# Expedition 396: Mid-Norwegian Continental Margin Magmatism

## Sites U1567 and U1568 Summary

### Highlights

Sites U1567 and U1568 comprise a transect of five holes that sample the upper part of the Modgunn hydrothermal vent complex. The vent complex is truncated by an erosional unconformity of early Eocene age, and overlain by 20 to 50 m of Eocene to recent sediments. It consists of a feeder system and a crater at the paleoseafloor. The crater was rapidly infilled during the Paleocene/Eocene Thermal Maximum (PETM), presenting an expanded section that consists of diatom-bearing mudstones and ash layers.

### Background and Objectives

A key objective of Expedition 396 was to constrain the role of breakup volcanism on the PETM. It has for a long time been argued that large igneous provinces may have a dramatic impact on the Earth's environment and likely caused mass extinctions. Explosive volcanism influences the climate by the eruption of large volumes of aerosols and ash into the stratosphere, affecting the climate over short time periods of days to years. Long-term climate effects of volcanism are mainly related to emission of sulfur dioxide, which may cause global cooling, and greenhouse gases such as carbon dioxide, which may cause global warming.

Very large volumes of greenhouse gases must be emitted in short time periods to trigger global warming. One potential mechanism for the eruption of several thousands of gigatons of carbon-bearing gases is the maturation of sedimentary rocks by igneous intrusions offshore mid-Norway. The key aspects of this hypothesis are that 1) magma injected as sill intrusions into organic-rich sedimentary rocks generates large volumes of greenhouse gases, i.e., methane and carbon dioxide, in metamorphic aureoles around the sills, and 2) pressure buildup due to gas generation causes fracturing of the host rocks, forming so-called hydrothermal vent complexes where the gas and associated solids are transported from the deep sediment basins to the hydrosphere and atmosphere.

While this process may release the amount of carbon required for the observed climate change, i.e., between 2,000 and 12,000 Gt, it is not immediately clear if the bulk of the intrusions were emplaced over the geologically short time span that is required to explain the observed spike in global warming during the PETM. Also, it is unclear in which form the carbon would have been emitted, i.e., as $CO_2$ or $CH_4$, which is a more potent greenhouse gas.

The hydrothermal systems associated with sill intrusions are manifested as pipe-like seismic anomalies that typically root at the tips of saucer-shaped sill intrusions. These so-called hydrothermal vent complexes are divided into a lower part (the pipe) and an upper part characterized by a crater, eye, or dome shaped seismic features at the paleoseafloor. The pipes are hundreds of meters high, but sometimes up to 6 km. The upper part is typically 1–2 km in diameter, but may vary in size from some hundreds of meters to >5 km. Many of the crater-shaped depressions are infilled by stratified seismic units and topped by characteristic mounds above the paleoseafloor. More than 1,000 of these hydrothermal vent complexes have been mapped in sedimentary basins along the northeast Atlantic margins.

Information on the nature of the pipes exists from cuttings from a well in the Vøring Basin and from field analogues, e.g., in the Karoo Basin in South Africa and the Tunguska Basin in Siberia. The nature of the mound structures, however, is largely unconstrained. Their interpretation reaches from mud volcano-like sediment deposition to buildup of massive sulfide deposits that are formed at the hydrothermal vent sites by precipitation from hot vent fluids.

Sites U1567 (proposed Site VMVM-31A) and U1568 (proposed Site VMVM-40B) are located on Modgunn Arch, some 50 km north of the basalt flows sampled at Kolga High on a dome structure that is interpreted to have formed in the Miocene. The sites were selected because the regional doming uplifted the vent sites to within reach of International Ocean Discovery Program drilling. Such shallow burial depths of vent complexes are currently only identified in the Modgunn Arch area in the Vøring Basin and in the Danmarkshavn Basin on the northeast Greenland shelf.

