GEOLOGY | THE GEOLOGICAL SOCIETY OF AMERICA®

https://doi.org/10.1130/G54231.1

Manuscript received 22 November 2025
Revised manuscript received 16 March 2026
Manuscript accepted 1 April 2026

Published online 20 April 2026

Up-current geomorphic events and local tectonics as primary controls on sediment transport by the West Spitsbergen Current and sedimentation in the Fram Strait since ca. 3 Ma

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ABSTRACT

International Ocean Discovery Program Expedition 403 recovered the longest sediment cores from the Svyatogor Ridge (SR) and Vestnesa Ridge (VR) to date, enabling hypothesis testing of competing influences on sediment drift evolution in the Fram Strait, with implications for ocean circulation. We found that regional geomorphic events and local tectonics

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CITATION: St John, K., et al., 2026, Up-current geomorphic events and local tectonics as primary controls on sediment transport by the West Spitsbergen Current and sedimentation in the Fram Strait since ca. 3 Ma: Geology, v. XX, p. , https://doi.org/10.1130/G54231.1

exerted first-order controls on Pliocene–Pleistocene accumulation rates in eastern Fram Strait sediment drift through modulation of sediment supply to the West Spitsbergen Current (WSC) and depositional accommodation space. Expedition 403 drill cores show significant reductions in sediment deposition ca. 2 Ma and ca. 1 Ma. Linear sedimentation rates (LSRs) were more than twice as high at SR compared to VR before ca. 2 Ma, suggesting SR was a more significant depocenter than previously thought. This disparity appears to be linked to tectonically influenced paleobathymetry associated with extensional faulting. A major decrease in LSRs ca. 2 Ma coincided with the Barents Shelf changing from subaerial to marine, likely reducing erosion and sediment supply to the WSC. A further decrease in LSRs occurred ca. 1 Ma, during the mid-Pleistocene transition. This change aligns with increased Barents Seaway excavation, suggesting that reduced sediment input to the northern margins relates to a reorganization of ocean circulation. A weakened WSC no longer served as the only route for current flow and sediment transport from the North Atlantic to the Arctic Ocean, as the Barents Sea route was also viable when ice free.

INTRODUCTION

Flowing to the Arctic Ocean through the eastern Fram Strait (FS), the West Spitsbergen Current (WSC) is the northernmost extension of the North Atlantic Current (NAC), and it is the primary source of heat, salt, and moisture to the Arctic region. This influx of warm, salty water is thought to control the extent and dynamics of Arctic ice sheets and sea ice (Kremer et al., 2018), and in turn, past and future global climate variability.

Given the importance of the WSC as a player in the ocean-climate system, International Ocean Discovery Program Expedition 403 (IODP Exp403) drilled several sediment drift sites (Fig. 1) to obtain core records suitable to reconstruct past WSC variability, particularly across global climate transitions. Sediment drifts are mounded depocenters that form under the influence of bottom contour currents (contourites) persistent over millions of years (Rebesco et al., 2014).

Two sediment drifts under the influence of the paleo-WSC are the Vestnesa Ridge (VR) and the Svyatogor Ridge (SR). The VR is an ~100 km elongate drift extending from the Svalbard continental margin, likely shaped by a westward-turning branch of the WSC. It lies east of the Molloy Ridge (MR) and north of the Molloy Transform Fault (MTF) and overlies the ocean-continent transition (Eiken and Hinz, 1993). The SR is a sediment drift (~45 km long; Johnson et al., 2015; Waghorn et al., 2018) extending off the NW flank of the Knipovich Ridge (KR) at the inner oblique junction with the MTF (Amundsen et al., 2011; Dumais et al., 2021); it overlies very young oceanic crust (ca. 7.3 Ma; Gaina, 2014) and is in an active rift environment with associated detachment faults (Waghorn et al., 2018). Both the MR and KR are ultraslow spreading ridges.

