF-A), U1602C (255.43–264.9 m CSF-A), U1602D (250.31–532.36 m CSF-A), and U1602E (537.07–1357.99 m CSF-A). Biohorizons used in the age model are based on calcareous nannofossils, planktonic foraminifers, and one bolboform species.

Calcareous nannofossils are present in most samples and have variable preservation, which generally degrades with depth below seafloor. A distinct interval where barren samples are more frequent occurs in the Pliocene to early Pleistocene. Seven biohorizons spanning the Pleistocene were identified in Hole U1602B, covering an interval from 0.09 to 1.71 Ma. The top of *Reticulofenestra pseudoumbilicus,* found in Hole U1602D, was the only recorded Pliocene biohorizon. The Miocene was well resolved in Hole U1602E, with 14 biohorizons covering the interval between 5.53 and 22.9 Ma. Finally, the top of *Reticulofenestra umbilicus*, found in the deepest recovered core catcher sample from Hole U1602E, indicates an early Oligocene (>32 Ma) age for the base of this hole.

Planktonic foraminifers also demonstrate variable preservation that decreases with depth, as well as highly variable abundance. Sample processing became more difficult as sediments became progressively lithified with depth (below ~100 m CSF-A). Despite the difficulties in sample preparation, good biostratigraphic control was achieved across the studied interval. A total of three Pleistocene, four Miocene, and one late Eocene planktonic foraminifer biohorizons were identified across the studied holes. Finally, bolboforms were rare and mostly moderately-to-poorly preserved. Despite that shortcoming, one Miocene biohorizon was recorded in Hole U1602E, using the Top occurrence of *Bolboforma metzmacheri*.

Physical Properties

Physical property measurements for Site U1602 consist of whole-round and half-round measurements on cores from Holes U1602A through U1602E. Discrete physical property measurements were measured from Holes U1602B, U1602D, and U1602E. Density increases with depth and has marked increases at ~350 and ~1050 m CSF-A. Density values measured on discrete samples are consistently higher than whole-round density values below ~500 m CSF-A, a discrepancy caused by the diameter of the core being smaller than that of the liner. Porosity shows the inverse trend of density, with values decreasing with depth and marked decreases occurring at ~350 and ~1050 m CSF-A. Whole- and half-round MS measurements covary, showing meter- to decameter-scale fluctuations from the top of the section until ~1050 m CSF-A, where more variability is observed. *P*-wave velocities increase sharply from 350 to 650 m CSF-A and increase at a gentler rate to 950 m CSF-A, after which their values show a wider range. NGR values increase from 300 to 400 m CSF-A, and fluctuate downhole to ~950 m CSF-A, followed by an overall decrease and reduced range. Red-green-blue, L*, and a* show meter- to decameter-scale variations between 0 and 1050 m CSF-A. Thermal conductivity of the sediments at Site U1602 increases slightly with depth.

Stratigraphic Correlation

A continuous stratigraphic splice was created from the seafloor to 169.45 m composite core depth below seafloor, method A (CCSF-A). The continuous splice for the upper 169.45 m CCSF-A includes cores from Holes U1602B and U1602D. Below this depth to ~270 m CCSF-A, there are three small (<1–2 m) gaps in the stratigraphic record. At these intervals, cores were appended to the base of the overlying core.

Paleomagnetism

Natural remanent magnetization (NRM) was measured for all sedimentary cores recovered from Site U1602, at a resolution of 2.5 cm. The cores were then demagnetized with a stepwise alternating field (AF) protocol. A set of ~260 discrete samples were collected to confirm the semicontinuous measurements. The inclination measured at the maximum demagnetization step

(20, 25, and 30 mT from Holes U1602B, U1602D, and U1602E, respectively) was used to interpret a downhole sequence of normal and reversed polarities. Magnetic polarities from Holes U1602D and U1602E were correlated with the geomagnetic polarity timescale (GPTS) chrons to establish an age-depth trend for Site U1602. Between ~1060 m CSF-A and the bottom of the hole, the NRM intensity and MS decrease, and the paleomagnetic inclinations were not suitable for a univocal magnetostratigraphic interpretation.

