National Transportation Safety Board
Office of Research and Engineering
Washington, DC 20594

DCA23FM036

MATERIALS LABORATORY

Factual Report 24-012

July 5, 2024

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A. ACCIDENT INFORMATION

Location: Atlantic Ocean
Date: June 18, 2023
Vehicle: OceanGate Experimental Submersible Titan
Investigator: Marcel Muise, MS-10

B. COMPONENTS EXAMINED

Videos of the Titan wreckage recorded by remote operated vehicles.
Acoustic emission and strain data from previous dives.

C. EXAMINATION PARTICIPANTS

Specialist Donald Kramer, Ph.D.
National Transportation Safety Board
Washington, DC

D. DETAILS OF THE EXAMINATION

Recorded videos from two missions to the Titan accident site were reviewed to examine and characterize the damage to the pressure vessel post mishap. The first mission was a search and rescue mission that spanned from June 22, 2023 to June 26, 2023. The second mission was a salvage mission that spanned from September 27, 2023 to September 29, 2023. Video frames with notable views of the wreckage were extracted using VLC Media Player software. Data collected by Titan's real time monitoring system for dives leading up to the accident were also examined. For information on the fabrication process and material characterization of the hull, see Materials Laboratory Factual Report 24-011.

1.0 Recorded wreckage review

Figure 1 shows the Titan main wreckage as discovered on the ocean floor. The aft dome, aft segment, aft portions of the hull, and rails were located together in a comingled mass. The forward dome was located by itself (figures 1 and 2). The forward segment and tail section were also located by themselves (figures 3 and 4, respectively). Other hull fragments, likely from the middle or forward portion of the hull were scattered about the ocean floor. Four views of the main wreckage from port side, bottom side, starboard side, and top side are shown in figures 5 – 8, respectively. A view from the forward end / top side is shown in figure 9. A nearly full-length segment of the hull was located near the top of the vessel (possibly offset toward the port side). There were few, if any, full thickness hull pieces. All of the visible hull pieces had delaminated, and multiple pieces had green surfaces, consistent with separation within or adjacent to the co-bonded adhesive layers. Many adhesive surfaces exhibited light/dark color patterns like that documented in

Materials Laboratory Factual Report 24-011. The aft segment was still attached to the aft dome by two flange bolts on the port side while a gap had opened between the segment and the dome on the starboard side.

Several notable hull pieces were identified and given labels: 'A', 'B', etc. The pieces all contained delaminations within or adjacent to the co-bonded adhesive interfaces and so pieces were also identified by layer. The nearly full-length piece from the top of the hull was labelled 'A'. A piece viewable from the port side of the wreckage, indicated in figure 5, was labelled 'B'. A piece viewable from the starboard / bottom sides was labelled 'C' as indicated in figures 6, 10 and 11. Finally, a piece that was hidden from view until the aft segment was separated from the aft dome was labelled 'D', as indicated in figure 11.

1.1 Piece 'A'

Piece 'A' spanned nearly the full length of the hull (Layers 4 and 5 from 'A' were recovered from the ocean floor and later examined at the U.S. Coast Guard facility in Newport, RI. That piece was 97 inch long). As found, 'A' was located near the top of the hull, possibly offset toward the port side. Several of the layers at the forward end had a machined appearance and bits of attached adhesive were observed. Images of 'A' during the second salvage mission are shown in figures 13 – 16. 'A' had delaminated into three layered pieces. The outer piece consisted of layers 4 and 5. The inner piece consisted solely of layer 1. The middle piece consisted of layers 2 and 3. As seen in figure 14, there was an additional delamination at the forward end between layers 2 and 3 and a fragment of layer 2 had separated from the rest of the piece. It could not be determined how far along the interface the layer 2/3 delamination extended. The outer surface of 'A' – layer 1 was green, consistent with separation within the adhesive layer. The layer 4 and 5 sub-piece examined at the U.S. Coast Guard facility had separated from the top of layer 3 adjacent to the layer 3/4 interface, primarily within the carbon fiber laminate.

1.2 Piece 'B'

As found, piece 'B' was located on the port side of the wreckage (figure 5). Images of 'B' are shown in figures 13 and 15 – 21. The dimensions of the piece could not be precisely established but based on the size of 'A' it was likely between 60 inch and 72 inch long (between 5 and 6 feet), over half the length of the hull (full length is 100 inch). The aft end of the piece is labelled in figure 15. As with 'A', the piece had delaminated into multiple layers: layer 1, layers 2/3, and layers 4/5. The delamination at the layer 1/2 interface resided within the adhesive as did much of the delamination at the layer 3/4 interface.

