IODP Expedition 403: Fram Strait Paleo-Archive

Site U1618 Summary

Background and Scientific Objectives

The Vestnesa Ridge is a roughly east-to-west oriented prominent bathymetric feature situated in Fram Strait on the western continental margin of Svalbard. Its evolution is linked to the tectonic, sedimentary, and climatic history of the region, making it a focal point for multidisciplinary scientific research. The 100 km long ridge is a sediment drift, generated by persistent bottom currents associated with the West Spitsbergen Current (WSC), that developed over oceanic crust since the Fram Strait opening (~19 My ago). While the chronology of the Vestnesa Ridge sediment record deposited since the last glacial is well established and regionally correlateable, the chronology prior to marine isotope stage (MIS) 3-4 is limited to extrapolation made through seismic data from previously drilled sites on the Yermak Plateau (Ocean Drilling Program [ODP] Site 912) and south of the Molloy transform fault (ODP Site 909).

The sedimentation and geological development in this area has been heavily influenced by the Plio–Pleistocene glaciations and the ice sheet extent over Svalbard and the Arctic Ocean. Depositional facies representing a range of glaciogenic and bottom current depositional processes including ice rafting events, dense glacial debris flows, and subglacial meltwater plumes, as well as turbidity flows, are well documented in the recent sedimentary record along the western Svalbard continental margin, and the Vestnesa Ridge. The presence of gas hydrates and associated fluid migration are additional controls on the sedimentary record of the Vestnesa Ridge.

Site U1618 (proposed Site VRE-03A) on the Vestnesa Ridge East termination was chosen for the close location to the continental margin and outer reaches of the former paleo Svalbard–Barents Sea Ice Sheet, making this site ideal to reconstruct the ice sheet dynamics in the northern area. Additionally, this location offers the opportunity to explore possible relationships (including feedbacks and tipping points) among paleo-ice sheets, gas hydrate stability, and tectonics stress.

For safety and to maximize recovery towards primary science objectives, Site U1618 was positioned away from the regional bottom simulating reflector, and the holes were located on a seismic line away from any visible chimneys.

Operations

We started our 1677 nmi voyage across the North Atlantic to Fram Strait Site U1618 (proposed Site VRE-03A) at 0800 h (UTC + 2 h) on 4 June 2024 in Amsterdam, The Netherlands. Throughout the transit all groups familiarized themselves with their respective laboratories and worked on writing their method chapters. The COVID mitigation protocol was followed until 11 June when it ended at 1815 h. We completed the transit on 14 June an average speed of 9.9 kt.

In total we spent 9.18 d on site and penetrated to a maximum depth of 414.3 meters below seafloor (mbsf), with a combined site penetration of 1104.3 m. The cored interval of 1102.3 m resulted in a recovered length of 1078.45 m (98%). Site U1618 consists of three holes that span a 50 m interval (25 m between holes), along seismic line CAGE20-5-HH-02-2D. We took 152 cores in total, with 26.3% using the advanced piston corer (APC) (40 cores), 11.2% using the half-length APC (HLAPC) (17 cores), and 62.5% using the extended core barrel (XPC) (95 cores). To minimize magnetic overprinting of the cored sediment, nonmagnetic collars and core barrels were used for all APC and HLAPC coring. All three holes had intervals where the sediments significantly expanded due to the presence of gas, resulting in recoveries often exceeding 100%. To mitigate the impact of expansion and the potential for core disturbance, and to release pressure, holes were drilled into the liner, both by the drill crew on the rig floor and the technical staff on the core receiving platform. Headspace gas C_1/C_2 ratios were being monitored in all holes for safety and began plotting on the margin of our safety envelope at ~263 meters below seafloor (mbsf) in Hole U1618A and below ~400 mbsf in Holes U1618B and U1618C, resulting in the precautionary termination of the holes.

