IODP Expedition 396: Mid-Norwegian Continental Margin Magmatism

Sites U1569 and U1570 Summary

Highlights

Sites U1569 and U1570 were drilled as a transect of five holes on the Mimir High, which is part of the Vøring Transform Margin. We recovered an expanded section of Paleocene and Eocene sediments including a thick interval of Paleocene/Eocene Thermal Maximum (PETM) deposits in three holes. The cores will allow us to constrain the climatic and environmental changes at high resolution and provide constraints on the biogeochemical changes influenced by hydrothermal venting. The expanded sedimentary sections show that the Vøring Transform Margin was a depocenter during Paleocene rifting and into the early Eocene until the marginal high formed during passage of the Aegir Ridge some 5 Ma after breakup.

Background and Objectives

Site U1569 (proposed Site VMVM-55B) and the four boreholes that comprise Site U1570 (proposed Site VMVM-56A) make up an east–west transect on the Mimir High at 2171 to 2270 m water depth. The Mimir High is a transform margin high on the Vøring Transform Margin. Such highs are characteristic structural elements of transform margins worldwide, e.g., offshore Ghana/Côte d'Ivoire, western Australia, and the Falklands. Transform margins are characterized by very narrow ocean continent boundaries and late uplift of the continental crust when the adjacent spreading center passes. Several processes are involved in the formation of the highs. They include lateral heat transport and associated thermal uplift, as well as erosion-enhanced uplift.

The Vøring Transform Margin is characterized by diminished breakup-related extrusive volcanism compared to the juxtaposed rifted margin segments of the Vøring and Møre margins. Nevertheless, thin extrusive basalts, intrusions, and a high-velocity lower crustal body have been documented for the Vøring Transform Margin. The reduced magmatic crustal thickening may be the result of lateral heat transport from the rifted Møre Margin into the continental Vøring Basin to the north, lowering the ambient mantle temperature and resulting in reduced melt supply. As a result, the basalt cover on the Vøring Transform Margin is generally thin and even absent on the Mimir High. However, an erosional truncation at the top of the high does not preclude that some basalt has originally existed and was subsequently eroded.

The absence of a basalt cover makes the Mimir High an exceptional place to study the stratigraphy at intervals coeval to and below the Paleogene basalt. These formations are not well known from drilling, as the closest boreholes, 6504/5-15 and 6603/5-16, are more than 100 km away. However, the strata are subcropping along a kilometer-high escarpment on the southwest flank of the Mimir High. This escarpment was sampled during two cruises conducted in 2000 and 2013 using gravity corers, dredges, and a remotely operated vehicle (ROV). The cruises documented the presence of Late Cretaceous to early Eocene successions, including outcropping doleritic sills with columnar jointing. While the recovered late Campanian and early Maastrichtian sediments were deposited in a coastal to shallow marine setting, the Paleocene samples indicate deep marine conditions with abrupt shoaling and formation of the Mimir High in the early Eocene. Towards the Vøring Basin, seismic data clearly show several large sill intrusions that affected this part of the margin, and that the strata generally dips from the Mimir High to the northeast.

The first objective of Sites U1569 and U1570 was to constrain the paleoenvironmental conditions during the Paleocene/Eocene transition. In particular we hoped to obtain high-resolution information about the timing, duration, and nature of the environmental changes due to rapid warming and subsequent cooling during the earliest Eocene.

The second objective of Sites U1569 and U1570 was to tie the borehole stratigraphy with reflection seismic data to constrain the vertical movements of this margin segment as an input for geodynamic melt production models. In particular, the timing of uplift and any further constraints on the amount of crustal stretching are important.

The third objective of Sites U1569 and U1570 was to characterize the Paleogene sediments and their potential for releasing hydrocarbons when intruded by sills. Here, the key parameter is the amount of total organic carbon in the sediments that may be transformed to greenhouse gases by contact metamorphosis.

In case any igneous rocks would be sampled, a further objective was to constrain the melting and emplacement conditions. This includes the composition of the magma and in particular the temperatures at which melting took place.

