IODP Expedition 396: Mid-Norwegian Continental Margin Magmatism

Site U1574 Summary

Highlights

Three holes were drilled at Site U1574, targeting the basement and the overlying sedimentary sequence of an Outer High, Eldhø, located on the northern flank of the Vøring Plateau. Hole U1574A was drilled with a rotary core barrel (RCB) bit, and sampled 94 m of pillow basalts, hyaloclastites, and a ~30 m thick interbasalt sedimentary interval. Both triple combo and Formation MicroScanner (FMS)-sonic wireline log data were acquired in the basement. Only one advanced piston corer (APC) core was collected in Hole U1574B, whereas a 170 m thick sequence of overburden sediments was almost completely recovered using APC coring in Hole U1574C. The last core of the expedition was an extended core barrel (XCB) core recovering 1.5 m of spectacular pillow basalts, sediments, and hyaloclastites.

Background and Objectives

Site U1574 (proposed Site VMVM-80A) probes the top of an Outer High called Eldhø. It is located on the northern flank of the Vøring Plateau at 2825 m water depth. Outer Highs are conspicuous volcanic seismic facies units that are located seaward of the inner seaward-dipping reflector facies units. While most volcanic seismic facies units are relatively continuous along a rifted margin, Outer Highs have a limited lateral extent of typically 10–20 km. They form elongate structures that rise above the top of the adjacent inner and outer seaward-dipping reflectors. Seismically, Outer Highs frequently display a high-amplitude top reflection of normal seismic polarity, chaotic internal reflection patterns, and high-amplitude reflections that extend from the Outer High into adjacent sedimentary sequences that overlie the seaward-dipping reflectors.

As Outer Highs are characteristic features of volcanic rifted margins located between inner and outer seaward-dipping reflectors, their presence likely signifies specific geological processes and provide clues to the evolution of volcanic passive margins. The pre-Expedition 396 interpretations of Outer Highs mainly relied on seismic volcanostratigraphic interpretations, field analogues, and geological reasoning. The facies unit was interpreted as dominantly hyaloclastite deposits formed when the eruption fissures were submerged during the initial phase of seafloor spreading. In this situation eruptions would happen at sea level or in shallow marine conditions, and lava would get into direct contact with seawater leading to phreatomagmatic eruptions. The formation of Surtsey between 1964–1968 may serve as a recent analogue.

The structure targeted at Site U1574 is a typical example of an Outer High. We call this structure Eldhø, meaning fire mountain in Scandinavian languages. The name is also inspired by the achievements of Professor Olav Eldholm, who was a pioneer in drilling and defining the

concepts of volcanic margins and large igneous provinces. Eldhø rises more than 1500 m above the adjacent inner seaward-dipping reflectors in the southeast and about 650 m above the outer seaward-dipping reflectors in the northwest, with numerous high-amplitude seismic reflections that transgress into the adjacent sedimentary basins south of the high. Its lateral extent is about 17 km in the dip (northwest–southeast) direction and about 30 km in along strike (southwest–northeast). A sedimentary basin, the Eldhø Basin with kilometer-thick post-basalt sediment deposits, is located landward of Eldhø.

The first objective of Site U1574 was to obtain information on the emplacement environment based on observations of the drilled volcanic facies. If Eldhø was indeed emplaced close to sea level, this will validate these aspects of seismic volcanostratigraphy and their presence may then be used as a marker for vertical movement. The second objective was to constrain the conditions in the melt region, i.e., the composition of the mantle before melting and the ambient temperature and pressure conditions in the melt region during the late phase of breakup volcanism based on the geochemical composition and petrology of the encountered rocks. Reaching the first two objectives will allow us to parameterize geodynamic models for excessive breakup volcanism.

Site U1574 was furthermore drilled to provide information on the suitability of the breakup basalt sequences and interbedded sediments for permanent geological storage of CO_2. If the Outer Highs indeed consist mainly of hyaloclastite deposits as postulated, they should be characterized by high porosity and permeability which may make them a suitable target for CO_2 storage. Finally, we hoped to obtain information on the earliest incursion of deep water into the North Atlantic and the extent of freshwater incursions into the young ocean during the early to middle Eocene by coring the overlying sedimentary strata.

