IODP Expedition 396: Mid-Norwegian Continental Margin Magmatism

Sites U1571 and U1572 Summary

Highlights

Sites U1571 and U1572 sampled the upper termination of the inner seaward-dipping reflectors on the central part of the Vøring Margin. At both sites two holes were drilled: the first one with the rotary core barrel (RCB) system to sample the basaltic basement, and the second one using the advanced piston corer (APC) system to sample the sedimentary overburden. The reason for drilling two sites only 5 km apart is the starkly different seismic character of the top basalt surface that we interpreted to be the boundary between different emplacement environments, with the upper sequence being emplaced in a wet or an aquatic environment. The sedimentary overburden is of late early Eocene age, which could be consistent with late emplacement of the last flood basalts on the Vøring Marginal High. However, there is a distinct possibility that the overlying sediments were not deposited immediately after the lava flows.

Background and Objectives

Sites U1571 (proposed Site VMVM-61A) and U1572 (proposed Site VMVM-07A) are located on the Skoll High on the Vøring Marginal High, about 15 km west of the Vøring Escarpment. The western part of the Vøring Marginal High is characterized by seaward-dipping reflector sequences (SDRS) that previously have been interpreted as up to 6 km thick volcanic complexes near the continent/ocean boundary. The first sampling of basalts on the Vøring Marginal High was accomplished in 1974 during Deep Sea Drilling Project (DSDP) Leg 38. Sites 338 and 342 were drilled into basement and 11 m and 12 m of basalt were recovered, respectively, in 6 cores. Subsequently, a 1277 m deep borehole was drilled into the upper termination of the seaward-dipping reflectors during Ocean Drilling Program (ODP) Leg 104 during the summer of 1985. Then, Hole 642E yielded more than 900 m of basalt and penetrated at least 135 lava flows and three dikes. The flows were interlayered with 59 volcaniclastic sedimentary units that mainly represent weathered basalt flow tops and one ignimbrite. Based on their geochemical and petrological composition, the volcanic succession was divided into an upper 800 m thick tholeiite series and a lower series that is at least 100 m thick and consists of dominantly basaltic andesite flows.

The extent and thickness of the breakup-related basaltic complex has subsequently been mapped along the mid-Norwegian continental margin using the concepts of seismic volcanostratigraphy and igneous seismic geomorphology. The seismic reflection data reveal substantial differences in the volcanic emplacement environments across the Vøring Marginal High in time and space. Distinct differences in the physical volcanology have been documented across the marginal high based on geomorphometric analysis of the top basalt surface. The eastern parts of the margin are characterized by a lava flow field that suggests that lava was flowing from eruption centers in the west towards the paleocoastline in the east where they form a lava delta. Incised valleys on the top basalt surface further suggest erosion by rivers flowing from west to east. The top basalt surface further west is characterized by a rough morphology with numerous semicircular anomalies that have been interpreted as rootless cones due to lava flowing across a wet substrate, leading to phreatomagmatic eruptions. This pitted surface belongs to a seismic sequence that onlaps onto the eastern flow field and must be younger than the subaerial basalts drilled at Hole 642E. Strikingly, the two domains also exhibit very different structural deformation. While there are only few normal faults with little displacement that offset the sequence with the pitted surface, the eastern lava flows towards the escarpment are offset by numerous north–south trending normal faults with offsets of tens of meters.

Site U1571 is located on the eastern faulted lava flow field, whereas Site U1572 is located on the pitted surface farther west. The morphological difference between the two sites and the onlap relationship suggest that the lavas have been emplaced diachronously, possibly in different environments. The first objective of the drilling sites was to obtain information on the emplacement environment based on the facies of the recovered basalt and sediments. This information will constrain the vertical movements of the margin, e.g., if both facies were indeed emplaced in a subaerial environment, or if there is a difference between the relatively well-constrained subaerial flows in the east and the possibly shallow-marine flows in the west. The second objective was to establish the time of emplacement of the two sequences to constrain the temporal evolution of the breakup volcanism. The third objective is closely linked to the first two: by analyzing the emplacement environment, we hoped to obtain information on the environment and by proxy the climatic changes during and shortly after the main phase of volcanism. This will be based primarily on biostratigraphic and geochemical analysis of the sedimentary succession immediately above the top of the basalt and possibly of sedimentary layers between basalt flows. The fourth objective was to constrain the conditions in the melt region, i.e., the composition of the mantle before melting and the ambient temperature from the geochemistry and petrology of the encountered rocks. Reaching this objective will help to parameterize geodynamic models that will distinguish between the relative importance of the drivers of excess volcanism.

