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REMOTELY OPERATED VEHICLE DIVE ON THE VERRILL STEPS, OFFSHORE NOVA SCOTIA

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Context

In 2019, the National Oceanic and Atmospheric Administration (NOAA) and partners conducted an ocean exploration expedition (EX1905L2) onboard the research vessel *Okeanos Explorer* along the Canadian Atlantic continental margin where they collected video footage and various samples using the Deep Discoverer underwater Remotely Operated Vehicle (ROV) (NOAA, 2019) (Fig. 1). One of the ROV dives took place inside Verrill Canyon, offshore Nova Scotia (Fig. 2). This dive aimed to explore the geological setting of step-like features which are believed to have been sculpted by turbidity currents. The ROV surveyed one of the « Verrill Steps » revealing for the first time high resolution images of its geomorphology.

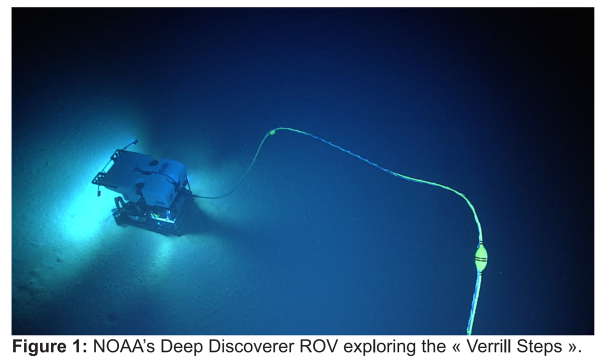

Figure 1: NOAA's Deep Discoverer ROV exploring the « Verrill Steps ».

The results of the dive on the « Verrill Steps » allows us to link theoretical knowledge of turbidity current bedforms to visual observation on the modern deep sea floor. High-resolution images allowed for the construction of a 3D image of a step and for the description of each component of a turbidity current bedform.

Study Area

The dive site is located in Verrill Canyon approximately 245 km off the south shore of Nova Scotia at depths that range between 2400 and 2500 m (Fig. 2 and 3). The Scotian Slope is incised by submarine canyons that were excavated over the past million years as continental glaciation lowered sea-level and the shelf was emergent. Sediment-rich glacial meltwater were discharged near the shelf break and turbidity currents flowed down the slope incising canyons. Further development of the canyons continued through failure of their walls due to oversteepening (Campbell et al. 2008).