The seismic data clearly show the presence of sill intrusions at shallow depth, ~1 km below seafloor, in the Modgunn Arch. The sills are located within a deformed sedimentary unit with weak reflections that terminate against an angular unconformity. A hydrothermal vent complex is interpreted above the upper termination of the sill. The unconformity truncates the dipping reflections within the upper part of the hydrothermal vent complex. At the center of the depression, i.e., immediately above the pipe structure, the reflections bend upwards forming a mound. This mound is overlain by draped and onlapping reflections up towards the seafloor.

The aim of Sites U1567 and U1568 was to sample the upper part of the Modgunn hydrothermal vent complex and a nearby reference site along a 500 m long transect, avoiding the dome-shaped central part of the structure, to characterize the geology of the vent complex.

The first drilling objective was to constrain the processes that form the seafloor depressions and the infill. At least four potential scenarios are conceivable for this. First, pipe initiation may be explosive due to interaction of sill intrusions with preexisting zones of overpressure that may lead to hydrofracturing of the host rock and rapid ascent of expanding gas. This will result in blowouts that can create craters with similar dimensions as the observed eye-structure within days and infill within a few hundred years. Second, they may be caused by long-term seepage of gas and aqueous fluids liquifying the surface sediments such as Lusi mud volcano in Indonesia. Third, they may be caused by repeated mobilization of mud by sills intruding into unconsolidated sediments leading to mud volcanism over a time span of thousands of years. Finally, they may result from venting of hydrothermal fluids and precipitation of pyrites and pyrotites over thousands of years. While the first two processes would require a later mobilization of the infill to form the observed domes at the upper termination, for example by gas-controlled seafloor doming, the domes in the latter two scenarios would be explained by the ejection of vent material.

Each of the four processes would be associated with very different types of material that was ejected during the time that the pipe was formed, both for the solid and the fluid phase. Therefore, understanding the formative processes for the eye structures is intrinsically linked to the second objective: to obtain information on the type of fluids (i.e., $CO_2$, $CH_4$, or higher hydrocarbons) and the amount of carbon release as this is crucial for understanding the potential role of hydrothermal venting as a driver of PETM climate change. This includes constraining the rates of fluid venting and its potential to reach far up into the water column if submarine venting occurred.

The third objective was to characterize the emplacement environment and age of the hydrothermal vent complexes and how they changed in response to venting and rapid warming during the PETM. This characterization includes the changes in microfossil assemblages before, during, and after the PETM. We also set out to determine whether there is evidence for environmental changes in the immediate vicinity of the proposed source of greenhouse gases.

The fourth objective of Sites U1567 and U1568 was to date the prominent unconformity at Modgunn Arch and the timing of uplift of the eye structure, as this constrains the vertical movement of the margin which is crucial input for melt generation models.

## Operations

Operations at Site U1567 revolved around three holes. The first hole reached 195.9 m below seafloor (mbsf). Three coring systems were used. The advanced piston corer (APC) system was used from the seafloor to 52.9 mbsf. The half-length advanced piston corer (HLAPC) system was deployed for a single core between 52.9 and 54.1 mbsf. After reaching piston coring refusal, the extended core barrel (XCB) coring system was deployed for the remainder of the hole. Half-length advances of the XCB coring system were employed to a depth of 69.4 mbsf, and the remainder of the hole was cored using full-length advances. After coring operations ended in Hole U1567A, the hole was prepared for wireline logging and then successfully logged with the triple combo and the Formation MicroScanner (FMS)-sonic tool strings.

Hole U1567B was offset ~165 m west of Hole U1567A in the direction of Site U1568. It was drilled without recovery to 25 mbsf and then cored with the APC system to 49.3 mbsf, where we experienced a partial stroke of the APC system on Core U1567B-4H. We then switched to the XCB system and continued coring with half-length advances to maximize core recovery. Hole U1567B was terminated at 83 mbsf after retrieving Core 11X. After the conclusion of coring, the drill string was pulled back above the seafloor and secured for transit under dynamic positioning

(DP) mode to Site U1568. The bit cleared the seafloor at 1850 h on 23 August 2021, ending Hole U1567B.