Furthermore, Sites U1571 and U1572 will address two auxiliary objectives laid out in the *Scientific Prospectus*. First, we hope to provide information on the suitability of the breakup basalt sequences and interbedded sediments for permanent geological storage of CO_2. This will require obtaining information on their porosity and permeability as well as their geochemical composition, in particular the abundance of olivine which may react with CO_2. Second, we hope to obtain information on the earliest incursion of deep water into the North Atlantic and the extent of freshwater incursions into the young ocean, e.g., during the Azolla event.

Finally, and akin to the other sites drilled during Expedition 396, we will use the drilling results to test and calibrate the volcanological predictions of seismic volcanostratigraphy and igneous seismic geomorphology for the landward flows and seaward-dipping reflectors and smaller-scale volcanic elements identified in the seismic reflection data.

Operations

Site U1571 consisted of two holes. The first hole was cored using the RCB coring system from the seafloor to 247.6 m below seafloor (mbsf) and then logged with the triple combo, Formation MicroScanner (FMS)-sonic and Ultrasonic Borehole Imager (UBI) logging tool strings. While the original plan called for a single hole to 240 mbsf, the poor recovery through a critical stratigraphic interval required an additional hole to be cored at the site. The APC and extended core barrel (XCB) coring systems were selected for the second hole at the site. Hole U1571B was cored with the APC system to APC refusal at 57.2 mbsf. The XCB coring system was deployed and cored with good results through 143.7 mbsf. Polycrystalline diamond compact (PDC) XCB cutting shoes were used to core through the hard layers experienced between 125–143.7 mbsf. Coring in Hole U1571B was terminated by the science office at 1005 h on 11 September 2021. The drill string was pulled back to the surface after clearing the seafloor at 1110 h. Upon clearing the seafloor, the vessel began moving in dynamic positioning (DP) mode to the next site, which was located 3.1 nmi away. The APC/XCB coring bit cleared the rotary table at 1351 h, ending Hole U1571B and Site U1571. A total of 124 h or 5.2 days were recorded while on Site U1571.

Fifty-nine cores were taken at the site. The RCB coring system was used for Hole U1571A. The RCB system cored 247.6 m and recovered 116.55 m of core with a recovery percentage of 47%. Hole U1571B used both the APC system and the XCB system. There were 7 APC cores taken over a 57.2 m interval. The recovery for the 7 cores was 58.73 m (103%). The XCB coring system was used for 13 cores over an 86.5 m interval and recovered 62% of the cored interval.

Site U1572 also consisted of two holes. The first hole was cored using the RCB coring system from seafloor to 330.5 mbsf and then logged with the triple combo tool string. Further logging was cancelled because of degrading hole conditions. The original plan called for a single hole to 320 mbsf. The poor recovery through a critical zone required that an additional hole be cored at the site. The APC/XCB coring system was selected for the second hole at the site. Hole U1572B was cored with the APC and half-length advanced piston corer (HLAPC) systems to APC refusal at 209.6 mbsf. The XCB coring system was deployed and cored the basement contact interval through 224.3 mbsf. PDC XCB cutting shoes were used to core through the hard layers experienced between 209.6–224.3 mbsf. Coring in Hole U1572B was terminated by the science office at 1045 h on 16 September. The drill string was pulled back to the surface after clearing the seafloor at 1235 h. On clearing the rotary table, the APC/XCB BHA was secured at 1612 h, ending Hole U1572B. The bridge was notified that the drill floor activities were complete. The thrusters and hydrophones were pulled back inside the hull of the vessel and the vessel began the sea passage to proposed Site VMVM-09A. A total of 122.5 h or 5.1 days were recorded while on Site U1572.

Seventy-nine cores were recorded for the site. The RCB coring system was used for Hole U1572A. The RCB system cored 330.5 m and recovered 139.53 m of core with a recovery percentage of 42%. Hole U1572B used the APC system, the HLAPC system, and the XCB system. There were 16 APC cores recorded over a 149.3 m interval. The recovery for the 16 cores was 154.45 m (104%). The HLAPC system was used for 13 cores over a 60.3 m interval and recovered 99% of the cored interval. The XCB coring system was used for 4 cores over a 14.7 m interval and recovered 28% of the cored interval.