The way in which the tectonic evolution of this complex ridge-transform system has influenced the development of sediment drifts in the region remains poorly understood. Informed by the paleocurrent contourite models of Eiken and Hinz (1993), Amundsen et al. (2011) hypothesized thick sediment packages built up within active half grabens on the western flank of the KR (i.e., at SR). Johnson et al. (2015) postulated that the VR and the SR were once connected and that a south-to-north bathymetric down-step across the MTF enhanced sediment accumulation north of the fault (i.e., at VR). In their reconstruction, the sediment drift buildup at the SR was thought to be much delayed. It was proposed to have started only when sediment delivery increased with the intensification of the Northern Hemisphere glaciation (iNHG; ca. 2.7 Ma) and the onset of shelf-edge glaciation of the paleo-Svalbard–Barents Sea Ice Sheet. Their observation of ridge-crest displacement suggested that the SR shifted westward over the past 2 m.y., away from a main path of the WSC, resulting in reduced sedimentation since that time.

Farther afield, modeling-based studies (Butt et al., 2002; Zieba et al., 2017; Patton et al., 2024) suggested that large expanses of the Eurasian Arctic switched from subaerial exposure to marine conditions ca. 2 Ma and that the Barents Seaway was open intermittently since 1 Ma and persistently since ca. 0.7 Ma. The latter time interval spans the mid-Pleistocene transition (MPT; Herbert, 2023). Barker et al. (2021) documented increased heat transport to the Nordic Seas via the NAC during the MPT and hypothesized increased Atlantic water inflow to the Arctic Ocean. Given that the NAC transitions to the WSC north of the Barents Seaway, we hypothesized that corroborating evidence for these events should exist in sediment drifts of the Fram Strait. Presumably, erosion rates would affect sediment supply to the WSC, and the diversion of the NAC into the shallow (~450 m) Barents Sea could affect the strength of the WSC heading to the Fram Strait.

In combination, the former hypotheses (Amundsen et al., 2011; Johnson et al., 2015; Barker et al., 2021; Patton et al., 2024) suggest a complex interplay of tectonic influences on local bathymetry and climatic and distant geomorphic influences on sediment input as controlling factors for sedimentation by the paleo-WSC. The hypothesized timing and pattern of depocenter evolution across the MTF can now be tested with the stratigraphic records from the Exp403 SR and VR drill sites. Exp403 recovered the longest sediment core records from these sediment drifts to date (Lucchi et al., 2026), extending hundreds of meters deeper than previous coring. In this study, we used Exp403 shipboard age models, long-term average linear sedimentation rates (LSRs), and lithologies from VR and SR drill sites to document the evolution of the drifts over the past 3 m.y. We then assessed if the proposed tectonic, geomorphic, and paleoceanographic changes in the region impacted sediment input to the main northward-flowing WSC and the strength variation of that current.

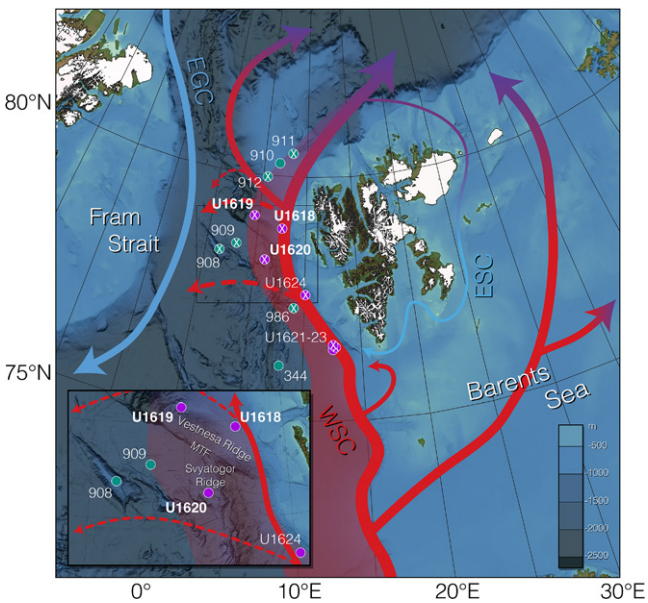

Figure 1. Map of International Ocean Discovery Program Expedition 403 (Exp403) sites (purple) and Ocean Drilling Program (ODP)/Deep Sea Drilling Project (DSDP) sites (teal) in the path of West Spitsbergen Current (WSC; red arrow and swath). Sites with crosses show decreased linear sedimentation rates (LSRs) at ca. 1 Ma. Recirculating current (dashed lines) placement is based on Walczowski and Piechura (2011) and Kalhagen et al. (2024). EGC—East Greenland Current; ESC—East Spitsbergen Current. Inset map: Bathymetric setting of Svyatogor Ridge (SR) and Vestnesa Ridge (VR) sediment drifts. MTF—Molloy transform fault.