The outermost piece (layers 4/5) was fractured and cracked in additional locations. Part of its forward end was missing, allowing line-of-sight visibility of the adhesive on top of layer 3. When the layer 4/5 piece was lifted and set aside by robotic arm (see figure 18), the underside exhibited multiple longitudinal cracks. The adhesive surface also exhibited a light/dark pattern, like that documented in Materials Laboratory Factual Report 24-011. Features consistent with voids were present on the surface of layer 1, but due to the layup sequence at the layer 3/4 interface, it could not be determined if some features at that interface were voids or longitudinal fiber fragments. The longitudinal through-thickness fracture on the clockwise (CW) edge of the piece appeared relatively straight, whereas the through-thickness fracture on the counterclockwise (CCW) edge was irregular (see figure 20).

1.3 Piece 'C'

Piece 'C' was found between the bottom and starboard sides of the wreckage (figure 6). Additional images of 'C' are shown in figures 10 – 12. Its dimensions could not be determined. As with 'A', the piece had delaminated into multiple layers: layer 1, layers 2/3, and layers 4/5. The layer 3/4 interface had a dark appearance with occasional patches of green, consistent with separation near the 3/4 interface but predominantly through the carbon fiber composite.

1.4 Piece 'D'

Piece 'D' was not originally visible from outside of the wreckage. The aft end of the piece was revealed after the segment was separated from the aft dome (figure 11). 'D' appeared to have been sandwiched between 'B' and 'C'. Additional photos are shown in figures 22 and 23. 'D' was a partial piece. Layer 1 was missing (the inner surface of the hull was painted white and no painted surface was seen). Along the CW side, the piece was delaminated through the adhesive. 'D' exhibited a sigmoidal buckle as indicated by the yellow dashed line in figure 22, with an inward bend and an adjacent outward bend. Between the bends, the separation within the adhesive layer transitioned into the adjoining composite material.

1.5 Rails

The top, port, and starboard rails were bent and/or fractured. The top rail, shown in figure 8 contained sigmoidal buckles at the forward and aft ends. The port and starboard rails are shown in figure 24. The ends of the rails were fractured and the forward end of the starboard rail was bent. The starboard rail was also bent mid-span. The port rail exhibited a counterclockwise twist.

2.0 Operational events

2.1 Acoustic emission system functionality

The Titan real-time monitoring system consisted of eight acoustic emission sensors and eight strain gage clusters distributed across the vessel. Acoustic sensors and strain gages were assigned channel numbers 1 through 8, but sensors and gages were not always placed in the same location. Table 1 shows the location of each numbered sensor and strain gage cluster.

Table 1. Location of each numbered acoustic sensor or strain gage cluster. Clockwise (CW) and counterclockwise (CCW) are designated as if standing aft of the vessel looking forward.

Location	Acoustic sensor number	Strain gage cluster number
Forward titanium dome	–	1
Forward titanium dome	–	2
Composite hull – 3.75 inch from FWD segment - 110° CW from top	1	3
Composite hull – 3.75 inch from FWD segment - 110° CCW from top	2	4
Composite hull – mid span - 110° CW from top	3	–
Composite hull – mid span - 0° (top dead center)	4	5
Composite hull – mid span - 110° CCW from top	5	–
Aft titanium segment - 110° CW from top	6	6
Composite hull – 3.75 inch from AFT segment - 0° (top dead center)	7	7
Composite hull – 3.75 inch from AFT segment - 110° CCW from top	8	8

OceanGate staff produced time-based plots of acoustic activity and strain gage output for each dive. Complete dives, correlated with the vessel's ocean depth, were available for dives 75, 76, and 79 – 83. Dive 75 took place on July 3, 2022.[1] Dive 83 took place on July 23, 2022, but at a different dive location and to a depth of only 2,954 m. The other dives all descended to approximately 3,840 m. Three of the eight sensors did not register acoustic events for any of the 2022 dives. Typical outputs for an active and inactive sensor are shown in figures 25a and b, respectively. Figure 25a shows acoustic events captured by channel 2. Figures 25b shows that no analogous