Operations

Site U1574 consisted of three holes. The first hole was cored using the RCB coring system from seafloor to 260.0 m below seafloor (mbsf) and then logged with the triple combo and FMS-sonic logging tool strings. The original plan for Site U1574 was to core a single hole up to 310 mbsf, but the objectives were achieved by 260 mbsf. After completing Hole U1574A, the Co-Chief Scientists decided to use the remaining expedition time to piston core the sediment section above the basement and to attempt to improve recovery of the sediment/basement interface. The APC/XCB coring system was selected for the second hole at the site. After assembling and lowering the APC/XCB system to the seafloor, the first APC core misfired and penetrated the seafloor at least twice. Hole U1574B was terminated after the poor mud line core at 9.5 mbsf. The vessel was offset 20 m south and Hole U1574C was piston cored to 169.2 mbsf. We conducted 4 borehole temperature measurements with the advanced piston corer temperature (APCT-3) tool on Cores U1574C-4H (38.0 mbsf), 7H (66.1 mbsf), 10H (94.6 mbsf), and 13H (118.7 mbsf). The Icefield MI-5 orientation tool was deployed for the first 10 cores. The XCB coring system was deployed after the last APC core and immediately cored basement. A

polycrystalline diamond compact (PDC) XCB cutting shoe was used to core a hard layer encountered at 169.2 mbsf. Coring in Hole U1574C was terminated at 1630 h on 1 October 2021 at a final depth of 171.5 mbsf. The last core was on deck at 1655 h. All coring tools were put away. The drill string was pulled back to the surface after clearing the seafloor at 1920 h. The drill collars were laid out to the drill collar racks and the outer core barrel was disassembled and secured. The drill floor was secured for transit at 0231 h on 2 October, ending Hole U1574C and Site U1574. A total of 182.5 h or 7.6 days were recorded while on Site U1574.

Fifty-nine cores were recorded for the site. The RCB coring system was used exclusively for Hole U1574A. The RCB system cored 260.0 m and recovered 88.41 m of core (34%). The APC system was used on both Hole U1574B and Hole U1574C. There were 20 APC cores recovered over a 178.7 m interval. The recovery for the 20 cores was 183.27 m (103%). The XCB coring system was used for one core over a 2.3 m interval and recovered 64% of the cored interval.

Principal Results

Lithostratigraphy

Site U1574 is located on the lower slope of the Vøring Plateau, on the southern flank of Eldhø. This Outer High was likely formed by subaqueous volcanism during the initial phase of seafloor spreading. The succession of recovered material consists of both sediments and basalts, and is divided into five lithostratigraphic units. The division of the units is based on changes in lithology, which coincide with changes in physical property trends. Units I, II, III, and IV are sedimentary, and Unit V consists of basalt, hyaloclastite, and minor interbasaltic sediments.

- Unit I consists of brown and brownish gray unconsolidated mud with intervals of rare pebbles, likely related to ice rafted debris, and rare to common foraminifers.
- Unit II consists of pale yellow and grayish green consolidated mud, in which the first Eocene-aged dinocyst zonations are encountered.
- Unit III is very dark gray mudstone with rare beds of sandstone and ash, and some parallel lamination and bioturbation, showing an increase in organic content downhole.
- Unit IV is very dark gray to very dark grayish brown organic rich mudstone with thin parallel lamination. Compared to overlying units, Unit IV is richer in foraminifera and nannofossils, with abundances increasing downhole within the Unit.
- Unit V consists of aphyric- to plagioclase-phyric pillow basalt with localized hyaloclastite and rare interbedded mudstone. Unit V has been divided into two subunits based on lithologic and geochemical variations, Subunits VA and VB. Both Subunits are overlaid by hyaloclastites. Subunit VA contains both massive and pillow basalts while VB contains is primarily pillow basalt and has a geochemical signature which is distinct from VA.