The 0.25 nmi move to Site U1568 was completed at 1936 h. With the thrusters already down, the move from Site U1567 to Site U1568 consumed only 45 min of vessel operations. Operations at Site U1568 consisted of two holes. Hole U1568A reached 200.0 mbsf. Two coring systems were used in the coring operations. The APC system was used from the seafloor to 51.7 mbsf. The final two cores, U1568A-6H and 7H, were both incomplete strokes and Core 7H advanced only 0.3 m into the formation. The XCB system was employed to advance the hole to the final depth of 200 mbsf. Then this hole was prepared for logging and we successfully conducted two passes each with the triple combo and the FMS-sonic tool strings. With operations at Hole U1568A complete, the vessel was offset along the seismic line by approximately 165 m in the direction of Site U1567.

Hole U1568B was washed down to 30 mbsf. The APC system was deployed and advanced to a depth of 49.0 mbsf, where we experienced a partial stroke of the APC system on Core U1568B-3H. The XCB system was deployed and coring continued with half-length advances to maximize core recovery to 114.8 mbsf. Hole U1568B was terminated at a depth of 124.6 mbsf after retrieving Core 17X with a full-length advance. After the conclusion of coring, the drill string was pulled back above the seafloor and secured for the DP transit back to Site U1567, thus ending Hole U1568B at 1900 h on 26 August. After completing operations at Site U1568 and with the APC/XCB drill string still deployed, the vessel moved in DP mode to reoccupy Site U1567. A total of 71.50 h or 3.0 days elapsed while conducting operations at Site U1568.

Forty-three cores were recovered at Site U1568. The APC coring system was deployed nine times over a 70.7 m interval and recovered 72.03 m of core. The recovery percentage was 102%. There were 34 XCB cores recovered over a 223.9 m interval. The XCB system recovered 75% of the interval cored or 167.34 m of core. The total interval cored at Site U1568 was 294.6 m with 239.37 m of core recovered for an overall coring efficiency of 81%.

After completing coring operations at Site U1568, we set the end of the pipe at 1666 m below rig floor (mbrf) and returned to Site U1567 in DP mode to core an additional hole between the positions of Holes U1567A and U1567B with the objective of improving the sampling across the Paleocene/Eocene boundary at this site. Once over the new hole coordinates, we spudded Hole U1567C at 2040 h on 26 August. The precision depth recorder (PDR) seafloor depth was 1706.1 mbsl. We drilled down to 30 mbsf without recovery and then APC/XCB cored to 106.0 mbsf (Cores U1567C-1H to 14X). Coring operations were completed at 0820 h on 27 August, the drill string was recovered back on board, and we secured for the sea passage to Site U1569. A total of 72.25 h or 3.0 days passed while conducting operations at Site U1567. Forty-six cores were taken at this site. The total interval cored at Site U1567 was 329.9 m with 303.35 m of core recovered (92%).

## Principal Results

### *Lithostratigraphy*

Sites U1567 and U1568 are described together and consist of five holes spread along a 500 m long transect of infilled sediments associated with cratering within the Modgunn hydrothermal vent complex. The succession recovered at the two sites is divided into six lithostratigraphic units, which were all identified in each of the five holes and are preliminarily tied based on unit boundaries. Generally, core recovery was high in all the holes, and the depths of most lithostratigraphic unit boundaries are well established. Lithostratigraphic Unit I is gray clay with trace to rare dropstones. Unit II consists of dark brownish gray sediment (clay- to pebble-sized nodules) rich in manganese and iron in the uppermost interval, and light yellowish-brown sand-rich clay throughout. Unit III is pale yellow to very dark greenish gray clay with silt, including clasts of clay and rare beds of siltstone. Unit IV is dark greenish gray to very dark gray claystone to siltstone, with common volcanic ash beds. Unit V is very dark gray to black parallel laminated claystone with common volcanic ash and lacking bioturbation. Unit VI is very dark greenish gray clay- to siltstone with moderate bioturbation.