Principal Results

The recovered sequence at Site U1618 consists of 152 cores and 1078.45 m of sediment with increasing lithification with depth. The sediments throughout all cores in Holes U1618A to U1618C are primarily siliciclastic, composed of silty clay, with interbedded coarser intervals, such as clayey silt and less frequent sandy mud. These lithologies contain varying amounts of detrital clasts and/or authigenic mineral precipitates. Small (<1 cm) to large (1–9 cm) clasts are identified throughout the cores from visual descriptions and X-radiograph observations. When present, clast abundance ranges from dispersed to occasional dense, poorly sorted, clast rich intervals (i.e., gravels and diamictons). Authigenic mineral precipitates (mostly calcite) range in size from millimeter-scale to 2–3 cm diameter concretions. While sedimentary structures are sometimes not visible on the split core surfaces, primary and secondary sedimentary structures are more commonly visible in the X-radiographs available from Hole U1618B and the deeper part of Hole U1618C. The sediments recovered from Site U1618 are divided into three primary lithological units and additional subunits based primarily on the lithological characteristics and secondarily on physical properties and geochemical data. The deepest and most continuous hole, U1618C, is used as the primary record to define the lithostratigraphic unit and subunit boundaries. The stratigraphic boundaries in Hole U1618C were subsequently transferred to Holes U1618A and U1618B based on the stratigraphic correlation. Clasts of varying sizes, interpreted to be iceberg-rafted debris (IRD), are observed throughout all units. The majority of these clasts are angular and <1 cm in size, but subangular clasts are also occasionally observed.

Unit I is composed of silty clay, with frequent intervals of coarser silty clay/clayey silt and few sandy mud intervals, low biogenic components, variable mineralogy, and absent to slight bioturbation. Unit II is characterized by low clast content and a firmer induration; however, the unit is also characterized by low natural gamma ray (NGR) and gamma ray attenuation (GRA) values. Unit II is also characterized by authigenic calcite formation and rare iron sulfide minerals. Unit III is characterized by increased clast concentration and increased bioturbation, particularly in the upper to middle part of the unit. The degree of core recovery, coring disturbance, and gas expansion varies with the depth of the cores and the type of coring method employed. APC cores exhibit minimal disturbance, although low recovery or fracturing is observed beginning around 55 mbsf in all holes, with an inconsistent pattern of low recovery beginning after this depth. Soupy intervals are noted in the upper sections of the first two to three cores from each hole and often result in mixed sediments. Most XCB cores from all holes are moderately to heavily disturbed, primarily by biscuiting. Coarser-grained intervals seem to stabilize the sediments and prevent them from becoming severely biscuited.

The sediments of Site U1618 were preliminarily examined for calcareous nannofossils, foraminifers, diatoms, and dinoflagellate cysts (dinocysts). None of these microfossil groups are consistently present throughout the sediment column and several levels are barren. Diatoms are present at the very top and only sporadically downcore. Foraminifers are present in the upper part of the section but disappear downcore as well. Calcareous nannofossils are generally present, but towards the base of Hole U1618C, the record is mainly barren. Dinocysts are present throughout the sediment column but are absent occasionally. All groups combined, with especially calcareous nannofossils and dinocysts, contribute to a first biostratigraphic and paleoenvironmental assessment and an age-depth model for Site U1618. The age model is based on a combination of biostratigraphical and paleomagnetic data. Three calibrated calcareous nannofossil age markers are identified within the three holes in this site, the last occurrence (LO) of *Emiliania huxleyi*, the last occurrence datum (LOD) of the small *Gephyrocapsa* group, and the LO of medium *Gephyrocapsa*. Moreover, two calibrated events of dinocysts are observed, the presence of *Protoperidinium stellatum* and *Filisphaera filifera*. Other patterns in the calcareous nannofossil assemblages, such as the presence of the acme of *Gephyrocapsa caribbeanica*, are considered to provide a constraint to within the late Pleistocene. Additionally, the LO of *Globigerinoides obliquus*, the presence of the diatom *Proboscia curvirostris*, and the record of the benthic foraminifer *Cibicides grossa*, are used to constrain the age-depth model for Site U1618.