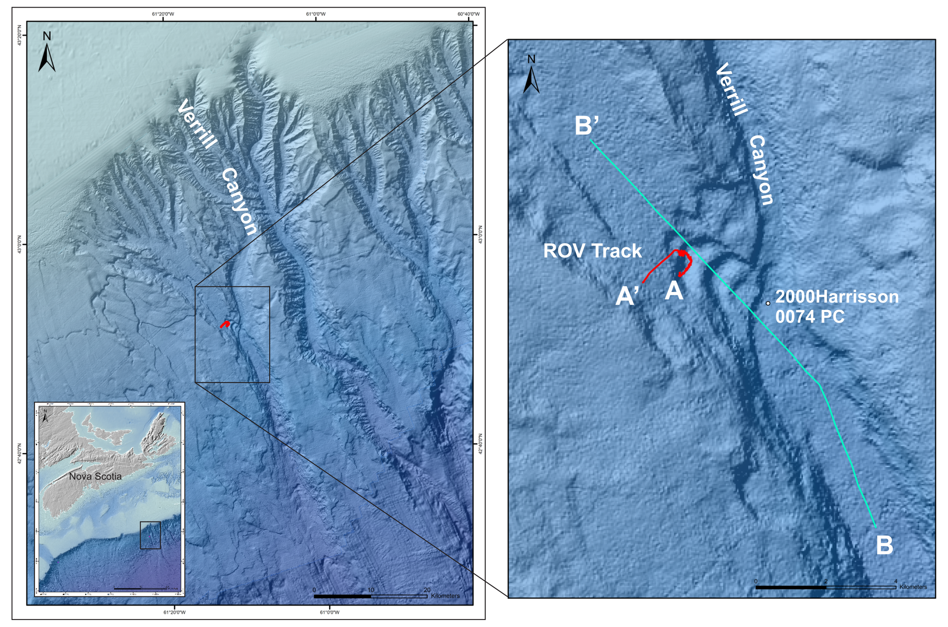

Figure 2. Location of NOAA's ROV dive (EX1905L2-Dive02) in the Verrill Canyon, on the Scotian Slope.

Cyclic Steps

Cyclic steps are upstream migrating long wavelength bedforms often found in submarine canyons and channels. In these settings, they are formed by supercritical turbidity currents (Froude number (Fr) > 1) flowing downslope. Cyclic steps can be divided into three different components based on their morphological characteristics and the hydrological properties of the overidding flow : **1- stoss side; 2 - lee side; 3 - trough** (Fig. 4).

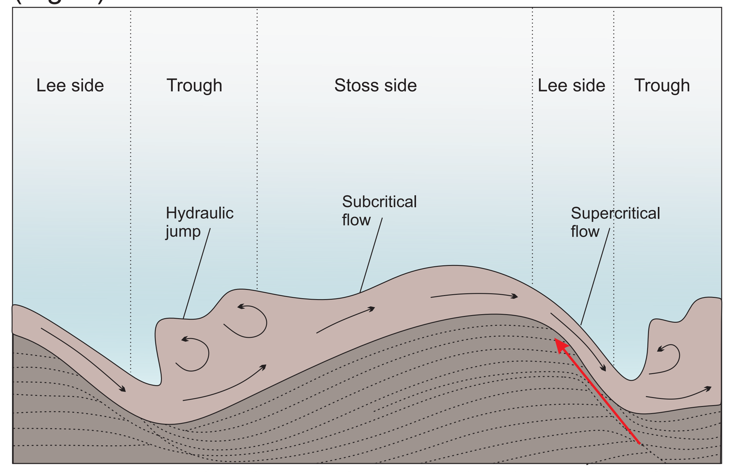

Figure 4. Morphology of a cyclic step bedform and hydrological characteristics of the overiding turbidity current. The red arrow shows the upstream migration of the step.

On the **stoss side** of the bedform, which corresponds to a low gradient negative slope, the overriding turbidity current is relatively thick and slow moving. It is characterised by a subcritical flow (Fr < 1) which leads predominantly to the deposition of finer grained sediment.

On the **lee side**, the slope increases which causes acceleration of the turbidity current and a decrease in flow thickness. The flow therefore becomes supercritical (Fr > 1) which leads predominantly to the erosion of the seabed. The erosion and deposition occuring respectively on the lee and stoss sides is responsible for the overall upstream migration of the bedform.

The **trough** corrponds to the depression formed by a sudden gradient change between the lee side and the stoss side. As the supercritical turbidity current encounters a drastic slope change, the flow is forced to decelerate and a hydraulic jump is formed leading to the deposition of coarse heterogenous sediment. Following the hydraulic jump, the turbidity currents reaccelerates on the stoss side.

Verrill Steps

The step-like features observed in Verrill Canyon have a similar morphological appearance to well-documented cyclic steps found on the eastern Scotian Slope (Normandeau et al., 2019). They appear to migrate upslope (Fig. 5) and they present the characteristic crescentic shape observed in many other settings (Symons et al., 2016). The crescentic shape is believed to be caused by the interaction of the bedform with the canyon wall. As the turbidity currents flow into a confined canyon, the velocity is greater in the center of the canyon leading to increased upslope migration compared to the side of the bedform where the velocity is slowed down by the friction with the walls.