### *Biostratigraphy*

The five holes cored at Sites U1567 and U1568 penetrated strata of predominantly early Paleogene age. A thin overburden was present at all holes in roughly equal thickness (~35 m) and assigned a Quaternary age based on planktonic foraminifer content. No Neogene sediments were identified. Below this, mid-early Eocene sediments were sampled in Holes U1567A, U1567B, and U1568A. Biostratigraphic and palynological analyses indicated earliest Eocene sediments were recorded in Hole U1568A, but their presence was not confirmed by biostratigraphic analyses in Hole U1568B nor in Holes U1567A–U1567C. The PETM succession below is identified based on the presence of the dinocyst marker species *Apectodinium augustum* (P6b) and supported by diatom marker taxa. The extremely expanded PETM deposits sit below the early or earliest Eocene sediments and span between ~20 m in Hole U1567A and a virtually unprecedented 70–80 m in Hole U1568A given the combined biostratigraphic and lithostratigraphic constraints.

Hole U1567B, and perhaps Hole U1568B, may contain a latest Paleocene sequence (Zone P6a), but this is not seen in any of the other holes, where the PETM succession rests unconformably on early late to middle Paleocene sedimentary successions.

### *Paleomagnetism*

The sediments at Sites U1567 and U1568 show low magnetic intensity ($I < \sim 10^{-3}$ A/m) in ~40% of the recovered sections. In some intervals both the magnetic intensity and the magnetic inclination angle vary greatly. The consistent distribution of these intervals with depth and across holes suggests that the low intensity is determined by the detrital source rather than representing a drilling artefact. In such intervals, magnetic polarity cannot be reliably determined. The magnetic inclination data, after 20 mT alternating field (AF) demagnetization, is typically used to determine magnetic polarity and to place the core sections in a magnetostratigraphic age framework. On the other hand, there are also intervals with moderate to high magnetic intensity ($I > \sim 10^{-3}$ A/m). These present both magnetic reversals and magnetic excursions, particularly in Hole U1567A (Core 4H), Hole U1567B (Core 2H), and Hole U1568A (Cores 4H-3 to 5H-3). These reversals, having similar inclination angles in normal and reverse polarity, pass the polarity test and therefore are interpreted as recording the geomagnetic field. The uppermost cores of each hole show a dominantly normal polarity and an inclination close to the calculated geomagnetic dipole field inclination (~77°) for these latitudes. These characteristics suggest that the paleomagnetic data of the youngest sediments accurately capture the geomagnetic field and its periodic reversals.

*Geochemistry*

Almost one hundred fluid and sediment samples were collected from the five holes along the transect between Holes U1567A and U1568A. For Hole U1568A, the site closest to the center of the Modgunn vent complex, several elemental profiles of interstitial water diverge from the conservative behavior observed in most of the other holes. The first evidence for this can be seen in the transition between Lithostratigraphic Units I and II (36 mbsf), where some elements decrease significantly downcore. These include K (from 12 mM to 11 mM) and Mg (from >50 mM to <45 mM). Some of the analyzed elements increase in concentration across this boundary, with the clearest rises observable in the profiles of Ca (from >12 mM to 13.5 mM), Sr (from 80 mM to 110 mM), and Li (from 30 mM to 40 mM). These shifts suggest a complex diagenetic environment, with evidence of marine silicate weathering (e.g., increasing Na, K) but also ash alteration (e.g., rising Ca and decreasing Mg). The elemental data for Unit IV in Hole U1568A corroborate the anomalous values of alkalinity and pH in these strata. Contents of B, Ca, Mg, Si, Sr, and Li are all diminished with respect to overlying and underlying sediments. Manganese, Fe, and $PO_4^{3-}$ covary in Hole U1568A, displaying clear enrichments in the uppermost section of the core but found in much lower values below 50 mbsf. Increased concentrations of these constituents in the upper sections lend support for microbially mediated oxidation of organic matter.