[1] Partial dive data was available for dives that took place in 2021. The data did not include the vessel's depth and the portion of the dive while at the ocean floor was not included.

events were captured by channel 1. Channels 1, 3, and 5 did not capture any apparent acoustic events for the 2022 dives.[2]

2.2 Change in strain response of composite hull

On July 15, 2022, the Titan dove to the Titanic, reaching a depth of 3,840 m (Dive 80). Shortly after surfacing, an audible "loud bang" was heard, according to the dive log. Acoustic emission and strain data, collected by the real-time monitoring system, were processed by OceanGate personnel after the dive, which was their typical procedure. Plots for acoustic activity and strain as a function of time for Dive 80, prepared by OceanGate, are shown for acoustic emission channel 7 and strain gage group 7 in figures 26a and b, respectively. The strain plots in figure 26b include hoop strain (R) and longitudinal strain (A). While at maximum depth, there was time-dependent reduction in hoop and longitudinal strain gage output.[3] When the vessel returned to the surface, the strain gage voltage outputs were lower than they were at the start of the dive. There was a burst of acoustic activity shortly after surfacing, between approximately 15:15 and 15:30 (Newfoundland Daylight Time). Plots for acoustic channel 2 and strain gage group 4 are shown in figures 26c and d. Channel 2 shows additional acoustic activity compared to channel 7 after the vessel surfaced. In addition, between 15:15 and 15:30 there was an abrupt increase in hoop strain (R) readout and reduction in longitudinal strain (A) readout. The acoustic signal and the strain gage outputs are shown together in figure 27, plotted in UTC. The large amplitude acoustic event coincided with the change in hoop and longitudinal strain gage output.

Changes were observed in the initial strain response of the hull following Dive 80. Figure 28 shows the variation in hoop strain gage output with ocean depth for group 4 on Dive 80 (prior to the audible event, which occurred after surfacing). For visualization purposes, strain gage output is plotted on the abscissa (horizontal axis) and ocean depth is plotted on the ordinate (vertical axis). Because of the strain reduction at depth, the ascent curve is at a lower strain value than the descent curve. Both descending and ascending curves appeared to be linear. A comparison with Dive 75 is shown in figure 29. Both dives showed the same linear response (as did Dives 76 and 79, which are not shown). Figure 30 shows a comparison with Dive 81, the first dive after the audible event. The strain response at low depth was non-linear after the event. The same non-linear response was observed for Dives 82 and 83. Figure 31 shows the strain/depth plots for Dives 75 and 80 – 83, focused on 0 m to 1000 m of ocean depth. Dives 81 – 83 all showed the same non-linear response between approximately 0 m and 500 m ocean depth. To illustrate the change in initial strain response, the slope of the depth/strain plots was calculated using a linear least squares fit to dive data between 15 m and 150 m of ocean depth. The slopes for

[22] For the dives in 2021, channel 5 recorded occasional high-amplitude events, not recorded by channels 1 or 3, that could have been acoustic events.
[3] A similar response was observed for other dives as well and may be a measurement artifact.

Dives 75 and 80, prior to the event, were 5.00 m/mV and 4.74 m/mV, respectively. After the event, the slopes for Dives 81, 82, and 83 were 8.76 m/mV, 8.09 m/mV, and 8.77 m/mV, respectively.

Changes in strain response were observed for other strain gages as well. Figure 32 shows the low-depth hull response for the group 4 longitudinal-oriented strain gage. After the audible event, the initial slop of the curve decreased. Figure 33 shows a discontinuity in the group 5 hoop-oriented strain gage during the ascent phase of the dive. There was an approximately 6 minute and 27 second gap in the recorded data between 2389.7 m and 2242.5 m ocean depth. When the gage readout resumed, the data had shifted to a lower gage output voltage and there was an initial change in the slope of the ascent curve (During the same event, the group 6 longitudinal gage stopped recording data and never resumed).[4] Group 5 hoop and longitudinal gage plots for the first and last 1000 m are shown in figures 34 and 35, respectively. There was a visible change in the longitudinal strain response below approximately 800 m, but no affirmative change in the hoop strain response. Gage group 8 hoop and longitudinal plots for the first and last 1000 m are shown in figures 36 and 37, respectively. There was a change in the hoop strain response below approximately 400 m. Groups 3 and 7 (the other two gage groups on the composite hull) did not show a significant change in strain response before or after Dive 80. For example, see the group 3 hoop strain response in figure 38. Additional strain response curves for the Ti dome and segment are included in Appendix A.