Paleomagnetic investigation of Site U1618 focused on measurements of the natural remanent magnetization (NRM) before and after alternating field (AF) demagnetization of archive half sections and vertically oriented discrete cube samples. All archive half sections were measured except for a few that had significant visible coring disturbance. Some archive half sections with high magnetic susceptibility (MS) ($\lesssim$750 IU) were too strong for the NRM to be measured on the superconducting rock magnetometer (SRM) and caused flux jumps even when the track speed was slowed by 10×, thus compromising our ability to collect quality data in these intervals. However, the intensity often was reduced after AF demagnetization and measurements could be made after demagnetization. APC and HLAPC archive half sections were measured before and after AF demagnetization. As XCB cores do not use nonmagnetic core barrels and are more susceptible to the viscous isothermal remanent magnetization (VIRM) drill string overprint, XCB archive half sections required higher AF demagnetization steps to remove this overprint. The NRM of the oriented discrete cube samples were stepwise demagnetized to higher fields up to either 50 mT if analyzed on the superconducting rock magnetometer (SRM) using the inline AF demagnetizing system or 100 mT if analyzed on the AGICO JR-6 spinner magnetometer using the D2000 static AF demagnetizer. These measurements were supplemented by measurements of MS and anhysteretic remanent magnetization (ARM) on samples from all holes and study of isothermal remanent magnetizations (IRM) on Hole U1618A samples. Two unoriented iron sulfide nodules were also sampled and subject to MS, ARM, and IRM analysis. The determination of polarity zones was complicated by the potential for chemical remanent magnetizations hosted by the authigenic mineral greigite. However, three major polarity zones that reflect the C1n (Brunhes; 0–773 ka), C1r–C2r (Matuyama; 773–2595 ka), and C2An (Gauss; 2595–3596 ka) chrons are still be identified. The interpretation of the normal polarity zone at the base of Holes U1618B and U1618C was informed through conversation with the shipboard micropaleontologists and not derived entirely independently.

The physical properties measured at this site included MS, GRA, NGR, *P*-wave velocities, and moisture and density (MAD). From the seafloor to ~150 mbsf, MS values covary with NGR and GRA bulk density. However, below ~150 mbsf, there is no obvious association with other downcore physical properties. Below ~150 mbsf to the base of the section, irregularly spaced, large peaks in MS become prevalent. These maxima are orders of magnitude higher than the background and are often associated with large nodules of authigenic Fe-sulfide minerals (e.g., greigite). The GRA bulk density record downcore shows a rapid increase from the seafloor that is likely related to increased compaction at depth. Several large peaks in bulk density, reaching ~2.4 g/cm^3, occur in several intervals and are likely associated with debris flows. Observed bulk density lows at ~150–200 mbsf are associated with Lithological Unit II. Below ~170 mbsf to the base, GRA bulk density is less variable, though this may be associated with the transition to XCB cores below ~120 mbsf. Generally, NGR mirrors GRA bulk density trends downcore, but correlations are less apparent below 360 mbsf. Whole-round sections were measured for compressional *P*-wave velocity on the Whole-Round Multisensor Logger (WRMSL). Below ~25 mbsf, the signal becomes dominated by noise, and from there on no downcore signal was detectable. Discrete *P*-wave velocity measurements were made in intervals that excluded excessive coring disturbances, voids, cracks, or large clasts. However, below ~50 mbsf, discrete *P*-wave measurements were abandoned due to increasing noise and eventual lack of a detectable signal. MAD bulk density increases sharply from ~1.5 g/cm^3 at the sediment surface to ~2.0 g/cm^3 at ~50 mbsf, corresponding to sharply decreasing porosity and water content from 67% to 54% and 43% to 32%, respectively. There is greater variability in MAD bulk density downhole to ~200 mbsf, below which values are generally stable around ~1.8 g/cm^3. Overall, MAD bulk density values correspond well with GRA bulk density trends downcore. The highest MAD bulk density values are found near the transition from Lithological Unit I to Unit II and at the switch from APC/HLAPC to XCB cores, at ~285 mbsf.