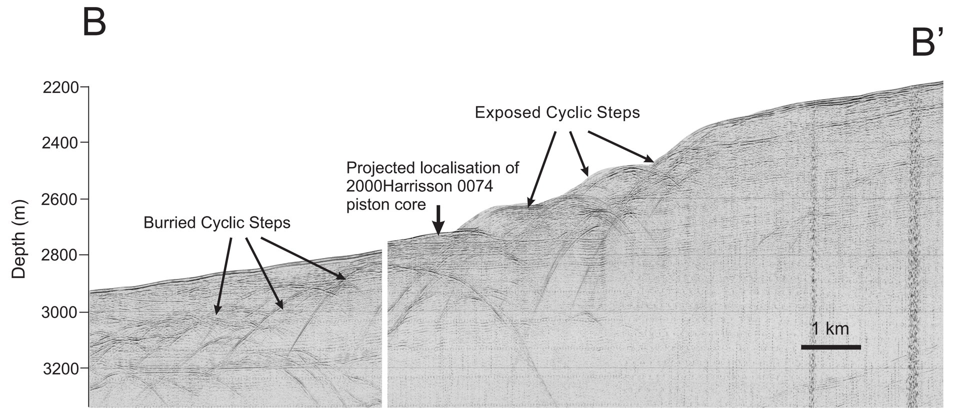

Figure 5. Sleevegun seismic profile of the Verrill steps, illustrating burried and exposed turbidity current bedforms interpreted as cyclic steps.

A sleevegun seismic profile collected across the Verrill Steps shows that downslope the steps have been burried by mass transport deposits (Fig. 5). However, exposed steps upslope create an opportunity to study and observe the seabed expression of cyclic steps using the ROV. The ROV followed the path from the stoss side up to the lee side (Fig. 6).

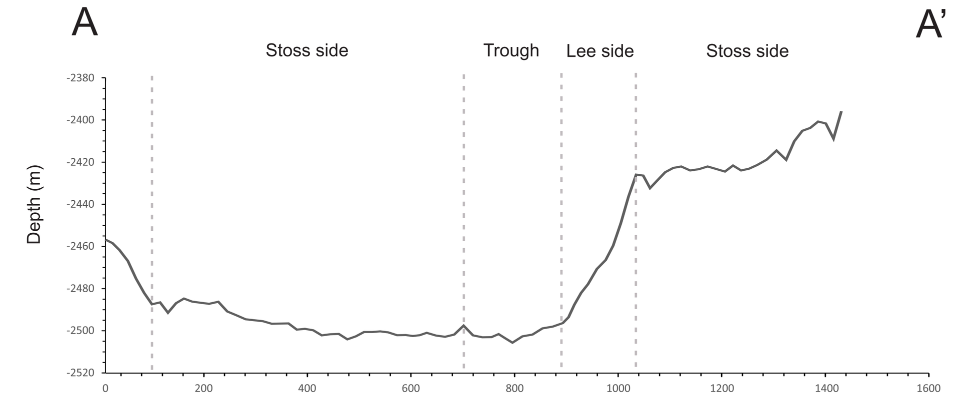

Figure 6. Profile of the ROV dive based on hull-mount mulitbeam bathymetry.

Based on a carbon-14 age of a shell found in a core on the canyon floor, at the base of the steps, the last turbidity current to have affected the area occured at about 11.4 cal ka BP (Fig. 7). This age is an estimate based on a sedimentation rate of 0.01 cm/yr observed on the eastern Scotian Slope during the Holocene (Normandeau and Campbell, 2020). However, the fine-grained turbidites observed in the core might not have been responsible for the migration of the cyclic steps as many types of turbidity currents coexist and they do not all lead to the migration of cyclic steps. Therefore, the age of 11.4 cal ka BP corresponds to the latest turbidity current activity inside the canyon, before hemipelagic sedimentation became the dominant process.

ROV imagery results

Stoss Side

Geology: The stoss side consists of fine-grained mud with few pebbles and cobbles. The stoss side is likely draped by Holocene mud with no to little outcropping cobbles or boulders.