The amplitude of acoustic activity marginally increased for channel 2 during the descent phase of Dive 81 compared to Dive 80 (figures 39a and b). Four acoustic events during the descent qualified as a "hit". None of the other channels registered hits during this phase of the dive. The acoustic activity for channel 2 generally decreased for Dives 82 and 83 relative to Dive 81 (figures 39c and d), except for one notable hit registered during the descent phase of Dive 81.

2.3 2022/2023 stowing and 2023 towing

After the 2022 expedition, the submersible was initially stowed at an outdoor location in St. John's, Newfoundland and was moved indoors in the late 2023 winter/early 2023 spring. See the Operations Group Factual Report for additional details.

During the 2021 and 2022 expeditions, the Titan and its launch and recovery system (LARS) were transported to the dive site on the deck of a support ship. For the 2023 expedition, the Titan and LARS were towed behind a different support ship. The Titan and LARS experienced multiple tipping/upset events during the 2023 expedition leading up to the first attempted dive. Images of three known events are

[4] The group 5 hoop gage showed drift in gage output from dive to dive. See Appendix A for details. None of the other gages attached to the composite hull showed similar drift from dive to dive.

shown in figures 40a – c. The first image shows the vessel after recovery from a known mishap. The bow of the LARS had tipped downward, causing damage to the tail cone (figure 40a). The vessels underwent unspecified inspections and repairs. Two additional tipping events are shown in figures 40b and c.

Submitted by:

Donald Kramer, Ph.D.
Sr. Materials Engineer

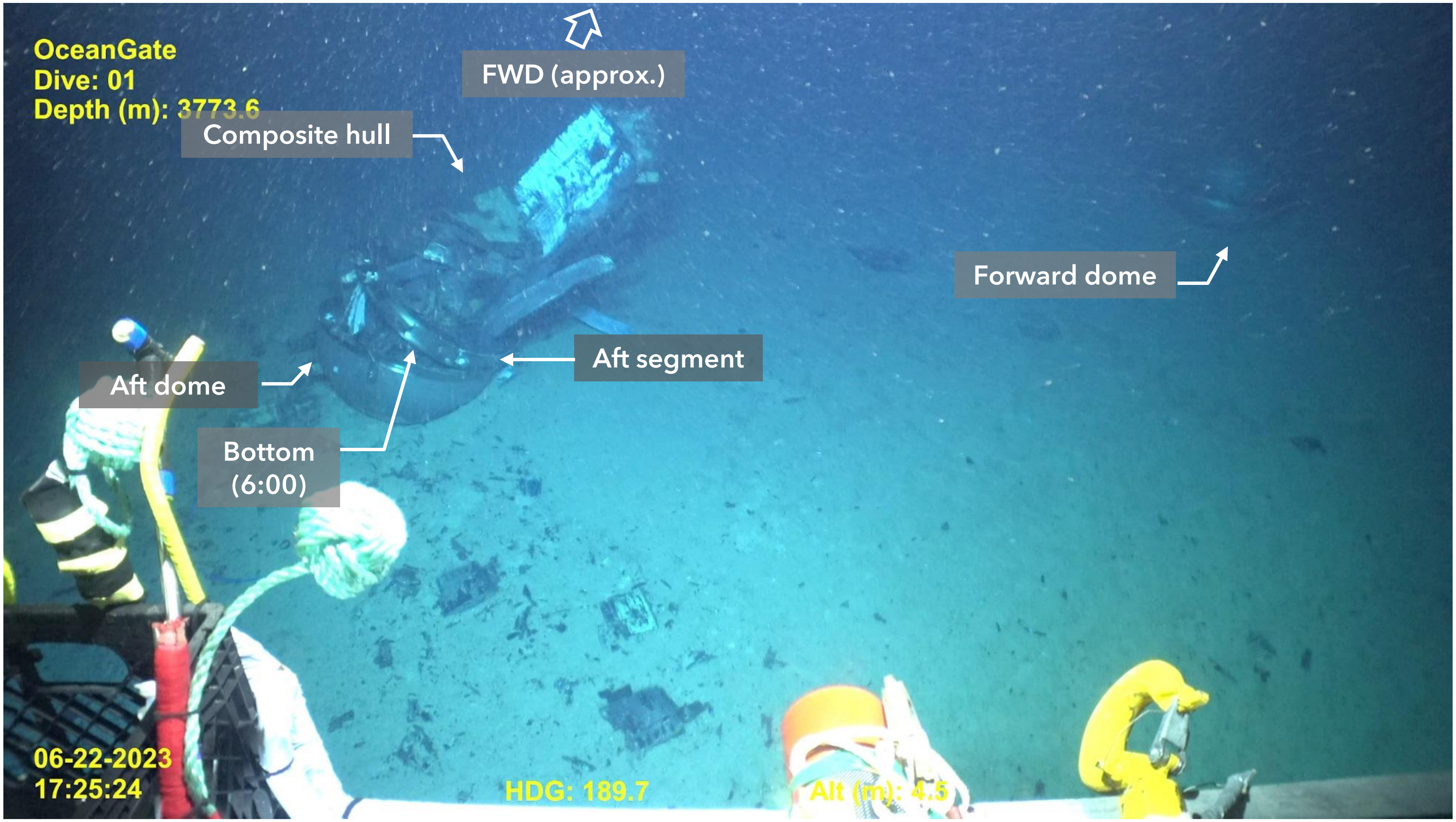


Figure 1. Titan main wreckage as discovered on the ocean floor.