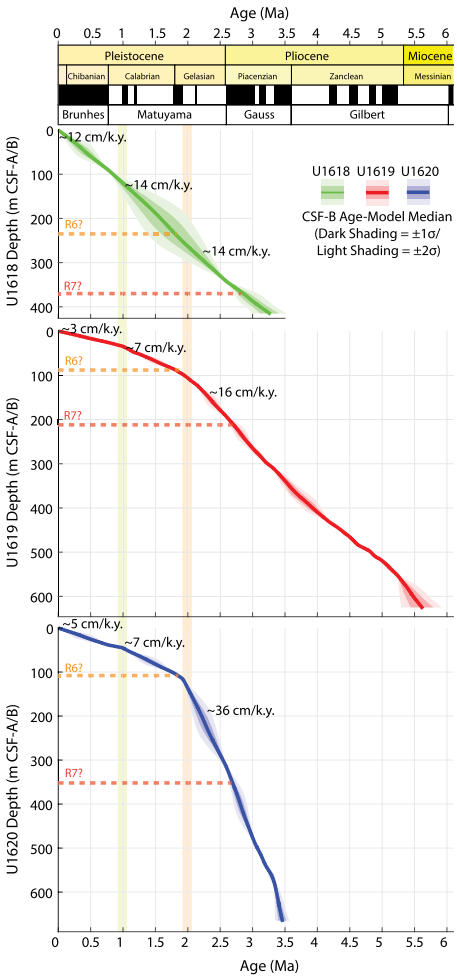

Figure 2. Age models for International Ocean Discovery Program (IODP) Sites U1618 (green), U1619 (red), and U1620 (blue). Time scale is from Gradstein et al. (2020). Depths of R6(?) and R7(?) seismic reflectors are indicated by horizontal dashed lines (see Supplemental Material [text footnote 1]). Core Depth Below Seafloor method A (CSF-A) and method B (CSF-B) are defined in the Supplemental Material.

MATERIALS AND METHODS

Exp403 drilling included two sites in the VR and one site in the SR contourite systems. Site U1618 was drilled into the eastern termination of the VR, which likely overlies continental crust. U1619 lies at the western termination of the VR, and U1620 was drilled into the SR sediment drift (Fig. 1); both overlie oceanic crust. All Exp403 sites are under the influence of the WSC.

Lithostratigraphic intervals were determined through visual description of the split core surfaces, X-radiographs, and smear slides (Lucchi et al., 2026). Age models were constructed using magnetostratigraphic and biostratigraphic data, with uncertainties estimated using the Undatable software (Lougheed and Obrochta, 2019). Long-term average LSRs (cm/k.y.) were determined based on the magnetostratigraphic and biostratigraphic age-depth events. See Supplemental Material[1] for coring and age model construction.

RESULTS

Sites U1619 and U1620 extend to the late Miocene and mid-Pliocene, respectively (Lucchi et al., 2026). At both sites, major inflection points in LSRs occur at 2.1–1.8 Ma (base of the Olduvai to the top of the Reunion subchrons; hereafter referred to as ca. 2 Ma) and at ca. 1 Ma (Fig. 2; Table S1). At both of these junctures, LSRs decreased, with the most prominent change at ca. 2 Ma: Site U1620 LSRs decreased from ~36 cm/k.y. to ~7 cm/k.y., and Site U1619 LSRs decreased from ~16 cm/k.y. to ~7 cm/k.y. Circa 1 Ma, LSRs decreased further, to ~5 cm/k.y. at Site U1620 and to ~3 cm/k.y. at Site U1619.

Site U1618 extends to the late Pliocene, slightly older than ca. 2.6 Ma. Here, no change in LSR is observed at ca. 2 Ma, but the ca. 1 Ma inflection point in LSRs is present, marking a decrease in LSRs from ~14 cm/k.y. to ~12 cm/k.y.