Topography: Flat to slightly undulating.

Flow dynamic: Thick and relatively slow-moving subcritical flow depositing fine sand and mud.

ROV images: The ROV imagery corroborates the theoretical knowledge of the stoss side caracteristics. As it surveys the stoss side of the step, the ROV navigates above a relatively smooth surface (Fig. 8) with a muddy appearance which is likely due to hemipelagic sedimentation during the Holocene, after the last activity of the turbidity currents.

Figure 8. ROV imagery of the stoss side of one of the « Verrill Steps ».

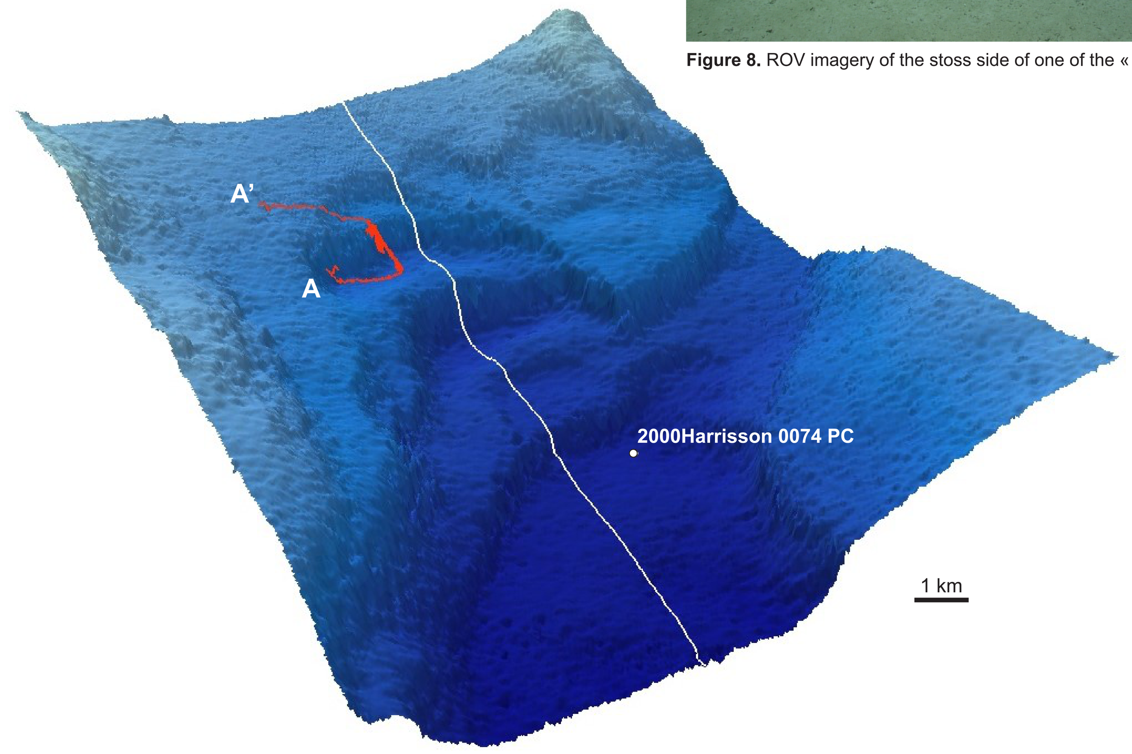

Figure 3. A 3D view of NOAA's dive track (red) navigation up one of the « Verrill Steps ». The white line shows the location of the sleevegun seismic profiles collected across the steps and presented in Figure 5.