Biostratigraphy

Holes at Site U1574 (U1574A–U1574C) comprise up to ~170 m of sedimentary strata above the igneous basement. Except for Cores U1574A-1R through 3R, all sedimentary core catcher samples from Hole U1574A were processed for palynology. These samples, including two taken from between basalt flows (Samples U1574A-32R-CC and 33R-CC), are assigned a late early Eocene age based on marker dinocyst taxa and broader assemblage characteristics. The overlying Quaternary strata yield calcareous and rare biosiliceous fossil remains, but these are largely absent from most of the expanded late early Eocene strata. A significant exception is the lower ~20 m of sediment on top of the igneous basement (Samples U1574A-17R-CC and 18R-CC), which contains calcareous remains, including planktic and benthic foraminifers and micromolluscs, and including fine preservation of aragonitic pteropods. Benthic foraminifers are mostly mineral filled, and diatoms are replaced by or coated with pyrite microframboids. These samples are tentatively attributed to planktonic foraminifer zone E7a of Wade et al. (2011), in line with inferences from dinocyst biostratigraphy.

Paleomagnetism

Units I, II, and III are characterized by low average intensity of magnetization of 0.02 A/m, 0.006 A/m, and 0.02 A/m, respectively, whereas their median coercivity is 1.69, 1.31, and 0.87. The lower intensity of magnetization and coercivity may be owed to a smaller population of magnetic minerals. No discrete samples were measured for these three units. Unit IV has a slightly higher average intensity of magnetization (0.006 A/m) than Units I, II, and III. The bulk magnetic susceptibility (MS) is 1.06×10^{-3} to 0.014×10^{-3} SI, indicating a ferro + paramagnetic anisotropy of magnetic susceptibility (AMS) without magnetite. Median coercivity (2.61) is much higher than in Units I, II, and III. The corrected degree of anisotropy in the range of ~1.1 and median coercivity of 2.61 indicate the absence of micaceous minerals and a higher population of goethite and hematite, respectively. Only one of the two discrete samples presents stable magnetization directions, Sample U1574A-17R-1, 111–113 cm. The low coercivity remanent magnetization component is erased by a field of 10 mT. The high coercivity component is removed at an applied field of 100 mT.

The average intensity of magnetization (4.38 A/m) in Unit V is several orders of magnitude higher than in others. The median coercivity (2.61) is the same as in Unit IV. The bulk MS is $\sim 15 \times 10^{-3}$ SI, and the corrected degree of anisotropy is ~1.1. Two magnetization components are evident. The low coercivity component is erased by application of 10 mT. The high coercivity component is removed by a field of 40–60 mT. The magnetic signals are apparently carried by magnetite.

Magnetic polarity is normal down to Section U1574A-4R-2, 31.05 mbsf. The polarity them remains dominantly reversed to the bottom, i.e., Section 38R-3, 258.15 mbsf. This long, dominantly reverse polarity episode is truncated by short-lived positive polarity events.

Geochemistry

Site U1574 consists of two holes, one which targeted the basement (U1574A) and a second one that was aimed at obtaining high recovery of the overlying sediments (U1574C). The hard rock sampled at Hole U1574A consists of low-Ti basalts. Significant variability of some geochemical parameters (TiO_2, Mg#, Ni, and Zr) downcore suggests recovery of multiple flow units. Interbasalt sediments contain what appears to be dolomite.

The sediments consist of an expanded section from the early late Eocene period. Interstitial water (IW) compositions indicate a diagenetic environment dominated by the weathering of primary silicate phases and the formation of authigenic clays and carbonate. Calcium and strontium decrease downcore, due to their release in the formation of smectite and other clay minerals. The same formation reactions lead to the removal of Mg and K from the IW, resulting in decreasing Mg and K content downcore. Enrichment of other elements (e.g., Si and B) in the upper 40 m of the core suggest a lithology-controlled elemental composition of the IW.