The lithostratigraphy at all three sites is primarily siliciclastic, composed of silty clay, clayey silt, clay, and sandy mud (Fig. S2). Major changes in lithology (i.e., divisions of lithologic units or subunits) do not correspond to changes in sedimentation rates. Clast abundance is high since the iNHG, and it is generally higher at Svalbard-proximal Site U1618 with respect to the more distal Sites U1619 and U1620. Laminations are occasionally present, especially in the late Pliocene and older stratigraphic intervals of U1619 and U1620. Bioturbation is more common in all records before ca. 1 Ma (Lucchi et al., 2026). Sediment lithofacies are consistent with deposition by contour currents and ice rafting.

DISCUSSION

Prior to ca. 2 Ma, high LSRs at Site U1620 on the SR were more than double the LSRs for the presumably contiguous VR, to the north. This finding suggests that the SR was a more important depocenter than Johnson et al. (2015) hypothesized, both prior to and continuing through the iNHG. Instead, our results confirm a prediction by Amundsen et al. (2011) of contourite depositional rates as high as 20–40 cm/k.y. on the western flank of the KR. While the iNHG is documented by an increase in clast (dropstone) abundance (Fig. S2), there is no obvious change in LSRs at Site U1619 or Site U1620 (Fig. 2).

The LSRs support the idea that tectonic controls led to differences in accommodation space available for the depocenter evolution of the VR and SR sediment drifts. However during the past 3.3 m.y., the highest LSR at U1620 reveals that these controls were mainly favorable for sediment deposition south of the MTF (i.e., the SR side; Fig. 3), contrasting the original model of Johnson et al. (2015).

The depositional accommodation space at SR may be the result of significant extensional faulting associated with detachment as the KR opened, followed by subsidence at a highly faulted zone in the corner between the MTF and the KR (Waghorn et al., 2020). This zone was likely subjected to transtensional stresses due to the complex oblique relation between the Molloy and Knipovich spreading ridges (Dumais et al., 2021; Domel et al., 2022). Large-scale basement faults, as well as sedimentary growth faults, are present, including SW of Site U1620 (Fig. S1C). Growth faults reaching close to the present-day seafloor are evidence of movement on previously sedimented detachment faults (Waghorn et al., 2018, 2020). Deposition synchronous with faulting is evidenced by bowed-down seismic reflections at Site U1620 (Fig. S1C). The crustal age and its thermal history, as well as the isostasy effect, are other factors that would influence the amount of accommodation space and deposition regime across the MTF. Such factors require regional investigations, for which these Exp403 findings provide additional motivation.

While tectonic influences such as reduced accommodation space and/or lateral migration of the depocenter away from the main WSC path could contribute to reduced LSRs at SR and VR at ca. 2 Ma, climatic and geomorphic influences on sediment supply to the broader region were also occurring. Decreased LSRs at ca. 2 Ma coincide with the decrease in regional erosion rates as the Eurasian Arctic Barents Shelf switched from subaerial exposure to marine conditions (Patton et al., 2024). A major reduction in sediment supply to the WSC is recorded at the SR and western VR depocenters when the Barents Shelf became marine-based (Fig. 4). No LSR change is recorded at the eastern VR site because of its proximity to Svalbard and thus more continuous influx of glacigenic sediments.

A second decrease in LSRs ca. 1 Ma is recorded regionally at all 11 Ocean Drilling Program (ODP) and IODP sites within the WSC influence with sufficient age control or stratigraphic time frame (Fig. 1; Myhre et al., 1995; Channell et al., 1999; Gruetzner et al., 2022; Lucchi et al., 2026). The decrease in LSRs at ca. 1 Ma occurred during the global MPT, a time when glacial cycles transitioned from a dominant low-amplitude 41 k.y. periodicity to a higher-amplitude 100 k.y. dominant periodicity, resulting in more intensified and prolonged glacial periods (Herbert, 2023). The decrease in bioturbation after ca. 1 Ma at the VR and SR

[1]Supplemental Material. Further information on Sites U1618, U1619, and U1620 drilling and core recoveries, age models, seismic reflectors, lithostratigraphies, and the tectonic model. Please visit https://doi.org/10.1130/GEOL.S.31931367 to access the supplemental material; contact editing@geosociety.org with any questions.

