IODP Expedition 396: Mid-Norwegian Continental Margin Magmatism

Site U1566 Summary

Highlights

Site U1566 recovered a complete section of the feather edge of a seaward-dipping reflector sequence below a thin Quaternary sediment unit. The basalt flows and interbasalt sediment units were deposited in a subaerial environment and overlay the weathered granitic basement sampled at Site U1566.

Background and Objectives

Site U1566 (proposed Site VMVM-23A) is a companion to Site U1565. Both sites are located on the western flank of Kolga High about one km apart in water depth just above 2000 m. As described for Site U1565, the Kolga High is one of several areas along the rifted margin that are characterized by a thin sediment cover above the top basalt surface and a rapidly westward shoaling of the Base Cretaceous Unconformity (BCU).

Interpretation of extensive 3-D seismic reflection data shows that Kolga High is covered by breakup related basalts except for two small windows (5 × 3 km-sized) just west of the summit of the Kolga High. Characteristic seaward-dipping reflectors (SDRs) lap onto the Kolga High along its western margin, thinning towards the basalt windows where the lavas most likely have been eroded, making the Kolga High one of the few sites along the Vøring and Møre margins where the transition from the lowermost extrusive volcanic rocks to the subbasalt strata is accessible by drilling. A previous attempt of determining the nature of this boundary was carried out during Ocean Drilling Program (ODP) Leg 104 in 1985 on the Vøring Marginal High. Hole 642E showed that the seaward-dipping reflections represent thick piles of subaerially emplaced basalt flows, but unfortunately did not get through the entire lava pile. The Norwegian Petroleum Directorate drilled the eastern part of the Kolga High in 2014 (hole 6403/1-U-1) and recovered 38 m of hyaloclastite with a tholeiitic composition in the upper part of a lava delta as defined by eastward prograding reflections, but did not penetrate through the entire extrusive volcanic sequence.

The primary objective of Site U1566 was to sample the lowermost part of the SDRs on the Kolga High and, if possible, drill through the entire basalt sequence, but this was not the primary target as the nearby Site U1565 targeted the subbasalt units. By drilling Site U1566 we first aimed at determining the emplacement environment of the initial volcanism on the Kolga High as it provides important constraints on the vertical movement of the margin prior to the onset of extrusive volcanism and the extension during the final rifting phase prior to breakup. A second objective at Site U1566 was to constrain the timing of the onset of extrusive volcanism in this area and to provide further insights into the hypothesis that breakup and extrusive volcanism on the Møre Margin predated breakup along the Vøring Margin. A third objective of Site U1566 was to characterize the magma source of the earliest extrusive basalts and to determine if it was primordial, which would imply rapid ascent through the crust or evolved during storage at crustal levels with potential incorporation of continental crustal rocks. A fourth objective was to constrain the rates of magma production both from geochemical analyses and potentially by biostratigraphic dating of interlayered sediments, although these were expected to be highly altered unless the lava flows were emplaced over a long time interval. The final objective of Site U1566 was to get information on the extent of the basement lithologies drilled at Site U1565 and on lava-subsurface interaction if the bottom of the lava pile could be reached. Although Site U1566 was placed only 1 km away from Site U1565, the seismic data are inconclusive about the dip of the basal surface of the lava pile and hence the depth to this interface. While high-resolution seismic data may indicate that this base basalt is as shallow as 200 m below seafloor (mbsf) (depending on the choice of seismic velocity), 3-D exploration seismic data suggested that the basal surface may be up to 400 m deep and out of reach of the planned 200 m deep hole.

Operations

Site U1566 consisted of a single hole cored to 181.7 mbsf and wireline logging. Coring started at 0525 h on 16 August 2021 and ended at 2230 h on 19 August to accommodate the Versatile Seismic Imager (VSI) logging run in daylight hours on 20 August. Thirty-three cores were taken with the rotary core barrel (RCB) system, recovering 100.5 m (55%) of core. Cores U1566A-1R to 3R and 32R to 33R were taken with full-length advances. Cores 4R (26.2 mbsf) through 31R (162.3 mbsf) were taken with half-length advances to improve core recovery of the basaltic basement.

All four logging tool strings—the triple combo tool, the VSI tool, the Formation MicroScanner (FMS)-sonic tool, and the Ultrasonic Borehole Imager (UBI)—were run to a depth of 145 mbsf in the hole. After the conclusion of wireline logging, the drill string was pulled back to the surface and secured, ending Hole U1566A and Site U1566 at 0230 h on 21 August. The time spent on Hole U1566A was 124 h or 5.2 days.

Lithostratigraphy

The succession recovered at Site U1566 is divided into three lithostratigraphic units. Lithostratigraphic Unit I (0 to 19 mbsf) is unconsolidated clay with varying amounts of silt and sand, and foraminifera. Some of the intervals contain clasts and nodules. Unit II (19–148 mbsf) is basalt and interbasaltic sediment. This unit is divided into 14 basaltic lava flow subunits and 13 sedimentary subunits, with a total cored thickness of 121.8 m. Unit III (148–175.4 mbsf) is weakly to moderately altered medium-grained granite with biotite, alternating with decomposed granite and granite derived sandstones.