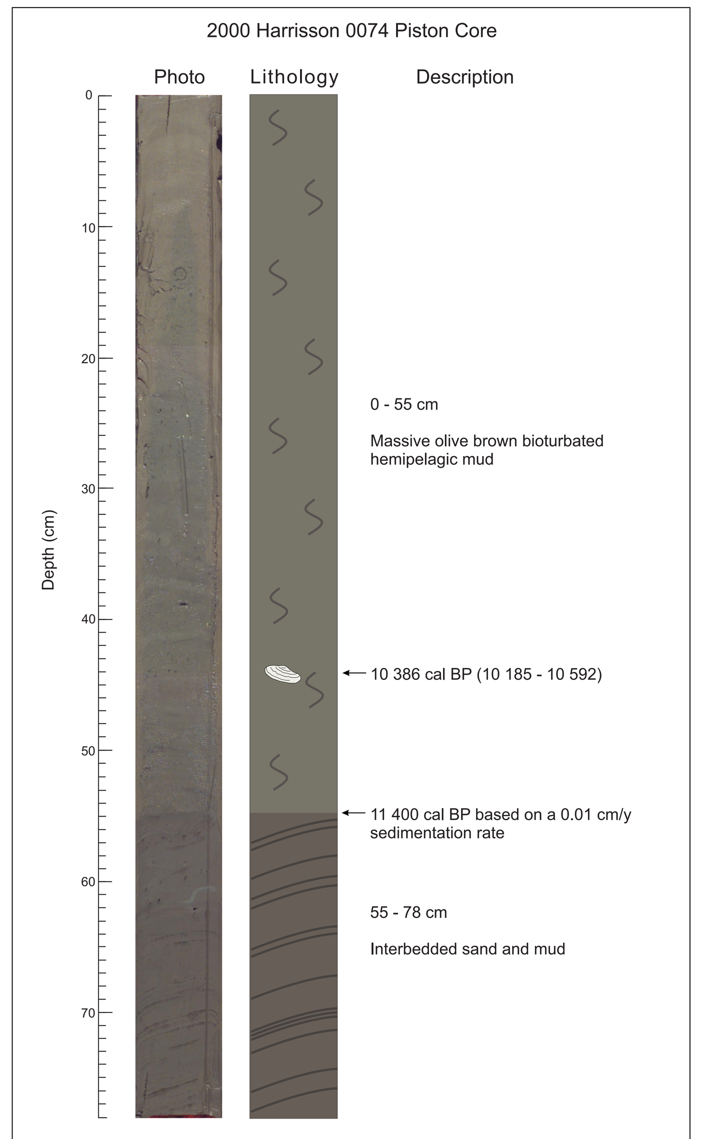

Figure 7 : Description of the 2000 Harrisson 0074 piston core.