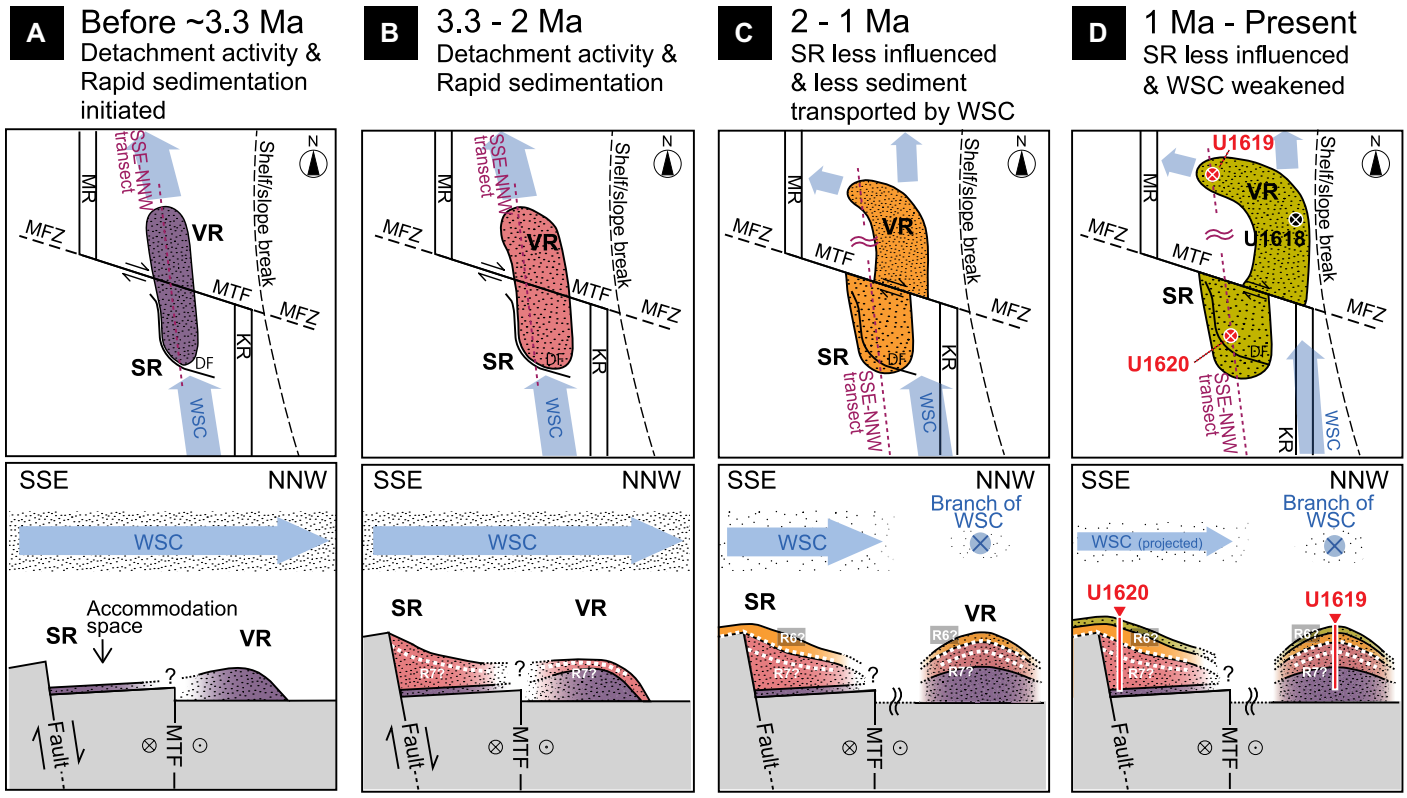

Figure 3. Tectonic influences on sedimentation at Svyatogor Ridge (SR; U1620) and Vestnesa Ridge (VR; U1618 and U1619) sediment drifts through time (A–D) in map and cross-sectional view, after Johnson et al. (2015). Detachment morphology is from Waghorn et al. (2020). Sediment colors represent their relative age. White dashed lines represent seismic reflectors R6(?) and R7(?). See Figure S1 and Table S2 for seismic profiles and reflector data (see text footnote 1). Unknown sedimentary structures were omitted by gradual degrading, denoted with question mark. MR—Molloy Ridge; KR—Knipovich Ridge; MTF—Molloy Transform Fault; MFZ—Molloy Fracture Zone; WSC—West Spitsbergen Current; DF—detachment fault. Dot clouds associated with WSC represent relative volume of sediment transport. W-to-E cross section is shown in Figure S3 (see text footnote 1).

sites may point to less favorable bottom water conditions for benthic life. Changes in ocean circulation and removal of regolith have been proposed as potential triggers for the MPT (Clark and Pollard, 1998; Williams et al., 2024). Nordic coring and climate model simulations suggest that increased Atlantic water inflow to the Arctic Ocean at this time could have accelerated ice-sheet growth by enhancing precipitation over moderately sized ice sheets (Barker et al., 2021).