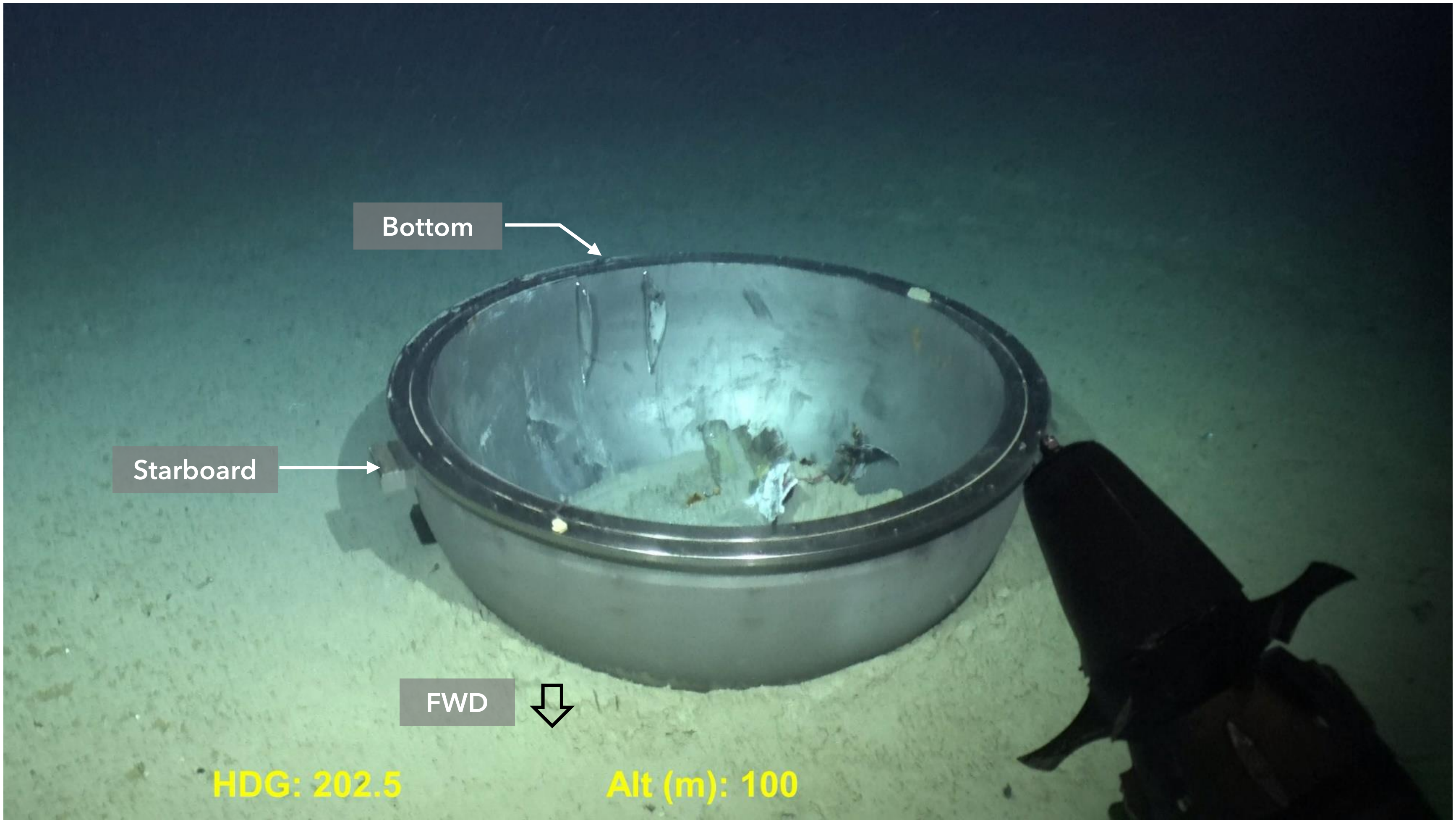


Figure 2. Forward dome, discovered with forward end down.

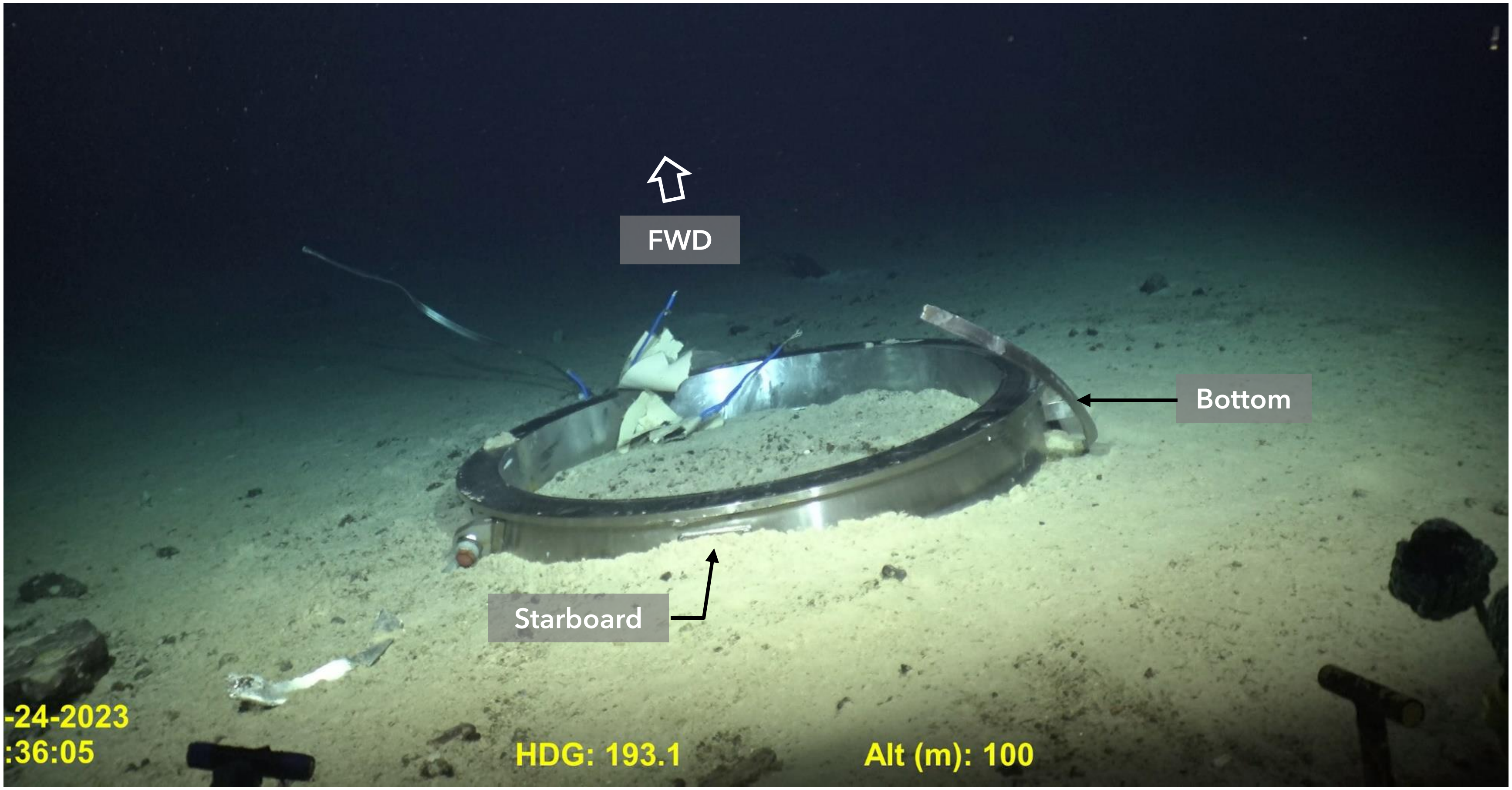


Figure 3. Forward segment, discovered with forward end up.