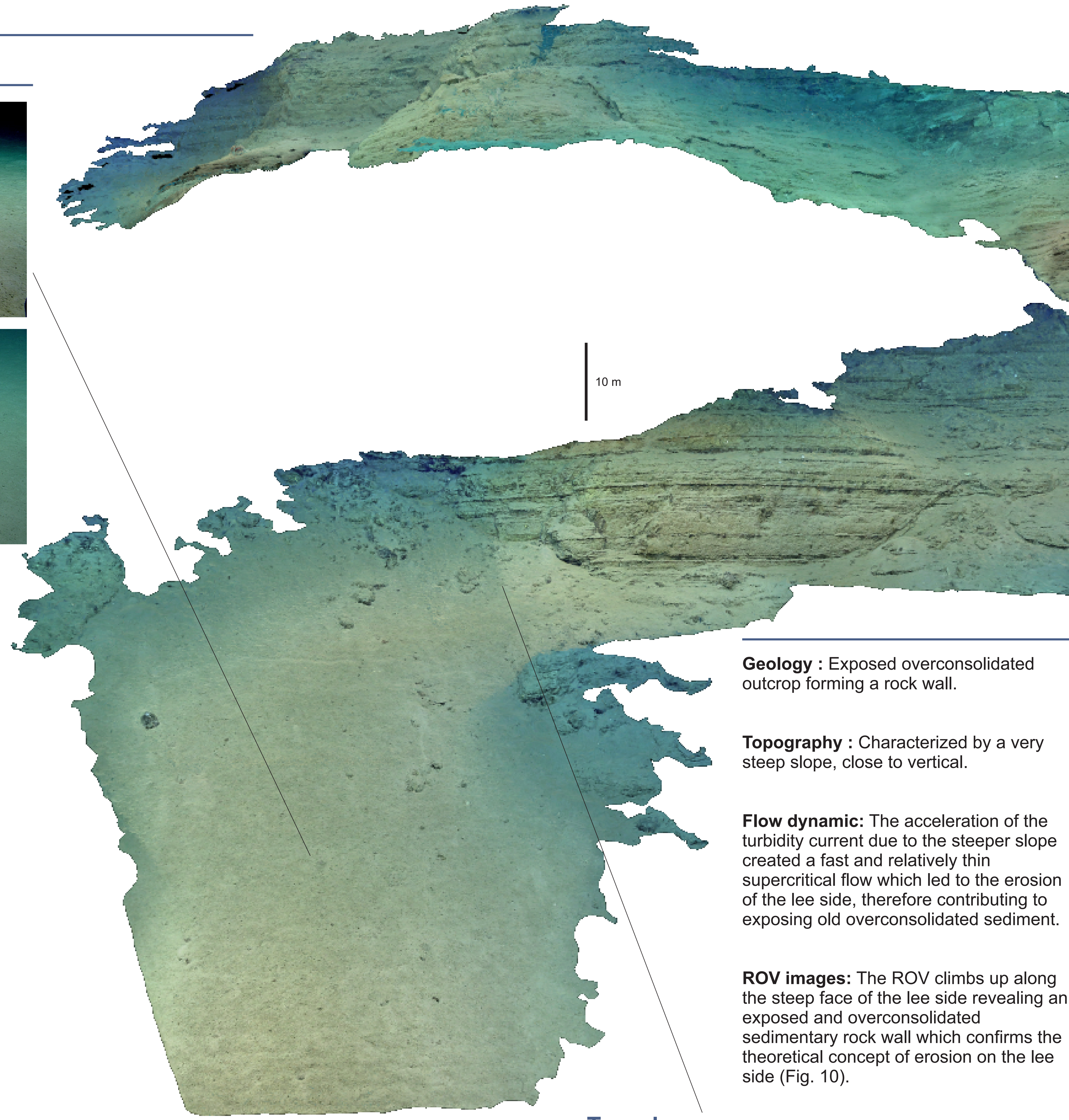

Figure 9. 3D perspective view of the dive produced by structure-for-motion from ROV video.

Lee Side

Geology : Exposed overconsolidated outcrop forming a rock wall.

Topography : Characterized by a very steep slope, close to vertical.

Flow dynamic: The acceleration of the turbidity current due to the steeper slope created a fast and relatively thin supercritical flow which led to the erosion of the lee side, therefore contributing to exposing old overconsolidated sediment.

ROV images: The ROV climbs up along the steep face of the lee side revealing an exposed and overconsolidated sedimentary rock wall which confirms the theoretical concept of erosion on the lee side (Fig. 10).