Enhanced preferential erosion from more dynamic marine-based ice sheets after 1 Ma in the Barents Shelf region resulted in an intermittently open Barents Seaway when ice free (Patton et al., 2024). By ca. 0.7 Ma, this seaway was permanently in place as an additional circulation pathway at least during warm times. While long-term average LSRs are not available at a scale to resolve glacials versus interglacials, we propose that the overall decrease in LSRs after ca. 1 Ma observed at the SR, VR, and other sites along the WSC path may be the record of this change in ocean circulation. In sum, after ca. 1 Ma, the WSC weakened and no longer served as the only route for current flow and sediment transport from the North Atlantic to the Arctic (Fig. 4).

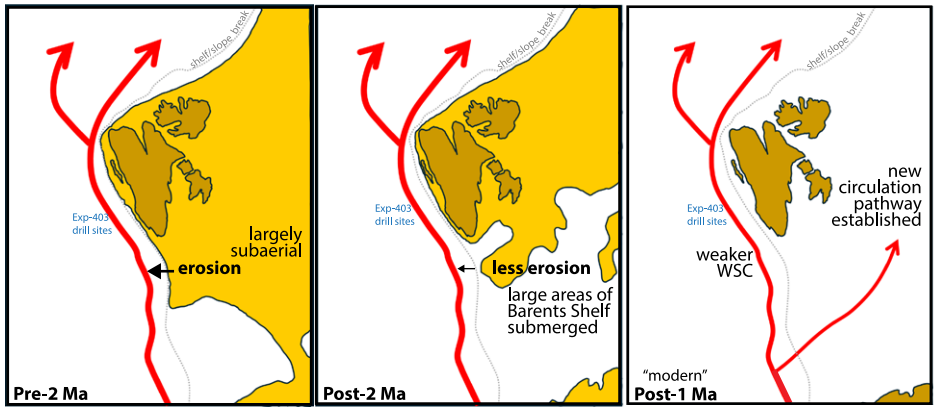

Figure 4. Impact of submergence (at ca. 2 Ma) of Barents Shelf and opening of Barents Seaway (after ca. 1 Ma) on West Spitsbergen Current sediment supply and strength. Current (red arrows), Svalbard (brown), and changing Barents Sea land areas (yellow) are shown. Changes in land area are after Patton et al. (2024).

If the decrease in LSRs at ca. 1 Ma at sites within the eastern FS reflects a weakening of the WSC, as we propose, then this is contrasts with the hypothesis (Barker et al., 2021) of increased Atlantic water inflow to the Arctic based on modeling results and drilling sites in the North Atlantic and Nordic Sea (south of 70°N), and to increased LSRs in the Norwegian Current at this time (Wolf and Thiede, 1991). Reconciliation of these findings with the drilling records from the WSC region is needed. It may be that such reconciliation can be achieved by considering the combined inflow to the Arctic by both the WSC and the Barents Seaway during the MPT.

CONCLUSIONS

Shipboard age models and derived LSRs from IODP Exp403 provide ground-truth data

with which to evaluate previous hypotheses of sediment supply, ice-sheet dynamics, and depocenter evolution at the VR and SR since ca. 3 Ma. Results suggest that the first-order controls on sedimentation rates were a combination of (1) local tectonic-related bathymetric influences on the depocenters, and (2) climate-related regional "up-current" geomorphic influences on erosion rates and paleocurrent patterns affecting sediment supply.

ACKNOWLEDGMENTS

Special thanks go to the International Ocean Discovery Program Expedition 403 (Exp403) project proponents, technicians, and crew. We are grateful for the feedback from P.T. Osmundsen and an anonymous reviewer. Funding for Exp403 and the *JOIDES Resolution* Science Operator (JRSO) was provided via National Science Foundation award OCE1326927. We acknowledge open access funding from MUR for ECORD-IODP Italia and the Geology and Environmental Science Department at James Madison University.

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Printed in the USA