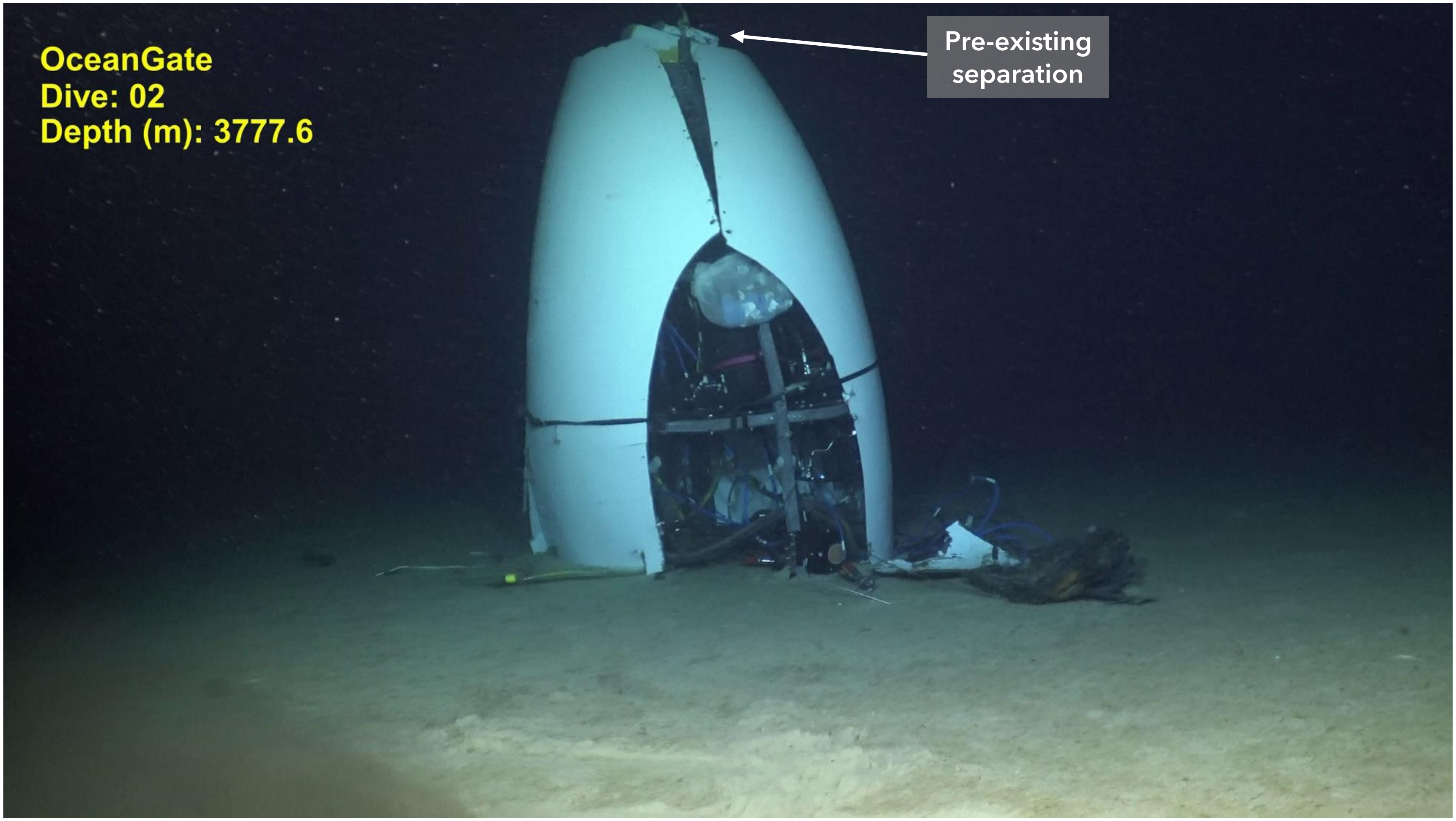


Figure 4. Tail section, originally attached to the aft end of the hull, as discovered. Note: The aftmost portion of the tail section separated prior to the dive.