*Physical Properties*

Physical properties were measured for all cores in the five holes at Sites U1567 and U1568. Lithostratigraphic Unit I consists of up to 35 m thick Quaternary glacial and interglacial deposits with a mean bulk density of 1.81 g/cm$^3$ and porosities between 47% to 67%. The unit shows a relatively high gamma radioactivity with an across-borehole median value of 40 counts/s. The *P*-wave velocities measured by the Whole Round Multisensor Logger (WRMSL) range from 1480 to 2978 m/s, with a median of 1572 m/s, while Gantry *P*-wave point measurements never exceed 1702 m/s, attesting to the soft and poorly compacted nature of the sediments. Unit II is generally less than 2 m thick and consists of Pleistocene clay characterized by a rapid decrease in velocity and density with respect to Unit I. The underlying mid-early Eocene Unit III is characterized by a gradual increase in density (mean value of 1.71 g/cm$^3$) with a corresponding increase in magnetic susceptibility (MS) that increases most substantially toward the base of the unit, reaching maximum values in all five holes. The peak MS transition associated with the Unit III/IV boundary generally decreases laterally from Hole U1568A (maximum of 1772 × $10^{-5}$ SI and mean of 451.3 × $10^{-5}$ SI) to Hole U1567A (maximum of 740.5 × $10^{-5}$ SI and mean of 225.3 × $10^{-5}$ SI). The highest MS values above this horizon (greater than 1700 × 10-5 SI as measured by the Section Half Multisensor Logger [SHMSL]) occur in the two holes most proximal to the center of the vent complex (Holes U1568A and U1568B). We suggest that the basal high MS layer (with values greater than 1700 × $10^{-5}$ SI) in the two proximal boreholes may pinch out prior to reaching the three more distal Site U1567 boreholes where the values ~700–800 × $10^{-5}$ SI are recorded.

The recovered thickness of Unit IV varies from ~6 m in Hole U1567A to more than 65 m in Hole U1568A. The recorded *P*-wave velocity (mean of 1922 m/s and median of 1903 m/s) is the highest amongst all units, associated with relatively high mean bulk density of 1.74 g/cm$^3$ and relatively low MS of 90 × $10^{-5}$ SI. The general trend of decreasing MS with depth appears to be linked to a reduction of ash layers with depth in Unit IV. Units V and VI reveal generally low and consistent *P*-wave velocities of around 1600 m/s, with accompanying low bulk densities with a mean of 1.43 g/cm$^3$ and 1.42 g/cm$^3$, respectively. In summary, the cored sequences revealed physical properties that are consistent with a very weakly compacted mudstone-dominated sequence with fine-scale internal physical property variations linked to ash deposition.

*Downhole Measurements*

Logging data were collected over a total open hole interval of ~112 m in Hole U1567A and ~105 m in U1568A, yielding high-quality data from both the modified triple combo and the FMS-sonic tool strings. Four logging units were defined for Hole U1567A and three for Hole U1568A, which broadly correspond to the lithostratigraphic units. The velocities and densities are low with few anomalies in the reference hole, U1567A, around 1.55 km/s and 1.45 g/cm$^3$, respectively. However, a well-defined natural gamma radiation (NGR) peak of 65 gAPI is clearly defined. The proximal vent hole, U1568A, shows a large variation of seismic and NGR properties, with a velocity range of 1.5 to 2.7 km/s, densities from 1.55 to 1.9 g/cm$^3$, and NGR from 30 to 40 gAPI. Logging Unit 3 of Hole U1568A has an anomalously high photoelectric factor (indicating high average atomic number) at the top which may indicate the presence of heavy elements such as Ba. FMS image log data from both holes nicely show fine-scale sedimentary structures and stratification.