Operations

The original plan for Site U1569 called for dual coring of key stratigraphic intervals, including a hole to 300 m below seafloor (mbsf) to be cored with the advanced piston corer (APC) and the extended core barrel (XCB) system, and a second hole 800 mbsf to be cored with the rotary core barrel (RCB) system. In case we could not properly sample the complete stratigraphic target at Site U1569, four offset holes of 200 m each were proposed along a transect of outcropping strata extending west of Site U1569, where deep stratigraphic targets were present at shallower subseafloor depths, as an alternative drilling strategy.

Hole U1569A was cored with the RCB system to the shortened depth of 404.6 mbsf after coring through the Paleocene/Eocene Thermal Maximum (PETM), our scientific target, and penetrating 50 m into the late Paleocene. Estimating that the base of the Paleocene could be much deeper, and to improve core recovery of the Paleocene/Eocene boundary, we ended coring in Hole U1569A in favor of sampling the older strata at much shallower depths at proposed Site U1570. Coring the PETM strata at a shallower location also allowed us to sample less mature PETM sediments with better microfossil preservation.

After ending coring in Hole U1569A, we conditioned the hole and released the RCB bit at the bottom of Hole U1569A in preparation for wireline logging. The hole then was displaced with 125 barrels of 10.5 ppg mud and the end of the pipe was set at 84.0 mbsf. The triple combo tool string was rigged up and deployed to log Hole U1569A. The initial logging run failed to pass a bridge at 127.4 mbsf. With very little open hole to log, the tools were pulled back to the surface and logging operations were terminated. After the conclusion of logging, the drill string was pulled back to the surface. The remaining top half of the mechanical bit release (MBR) cleared the rotary table (RT) at 2220 h, ending Hole U1569A and Site U1569. Forty-four rotary cores were retrieved from the site, five of which were half-length coring advances. The RCB system cored 404.6 m and recovered 144.91 m of core (36%). A total of 74.25 h or 3.1 days were recorded while at Site U1569.

The coring plan at Site U1570 was the same for all four holes: to core to 200 mbsf and to sample the Paleocene/Eocene boundary interval at considerably shallower depths than at Site U1569. Three of the four holes were completed after reaching the Environmental Protection and Safety Panel (EPSP) approved depth of 200 mbsf, and the fourth hole was terminated at 163.6 mbsf after we determined that the science objective for the hole had been met. All four holes were cored with the RCB coring system with a combination of half-length (4.6 m) and full-length (9.6 m) advances. The half-length advances were used to maximize core recovery in zones of interest at the expense of the additional wireline time. After coring was completed in Hole U1570D, the hole was conditioned for wireline logging, the RCB bit was released at the bottom of the hole, and the end of pipe was set at 76.0 mbsf. The triple combo and the Formation MicroScanner (FMS)-sonic tool strings were successfully deployed to the full depth of the hole. After the conclusion of logging, the drill string was pulled back to the surface. The BHA was racked back in the derrick and the outer core barrel was disassembled and inspected. The rig floor was secured at 2348 h and the bridge was notified that operations were complete at Site U1570. One hundred and twelve RCB cores were taken at the site. The RCB system cored 763.6 m and recovered 270.09 m of core with a recovery percentage of 35%. A total of 147.50 h or 6.2 days were recorded while at Site U1570.

Principal Results

Lithostratigraphy

Sites U1569 and U1570 consist of five holes on the northeastern flank of the Mimir High, a transform margin high. The holes sampled northeast dipping stratigraphy along a 5 km long transect where Paleogene-age seismic reflections truncate below thin Quaternary sediments at Site U1570. The succession recovered at the two sites is divided into ten lithostratigraphic units:

- Unit I is grayish brown and brown unconsolidated mud.
- Unit II consists of dark greenish gray consolidated mud which is locally slightly bioturbated.
- Unit III is grayish brown sand rich clay with nodules.
- Unit IV is very dark gray mudstone.
- Unit V is divided into two subunits. Subunit VA is very dark gray mudstone with sparse parallel lamination and slight localized bioturbation, with rare limestone intervals and common ash beds. Subunit VB is very dark gray mudstone with sparse parallel lamination and slight localized bioturbation, with common ash beds and diagenetic pyrite.
- Unit VI is a hypohyaline garnet dacite with cordierite, pyrite, and graphite.
- Unit VII is dark gray ash-rich mudstone with parallel lamination and common pyrite.
- Unit VIII is dark greenish gray to dark gray bioturbated mudstone.
- Unit IX is light gray limestone.
- Unit X is very dark greenish gray bioturbated mudstone, with common ash, and some beds of limestone and volcaniclastic conglomerate.