Stratigraphic correlation in the upper part of the holes (<125 mbsf) was primarily established using MS and GRA data from the WRMSL. Below this depth, gas caused substantial expansion of the sediments and resulted in many gaps in the cores. In some cases, expansion caused shattering of the liners and made it difficult to extract them from the core barrel. These causes resulted in relatively high growth factors, disturbed sediment (especially in section 1 of XCB cores in Holes U1618A and U1618B), and voids, which affected the physical properties (e.g., density) resulting in stratigraphic inconsistencies among holes. In the deeper sections (>125 m), the erratic occurrence of detrital and authigenic iron sulfide minerals as well as diagenetic overprint added uncertainty to the correlation and splice. GRA bulk density and NGR data were helpful in making the correlations. Although we relied on MS data, we note that the NGR data are less noisy than other data sets and may be useful in comparing with climate records (e.g., high-density sediments delivered by ice sheet versus low-density sediments delivered by bottom currents). The correlators constructed two spliced intervals, one from 0 to 294.2 m core composite depth below seafloor (CCSF) based on correlations among the three holes and from 294.2 to 474.15 m CCSF based on a correlation between Holes U1618B and U1618C.

Samples for headspace gas, interstitial water (IW) chemistry, and bulk sediment geochemistry were analyzed at Site U1618. Headspace hydrocarbon gas measurements showed low concentrations in the upper 16.50 m (0 to 1 ppmv) and higher concentrations of methane below this depth (2000 to >35,000 ppmv). An increased presence of ethane was observed below about 400 mbsf, reaching concentrations of >150 ppmv. The main findings from IW analysis suggest anaerobic conditions and possible fluid migration in the sediments, leading to diachronous iron mineral formation. Elemental analysis of bulk material revealed overall high concentrations of carbon and nitrogen across most intervals. The Vestnesa Ridge is an area of active methane gas seeps. The methane migrates up toward the ridge crest from deeper reservoirs through gas chimneys that penetrate the gas hydrate stability zone. Previous studies indicate that the hydrate stability zone is several hundred meters in thickness and can extend to the seafloor. While Site U1618 is not located near a known gas hydrate-related bottom seismic reflector, the headspace gas, IW geochemistry, and bulk sediment geochemistry indicates the presence and influence of gas hydrates at depth.

Sedimentary ancient DNA (sedaDNA) samples were taken in contamination-controlled conditions at low resolution for the entire record of Hole U1618B, and at a higher resolution in Hole U1618C to examine the MIS 6 (glacial) to MIS5e (interglacial) transition through to the recent past. In total, 87 sedaDNA samples were taken across the two holes; these samples will be analyzed postexpedition. As the drill fluid contains seawater, and thus a potential source of biological contamination through modern DNA, the drill fluid was infused with chemical perfluorocarbon (PFT) tracers to assess whether the sedaDNA samples had been contaminated. At this site a total of 138 PFT samples were analyzed shipboard on an Agilent 6890 gas chromatograph with a microelectron capture detector. In total 87 PFT samples came back negative, and 51 samples were positive, and thus might indicate potential contamination.

In situ temperature of formation was measured during Cores U1618A-4H, 7H, 10H, and 13H using the advanced piston corer temperature (APCT-3) tool. While coring using the XCB, in situ formation temperature was measured before Cores U1618A-35X, 42X, and 53X using the Sediment Temperature 2 (SET2) tool. Temperature increases almost linearly with depth. In Hole U1618B, downhole wireline logging using the triple combination (triple combo) and Formation MicroScanner (FMS)-sonic tool strings was performed to obtain multiple in situ properties. Logging data were processed at Lamont-Doherty Earth Observatory (LDEO). Seismic imaging using the Versatile Seismic Imager (VSI) was cancelled because the *z*-axis accelerometer used to record the vertical position of data was not operating properly, and the backup VSI tool suffered from an electrical malfunction.

The drill bit was set at a depth of 79.6 mbsf to stabilize the hole. The triple combo string was set to a depth of ~370 mbsf for two runs. Based on the caliper measurements, the borehole diameter was enlarged for most of the hole, which can adversely affect MS and porosity values. NGR shows virtually the same trends as shipboard scanning data with the NGRL. The FMS-sonic string successfully logged NGR, acoustic velocity, neutron porosity, and borehole resistivity images.