Physical Properties

The topmost lithostratigraphic Unit I has characteristic high bulk densities (mean value of 1.82 g/cm^3) and natural gamma radiation (NGR) values (average of 38 counts/s), with relatively low *P*-wave velocities (~1575 m/s) and MS (~45 × 10^{-5} SI). Eight moisture and density (MAD) samples collected throughout this unit showed an average bulk density of 1.82 g/cm^3, grain density of 2.76 g/cm^3, and porosity of 54%. Six thermal conductivity measurements range from 1.1 to 1.5 W/(m·K) and an average of 1.3 W/(m·K).

Within Unit II, *P*-wave velocities, gamma ray attenuation (GRA) bulk densities, MS, and NGR average ~1550 m/s, 1.43 g/cm^3, ~21 × 10^{-5} SI, and 19 counts/s, respectively. Analysis of two MAD samples resulted in an average porosity of 83%, a grain density of 2.70 g/cm^3, and a bulk density of 1.31 g/cm^3, consistent with poorly compacted clay rich sediments.

Twenty-five discrete MAD sample analyses indicate a mean bulk density of 1.59 g/cm^3 for the ~90 m thick Eocene Unit III, slightly lower than the mean GRA bulk density of 1.62 g/cm^3. Porosities ranged from 37% to 82%. The baseline values of the measured physical properties generally increase with depth throughout Unit III. Whole-round core *P*-wave velocity values are on average 1560 m/s, that is ~250 m/s slower than velocities measured through 30 discrete Gantry *P*-wave caliper (PWC) measurements, and have a significant spread with a standard deviation of 120.5 m/s. MS increases compared to the overlying Unit II, having an average of 105 × 10^{-5} SI, and features increased scattering linked to the occurrence of ash layers.

Reduced MS scatter (mean ~90 × 10^{-5} SI) is observed for the underlying Unit IV. Mean gamma ray attenuation GRA (~1.83 g/cm^3) and MAD (n = 8, ~1.73 g/cm^3) bulk densities correspond well with an associated average porosity of 59%. Whole-round core *P*-wave velocities with a mean of 1565 m/s are within 20 m/s of the mean recorded by Gantry PWC, and similar to

average *P*-wave velocities found for Unit III. NGR values increase slightly compared to the overlying unit, having a constant value around 51 counts/s.

The massive basalt and pillow basalts from Unit V have significantly higher *P*-wave velocities, bulk densities (2.4 to 2.6 g/cm^3), and MS (1000 to 2000 × 10^{-5} SI) than those found for the overlying sedimentary successions. Similar to interbasaltic sediments, the NGR counts, *P*-wave velocities, and bulk densities measured for the hyaloclastite intervals feature a similar but inverse response to those measured for the pillow and massive basalts as *P*-wave velocities were on average 1000 to 1500 m/s lower than the 4000 to 5000 m/s typically associated with the pillow lavas and massive intervals. Mean *P*-wave velocities of the massive basalt intervals typically featured on the lower end of this range. The unit has relatively low porosities (15% to 20%), while significantly higher porosities are recorded for the interbasaltic heterogeneities.

Downhole Logging

The priority target for Hole U1574A was to characterize the basement nature of Eldhø. Logging operations achieved collecting important data for intervals with poor core recovery in challenging logging conditions, where hole instability resulted in only partial data collection for the bottom ~50 m of the open hole section. The basaltic composition pillow lavas are characterized by high densities ~2.6 g/cm^3 and fluctuating velocities ranging from ~3 to 5.2 km/s with associated low gamma ray (GR) values (~9 gAPI). FMS imaging of the formation reveals pillow structures and the presence of lava flow units which correspond to highly vesicular basalt in the recovered core. Wireline data also show the presence of three thin elevated GR sediment layers along with a much thicker interval of high GR ~70 gAPI stratigraphy associated with an interval of ~30 m with almost no core recovery. This layer is imaged with the FMS, which records a resistive fractured nature with traces of potential pillow-like features and possible sediment layering towards the base.