Biostratigraphy

Sedimentary samples analyzed from the first three cores of Hole U1566A yield common to trace diatoms and other biosiliceous debris, trace in situ dinoflagellate cysts, sporomorphs, rare ostracods, common to trace benthic foraminifers, and common planktonic foraminifers. Age-diagnostic microfossils indicate an overall Quaternary age for the sedimentary deposits above the uppermost igneous facies.

In addition, a single sample taken from sediments interbedded between igneous rocks in Section U1566A-11R-1 yielded a diverse terrestrial pollen and spore assemblage, and a few aquatic elements. Age-diagnostic pollen encountered at this level suggest an earliest Eocene age for this sample.

Paleomagnetism

Core sections were run through the superconducting rock magnetometer (SRM), which measured natural remanent magnetization (NRM) before and after alternating field demagnetization. Cores U1566A-1R to 3R show normal polarity, followed by reversed polarity from Core U1566A-4R to the bottom of the hole, with some data points showing evidence of normal polarity. Lithostratigraphic Unit I has an average initial intensity of NRM of 4.3×10^{-2} A/m. The average NRM of Units II and III is ~1.4 A/m, which is two orders of magnitude higher than that of the sediments.

Stepwise demagnetization was conducted on 32 discrete samples from Hole U1566A (thermal demagnetization) with a focus on unaltered basalt flow samples (30 samples). One sediment and one granite unit sample were also analyzed. The basalt sequence records mostly a reverse magnetic polarity.

Geochemistry

Alkalinity increases from the mudline (2.3 mM) to the deepest interstitial water sample taken at 18 mbsf (3.1 mM) in Hole U1566A. Measured pH is 7.8 in the mudline and declines to 7.7 at the base of the sediments. PO_4^{3-} content ranges from 4.04 µM at 2.95 mbsf to 2.16 µM at 18 mbsf. Ammonium (NH_4^+) is below detection limit in the mudline but increases to 56.6 mM in the deepest sample.

Total carbon (TC), total inorganic carbon (TIC), calcium carbonate, total organic carbon (TOC), total nitrogen (TN), and sulfur were determined on three discrete sediment samples. TIC content ranges from 1.1 wt% at 2.95 mbsf to 0.02 wt% at 18 mbsf. $CaCO_3$ values range from 0.2 to 11.3 wt%. TOC ranges from 0.21 to 0.03 wt%. All TOC/TN ratios are below 5, indicating marine organic matter. H and S were below detection limits.

Physical Properties

Physical properties were measured on all whole-round cores, archive and working-half sections, and discrete samples of Hole U1566A. Measurements included gamma ray attenuation (GRA) bulk density, magnetic susceptibility (MS), natural gamma radiation (NGR), *P*-wave velocity, X-ray imaging, moisture and density (MAD) and porosity (n. 102) analysis, and thermal conductivity (n. 30).

Unit I cores have *P*-wave velocities of 1489 to 2909 m/s, whole-round GRA bulk density from 1.51 to 2.10 g/cm^3, and whole-round MS has a mean value of 77.7 (SI units) compared to a mean value of 86.9 (SI units) from discrete half-round measurements. NGR values for the overburden sediments vary from 19 to 44 counts/s. The bulk density of discrete samples ranges from 1.54 to 1.82 g/cm^3 (n = 6), with grain densities ranging from 2.74 to 2.80 g/cm^3.

The ~121 m thick Unit II succession revealed dominantly very low gamma radiation counts (<10 counts/s) in the basalt subunits, while the intervolcanic sediment subunits show more variation and values up to 62.8 counts/s. Discrete samples have bulk densities ranging from 1.69 to 2.84 g/cm^3. Discrete measurements of *P*-wave velocity range from 1530 m/s to 5884 m/s and display systematic variations associated with the varying lithologies. In total, 23 successful thermal-conductivity measurements were made across a range of lithologies within Unit II with values ranging from 1–1.9 W(m·K). The MS values in the sequence (mean 482 SI units) are significantly higher than those of the overlying soft sediments (mean 78 SI units).

The granitic basement Unit III has higher gamma radiation readings (mean 53.5 counts/s) compared to the overlying volcanic sequence and discrete bulk densities range from 1.97 to 2.58 g/cm^3. Gantry *P*-wave velocity measurements range from 1502 m/s to 4501 m/s while thermal-conductivity measurements have a mean value of 2.1 W/(m·K).

Downhole Measurements

Wireline data from the four log runs collected sonic velocities, MS, NGR, bulk density, and resistivity measurements and imaged the basalt-sediment sequence of Unit II. The lava package displays a consistently low background gamma trend with three clear peaks in the natural gamma ray log linked to siliciclastic sediment interlayers. The MS log reveals clear variations with the basaltic lava flows with higher susceptibility values in the basalt flow subunits and almost zero MS of the interbasalt sediments. The porosity-dependent resistivity, bulk density, photoelectric factor, and *P*-wave and *S*-wave velocity logs show systematic variations throughout basalt subunits similar to logs collected in other subaerial basalt flow sequences. For instance, the *P*-wave velocity is as low as 2.5 km/s in the interbasalt sediments subunits and flow tops, increasing towards the massive basalt interiors, reaching values up to almost 6 km/s. The imaging logs (FMS-sonic and UBI) similarly display systematic variations in lava flow facies, with vesicular low-resistivity flow tops and massive resistive interiors with potential amygdales.