As expected from the seismic interpretation of the high-resolution 3-D seismic data, none of the five holes include all ten units. Unit boundaries are identified based on lithological change and supported by physical properties and biostratigraphy. Where recovery is high, boundaries between units are well established. Where core recovery is low, unit boundaries are placed at the top of the underlying unit.

Biostratigraphy

Quaternary sediments of Holes U1569A and U1570A–U1570D (~10–80 m) are characterized by glacially influenced hemipelagic mud, which unconformably overlies lower to middle Miocene strata. Uppermost Oligocene strata likely rest unconformably on lower Eocene strata. Below, a thin (0–20 m) sediment package assigned to the lower Eocene rests unconformably over a thicker lower Eocene deposit (>100 m), with much of the middle lower Eocene apparently missing. This deposit of early Eocene age sits on top of a thick PETM succession (at least 10–40 m). The sequences from Holes U1569A and U1570D, spanning the Paleocene/Eocene boundary, do not show any record of the presence of uppermost Paleocene sediments. Dinocyst chronobiostratigraphy suggests that at least ~1 My of the latest Paleocene is missing. The oldest sediments recovered are assigned to the middle Paleocene (Selandian, 61.6–59.2 Ma), recorded in samples from Holes U1569A and U1570C. Although Hole U1570B was expected to yield older sediments compared to Hole U1570C, the poor preservation, abundant reworking and absence of dinocyst marker taxa in critical intervals hampered detailed assessment of the lowermost recovered sediments. The lowermost sediments in Hole U1570B are assigned to a broad interval spanning the late and middle Paleocene, but seem unlikely to be older than those recovered from Holes U1569A and U1570C.

Paleomagnetism

For the post-PETM strata (Units I, II, III, IV, V, VI), the average intensity of magnetization varies from 2.26×10^{-2} to 3.22×10^{-2} A/m. The median coercivity varies from 1.06 to 2.17, indicating that the magnetic mineralogy is dominated by diagenetic hematite or goethite. There are six conspicuous episodes of magnetic reversals, marked by magnetic inclination <0°. The bulk magnetic susceptibility of one discrete sample from Interval U1569A-23R-1W, 28–30 cm, is over 1×10^{-3} SI, indicating a small ferromagnetic contribution, possibly from magnetite. This is also the only discrete sample presenting subhorizontal magnetic fabrics. The rest of the samples are paramagnetic with bulk magnetic susceptibility below 1×10^{-3} SI and have oblique magnetic fabrics, which may be owed to drilling-related disturbances. A low corrected degree of anisotropy (Pj < 1.028) indicates the absence of micaceous minerals.

The average intensity of magnetization of PETM strata (Unit VIII) is lower than the post-PETM strata (0.06×10^{-2} to 0.13×10^{-2} A/m). However, the median coercivity is higher (1.32 to 3.04), indicating higher hematite or goethite proportions. At least two short-lived episodes of normal polarity truncated the dominantly reverse magnetic polarity. All four discrete samples present oblique magnetic fabrics, low bulk magnetic susceptibility ($\kappa_m \leq 0.4 \times 10^{-3}$ SI) and low corrected degree of anisotropy ($P_j \leq 1.018$). Pre-PETM strata (Units VIII, IX, X) have the highest coercivity (2.77 to 4.41) compared to the post-PETM and PETM units. High coercivity may be due to higher proportions of hematite and goethite. Their intensity of magnetization (0.06×10^{-2} to 0.59×10^{-2} A/m) is lower than post-PETM strata but similar to PETM strata. All discrete samples have low bulk magnetic susceptibility ($\kappa_m \leq 0.5 \times 10^{-3}$) and a low corrected degree of magnetic anisotropy ($P_j \leq 1.077$). Just two discrete samples from Intervals U1570B-21R-2W, 56–58 cm, and U1570B-25R-4W, 92–94 cm, present subhorizontal magnetic fabrics. The rest of the samples have oblique fabrics, possibly due to drilling-related disturbances.