Geochemistry

Cores taken from Holes U1602B, U1602C, U1602D, and U1602E were analyzed for headspace gas, interstitial water (IW) chemistry, and bulk sediment geochemistry. Headspace methane concentrations range from 0 to 328 ppmv (n = 143), and low ethane concentrations (<4.6 ppmv) were detected in a subset of the headspace samples (n = 21). The pH and alkalinity of IW display an inverse relationship with depth. Alkalinity is near seawater values (3.68 mM) in the uppermost IW sample (U1602A-1H-1, 141–151 cm) and increases to 6.1 mM at ~103 m CSF-A (Sample U1602A-12H-2, 146–151 cm) before decreasing to low values (<1.0 mM) below ~320 m (Sample U1602D-44X-2, 123–130 cm). pH is generally constant in the upper ~340 m (7.9 ± 0.1) and increases downhole to 8.9 at ~786 m CSF-A (Sample U1602E-28R-3, 11–131 cm), below which limited IW extracted from the sediment prevented additional pH measurements. IW calcium ion (Ca^{2+}) concentrations display an increasing trend with depth; the highest Ca^{2+} concentrations occur at ~871 m (U1602E-37R-2, 103–108 cm). Magnesium ion (Mg^{2+}) concentrations display a general decreasing trend with depth; highest Mg^{2+} concentrations (51.6 mM) occur at top of the sediment column (1.4 m CSF-A; U1602B-1H-1, 141–151cm). Sulfate ion (SO_4^{2-}) concentrations display a decreasing trend downhole and reach the minimum value ~240 m CSF-A (U1602B-35F-2, 145–150 cm). SO_4^{2-} concentrations increase below ~600 m CSF-A to between 5 and 9 mM. Downhole trends in other dissolved elements, including barium (Ba), lithium (Li), potassium (K), and silicon (Si), indicate a change in concentration at around 388 m CSF-A. $CaCO_3$ content generally increases downhole, from ~0 to 30 wt% in the top 100 m CSF-A, to as high as ~80 wt% near the bottom of Hole U1602E (Sample U1602E-60R-1W, 3–4 cm). Bulk sediment generally exhibits low total organic carbon (TOC; <0.7 wt%), total nitrogen (TN; <0.2 wt%), and total sulfur (TS; ≲1.0 wt%). Bulk sediment major and minor element concentrations were also analyzed via inductively coupled plasma–atomic emission spectroscopy (ICP-AES) on select samples. Downhole variations in major oxides (e.g., SiO_2, Al_2O_3, TiO_2 K_2O, MgO, CaO) and trace elements (e.g., S and Sr) show variable concentrations that likely reflect changing lithologies.

Downhole Logging

After coring operations at Hole U1602E concluded, the hole was prepared for logging operations. The triple combo tool string became stuck during its first decent downhole and operations to recover the tool were successful, but all further logging operations at Site U1602 were canceled. Therefore, downhole logging data from Hole U1602E consists of a single downhole logging pass that includes measurements of natural and spectral gamma radiation, formation resistivity, and MS.

Seven logging units are defined for Hole U1602E, the divisions of which are primarily defined by notable changes in the NGR log, and in some instances from other logging responses. Logging Unit 1 (L1, 32–162 m wireline depth below seafloor [WSF]) is characterized by NGR measurements of ~27.7 gAPI, which fluctuate with depth. Increases in the gamma radiation positively correlate with increases in thorium and negatively correlate with uranium spectral gamma counts. Logging Unit 2 (L2, 162–340 m WSF) is defined by a step increase in NGR to ~35 gAPI. MS in Unit L2 has an average measurement of 259 SI and contains meter-scale fluctuations. The top of Unit L3, is defined by an increase in formation resistivity. Logging Unit 3 (L3, 340–588 m WSF) displays an average NGR of ~47 gAPI and shows meter- to decameter-scale fluctuations throughout. Several distinct intervals present very low gamma radiation measurements that correspond to increases in MS. Logging Unit 4 (L4, 588–630 m WSF) is defined by a large ~42 m long fluctuation in NGR and MS measurements. Logging Unit 5 (L5, 630–1039 m WSF) is defined by an initial decrease in NGR and an increase in MS, and shows fluctuations in NGR at meter, decameter, and hectometer scales. Logging Unit 6 (L6, 1039–1162 m WSF) is characterized by variable logging responses separated into five subunits. Logging Unit 7 (1162–1280 m WSF) shows meter-scale fluctuating cyclical NGR and MS responses. Below ~1250 m WSF, the values of MS increase; however, this could be a measurement artefact caused by deteriorating hole conditions and not a response to geological variation.

Four in situ formation temperature measurements were acquired in Hole U1602B between 33.7 and 116 m DSF.

Age Model

The age model for Site U1602 is based on a combination of paleomagnetic and biostratigraphic age determinations. Some of the biostratigraphic data are only upper or lower depth constraints because rarity and/or variable preservation makes them difficult to locate precisely. There is good agreement between the paleomagnetic and biostratigraphic data down to the base of Gilbert Chron C3r. Below that level, the paleomagnetic record continues to follow the expected reversal sequence down to the interpreted base of Subchron C5n.2n (11.06 Ma). However, the biostratigraphic data appear to depart from this trend. Some of the apparent discrepancies can be explained by problems associated with diachrony, reworking, and/or poor preservation of the fossils. The age model becomes increasingly uncertain below this depth. Planktonic foraminifers suggest that Hole U1602E terminated in the upper Eocene (>34.5 Ma), but that is based on a very poorly preserved assemblage from just one sample near the bottom of the hole.