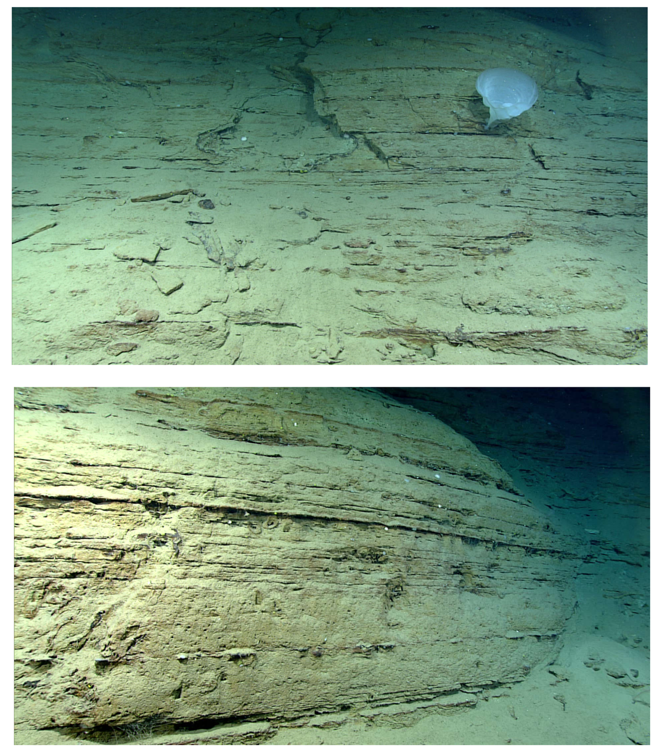

Figure 10. ROV imagery of the lee side of one of the « Verrill Steps ».

Trough

Geology: Heterogeneous material, conglomerate, boulders, cobbles, and debris mantled in fine grained sediment.

Topography: Characterized by a depression-like topography with a hummocky surface located between the stoss and lee sides.

Flow dynamic: Hydraulic jump leads to deposition of heterogenous sediments eroded from the lee side that spans from mud to pebbles.

ROV images: As the ROV approaches the steep face of the steps, the surface of the seabed becomes more hummocky due to the presence of heterogeneous material (Fig. 11).The ROV imagery supports the theory of cyclic steps and shows the presence of pebbles and fragmented rocks typical of hydraulic jump deposits consisting of coarser material.

Figure 11. ROV imagery of the trough of one of the « Verrill Steps ».

Human impact

Along the dive, the ROV captured images of various human generated debris at different points on the seabed. The debris were all observed on the stoss side. Anthropogenic pollution occured long after the last activity of turbidity currents so the hypothesis of turbidity currents transporting debris downslope is exlcuded in this particular case. It is presumed that the debris have simply sunken to the lowest point of the seabed in this area and deposited where the flow dynamic is slow moving and sedimentation is favoured.

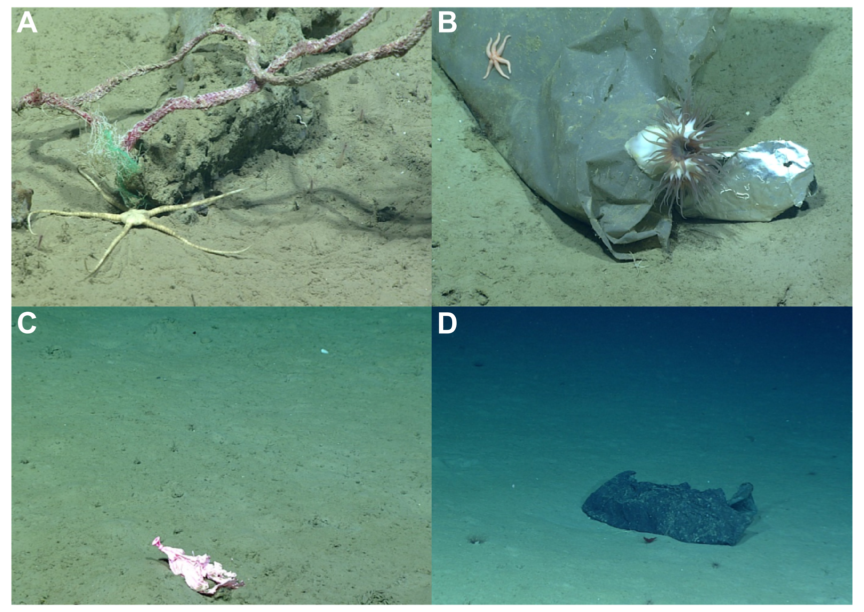

Figure 12. Various debris observed on ROV imagery during the dive EX1905L2-Dive02 ;

A. A piece of synthetic line
B. A plastic bag
C. A ballon
D. A degraded item.

Acknowledgements

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