Geochemistry

Geochemical data from the two Mimir High sites show substantial variability, both downcore, and between holes. At Hole U1569A, nonconservative behavior is observed for a range of measured interstitial water (IW) variables, with periods of high pH and low alkalinity similar to those observed at Sites U1567 and U1568. This is also similar to the profiles observed at Hole U1570C, and suggests lithological changes control the IW composition. At Holes U1570A and U1570B, however, elemental distributions appear to be primarily conservative, and suggest diffusion and advection are the primary controls on IW composition, potentially linked to the extensive fracturing of these rocks. At all holes, carbonate content is high in the upper units, before dropping to lower values further downcore. Occasional peaks in carbonate and organic carbon content suggest infrequent authigenic mineral precipitation. Unit IV of Hole U1570D was investigated via inductively coupled plasma–atomic emission spectroscopy (ICP-AES), appearing to be dacitic, and may represent a shallow intrusion into the sediment package. X-ray diffraction (XRD) analysis indicates the primary sedimentary components are quartz, calcite, and a range of clays. In some samples it was possible to identify clinoptilite as the primary clay mineral, a form of zeolite linked to ash weathering. The direct impact of volcanic ash deposition is present in the form of a range of pyroxene minerals.

Physical Properties

One hundred and fifty-one samples across the five holes cored at Sites U1569 and U1570 were measured for moisture and density (MAD) analysis, and 1344 *P*-wave velocity measurements were made on discrete samples to constrain and supplement physical properties measurements conducted on the core Whole-Round Multisensor Logger and Section Half Multisensor Logger. The results showed distinct petrophysical properties for the ten lithostratigraphic Units that were described at the sites. Similar to Sites U1567 and U1568, peaks in magnetic susceptibility (MS) are related to the presence of ash beds, such as in lithostratigraphic Subunit VA. However, the magnetic signature of ash beds dissipates in Subunit VB, and this characteristic is interpreted as evidence of weathering and sediment alteration. The dacitic Unit VI, which was sampled in Holes U1570A and U1570D, has noticeably high seismic velocity, relatively high density, and low MS. However, the highest seismic velocity out of all five holes is recorded in the lithostratigraphic Unit IX that represents the limestone bed found in Hole U1570B. This unit also has high density and the lowest porosity values.

Downhole Measurements

Wireline logging was conducted in Holes U1569A and U1570D, which extended to 404.6 mbsf and 200 m drilling depth below seafloor (DSF), respectively. Two wireline logging tool strings, the triple combo and the FMS-sonic, were planned for Hole U1569A; however, an obstruction encountered at 127.4 m wireline log depth below seafloor (WSF) during the first deployment of the triple combo prevented us from completing the logging plan. In contrast, two logging runs were performed successfully in Hole U1570D with the triple combo and the FMS-sonic tool strings over a total open hole logged interval of ~117 m.

Six logging units were defined in Hole U1570D, constrained by a combination of the lithostratigraphy, physical properties, and wireline data. In the main open-hole logged interval of U1570D, the wireline properties reveal several transitions that correspond closely to the lithostratigraphic units.

Logging Unit 1 corresponds to an interval of the hole logged through the pipe. It is best defined by slightly higher gamma radiation (GR) readings (~10 gAPI) from the seafloor to ~22 m wireline log matched depth below seafloor (WMSF) compared to the GR of the underlying Logging Unit 2 (~4 gAPI). This change corresponds well to the measured whole-round core natural gamma radiation (NGR) values for the poorly recovered sediments in lithostratigraphic Units I and II. The open-hole part of Logging Unit 2 reveals GR of ~45–50 gAPI, with low bulk density of ~1.6–1.7 g/cm^3, and low consistent velocity (V_p) of around ~1.65 km/s. Logging Unit 3 exhibits relatively high V_p (~1.8–2.3 km/s) and resistivity compared to its surrounding claystone dominated sequence, and corresponds closely to Lithostratigraphic Unit VI. Logging Unit 4 is characterized by relatively high GR, fluctuating between ~45–85 gAPI. Logging Unit 5 comprises a thin ~3 m thick interval with elevated density (~1.95 g/cm^3), V_p (2 km/s), and extreme photoelectric effect (PEF) enrichment up to ~33 b/e$^-$ coupled with a GR reduction. The remainder of the logged section is assigned to Logging Unit 6 with minor fluctuations in GR, density, and PEF.