Principal Results

Lithostratigraphy

The succession recovered from the four holes cored at Sites U1571 and U1572 has been divided into eight lithostratigraphic units. Units I–VI are sedimentary, Unit VII is igneous, and Unit VIII is characterized by primarily igneous rock interbedded with sediment and volcaniclastics. Units were determined based on macroscopic observations and microscopic analysis, and they are supported by physical properties and biostratigraphy. Hole U1572A is the only hole that includes all eight units. At Holes U1571B and U1572B, APC coring was used and recovery of sediments is more than 100% in many sediment cores. Where core recovery is low across unit boundaries, or fall-in is observed, boundaries were placed at the top of the underlying unit. Unit I is grayish brown and brown unconsolidated mud. Unit II is greenish gray consolidated mud and nannofossil ooze. Unit III is greenish gray mud, very dark gray diatomite and diatom ooze. Unit IV consists of greenish gray radiolarian ooze interbedded with gray to black ash. Unit V is very dark gray mudstone with parallel lamination and dark gray ash. Unit VI is biosiliceous ooze with mudstone and common ash. Unit VII is basaltic andesite and basalt lava flows. Unit VIII consists of hyaloclastites, basalt, and interbasaltic mudstone, and is divided into two subunits (VIIIA and VIIIB) based on compositional changes within the igneous material. The presence of Unit VII as the top basement unit at Site U1572 constitutes the main difference between the two sites and likely is the reason for the difference in seismic character.

Biostratigraphy

The Quaternary sediments recovered from the holes at Sites U1571 and U1572 (maximum thickness of ~80 m) are, like most other holes drilled during Expedition 396, characterized by glacially influenced hemipelagic muds, which typically unconformably overlie Miocene strata. Siliceous and organic-walled microfossils were found in various abundances below the Quaternary deposits, as was also observed at most sites of the expedition. Lower to upper middle Miocene strata overlie upper lower to upper Eocene and lower Oligocene strata.

In Holes U1571B, U1572A, and U1572B, sediments recovered from directly above the igneous facies yield *Azolla* spp. and associated dinocyst marker species. The well-documented Nordic Sea Azolla phase has been dated between ~49–48 Ma (mid C22n–mid C21r), at the end of the early Eocene (Ypresian). This constrains the earliest sediment accumulation to the very end of, or directly postdating, the Early Eocene Climatic Optimum (EECO). The middle and late Eocene sequence appears to be marked by a progressive deepening or increasing distance to shore. Due to a general absence of microfossils, no biostratigraphic age constraints are available from in between the igneous facies.

Paleomagnetism

The low recovery in Holes U1571A and U1572A prevents the construction of a meaningful magnetostratigraphic record; however, better magnetostratigraphic results were obtained in Holes U1571B and U1572B. In the sediments, lithologic Unit I shows mainly normal polarities in the uppermost 40 m, while the increase of the I_{20mT}/natural remanent magnetization (NRM) ratio with depth suggests a possible climatic change. The upper and lowermost parts of Unit II show normal polarity with a reverse polarity in the lower part. Unit III has the lowest magnetic intensities ($I_{NRM} < 10^{-4}$ A/m) for these sites. The dominantly normal polarities might be caused by drilling-induced magnetization. Unit IV shows evenly normal and reverse polarities. Unit V has exclusively normal polarities that are validated by discrete samples. Unit VI shows a mixture of normal and reverse polarities. The basaltic sequences show strong magnetization intensities, with dominantly reverse polarities, all validated by discrete samples. The magnetic carrier in these basalts has a low coercivity and may potentially carry a viscous remanent magnetization (VRM) that could be used for core reorientation. The anisotropy of magnetic susceptibility (AMS) of sediments shows that correction of magnetic inclination for inclination shallowing will not be necessary. The basalts carry a strong AMS resulting from viscous flow.

Geochemistry

The recovered basalt sequence from the Skoll High shows chemical and spatial variations between Sites U1571 and U1572. For example, TiO_2 concentrations indicate the presence of occasional high-Ti basalts, which are synonymous with large igneous provinces and correlate well with flows in East Greenland and flows found during previous drilling at Hole 642E during ODP Leg 104. The uppermost basalts at the two sites appear (based on geochemistry) to be representative of two different flow units. This supports the lithographic interpretation, which indicates an additional Unit (VII) at the top of the basalts at Site U1572. Interstitial water (IW) recovered from intrabasalt sediments shows unusually high pH and low alkalinity for saline water. Basalt alteration and associated clay authigenesis at both Sites U1571 and U1572 appears to be occurring, resulting in enriched IW Ca contents (released during clay formation) and depleted Mg and K, as these elements are incorporated into the clays. Elements in IW samples above the basalt/sediment transition show largely conservative behavior downcore. Dissolved silica concentrations are sporadically enriched, with these intervals corresponding to ash- and/or diatom-rich strata (e.g., Unit III). This is indicative of marine silicate weathering, and the high interstitial silica preserves some original features of volcanic glass, diatoms, and organic matter.

Physical Properties

Lithostratigraphic Unit I at Sites U1571 and U1572 comprises relatively high bulk densities (~1.74 g/cm^3) and natural gamma radiation (NGR) (42 counts/s) that transition abruptly downward into Units II and III, which generally comprise lower gamma ray attenuation (GRA) bulk density (~1.4–1.5 g/cm^3) and NGR (~23–25 counts/s) with accompanying reduction in magnetic susceptibility (MS). The underlying Miocene to Eocene strata comprising Units IV to VI are best preserved in Hole U1572B, where Units IV and VI reveal elevated NGR (mean >30 counts/s) compared with the intervening Unit V (mean 21 counts/s). MS is also elevated in these intervals, likely linked to increased ash content in the Eocene.

The basaltic andesite-dominated Unit VII is characterized by high GRA bulk densities (2.53 g/cm^3) and *P*-wave velocities (4120 m/s), and low NGR (11 counts/s) in line with the data recorded for the basalt interiors found in Subunit VIIIB but at slightly higher NGR associated with the more evolved compositions. Point and whole-round MS (592 and 401 × 10^{-5} SI) are a factor of 10 higher than for the overlying sedimentary units, but about half that observed for the underlying basalt dominated Unit VIII.

A clear distinction is seen between the hyaloclastite subunit VIIIA and lava dominated VIIIB. The former has relatively low *P*-wave velocities (~1800 m/s) and GRA bulk densities (~1.55 g/cm^3) more in line with the low velocity, low bulk density interbasaltic sediments. Basaltic lava flow units from Unit VIII reveal clear asymmetrical profiles of *P*-wave velocity and GRA bulk density ranging from ~5000 m/s and 2.9 g/cm^3 in the massive flow interiors down to as low as ~2000 m/s and 1.5 g/cm^3 for porous and variably altered flow tops and bases. Calculated grain densities average 3 g/cm^3 for the basaltic sequence and exceed 3.1 g/cm^3 in some cases. Abundant primary pore spaces in the form of unfilled vesicles are identified throughout the volcanic sequence, leading to calculated porosities commonly >30%, whereas in certain cases these pores are filled with secondary minerals such as calcite and zeolite.

Downhole Measurements

Wireline logging operations at the Skoll High delivered a comprehensive dataset covering approximately 147 m in Hole U1571A, of which there are about 80 m basaltic basement, and approximately 157 m with about 45 m basaltic basement in Hole U1572A. Gamma ray logging data aided in constraining the nature and distribution of more evolved igneous compositions within an uppermost interval of mixed volcanic and sedimentary interlayers. A key objective of the Skoll High sites was to constrain the nature of different seismic facies associated with the top basalt reflector between the two sites, and in particular the “pitted surface” seismic facies associated with Hole U1572A. The transition from sediment to volcanic dominated sequences at Hole U1571A comprises a more protracted sequence of interlayered hard volcanic units and softer sediments. In contrast, the transition from overburden sediments to the volcanic sequence is less protracted in Hole U1572A, with an initially sharp increase in density, photoelectric effect (PEF), and MS being followed by a gradual increase in density over the following ~10 m, culminating in a sharp increase in resistivity at ~220 m. Core observations suggest abundant lava-water interaction for lithostratigraphic Unit VIII, suggesting massive subaqueous flows and volcaniclastic units. This is consistent with the wireline data.

Gamma ray also aided the identification and thickness quantification of several interlava sedimentary units which will form key future targets for palynology and isotopic age dating efforts to appraise the timing and environmental conditions of the eruption sequence. FMS image log data revealed high resolution imaging of intricate volcanic intrafacies features such as ubiquitous unfilled vesicles, mineralized amygdales, pipe vesicles, and pillow lava features indicative of aqueous eruptions during the volcanic pile evolution.