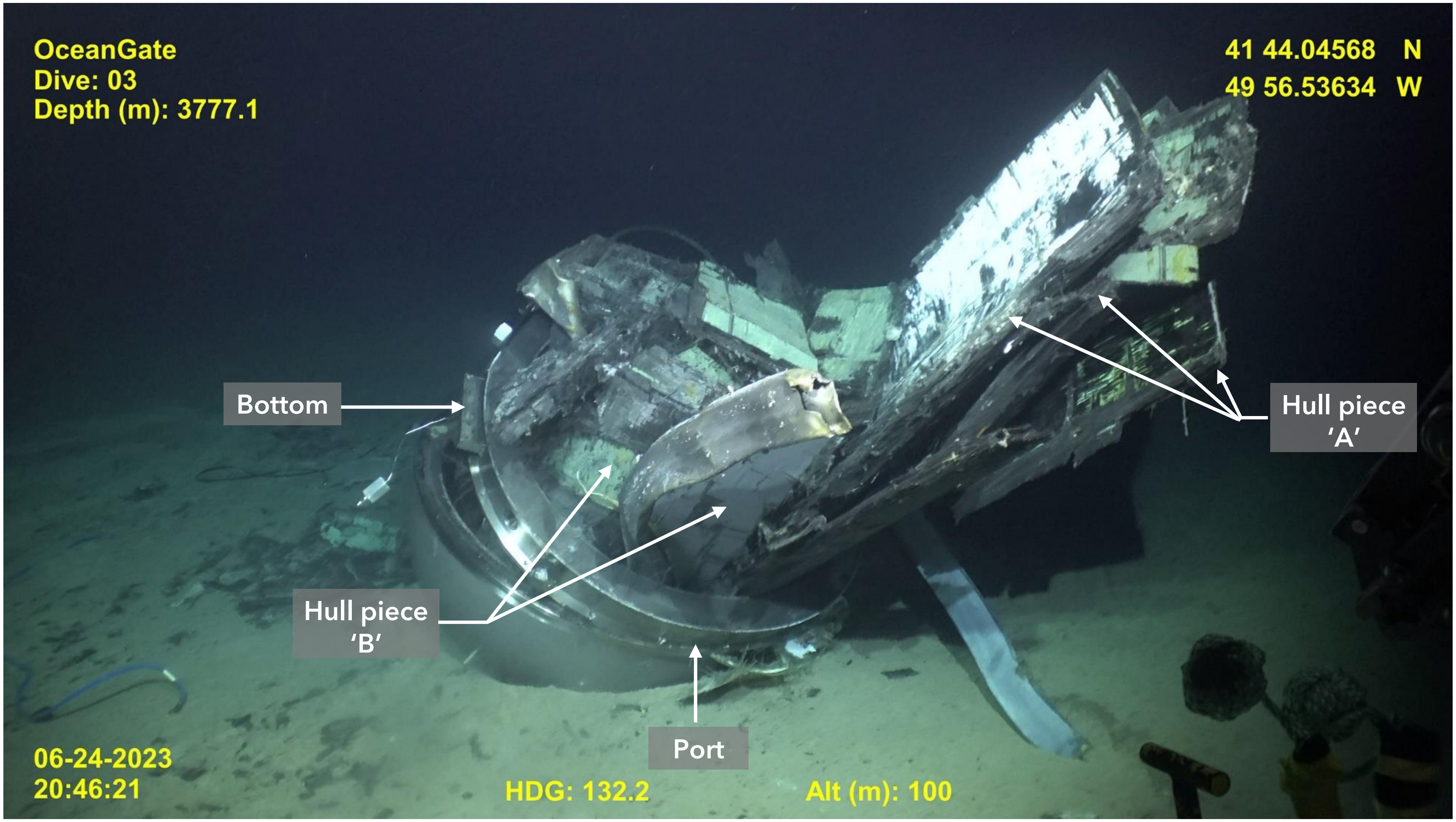


Figure 5. Main wreckage viewed port side.

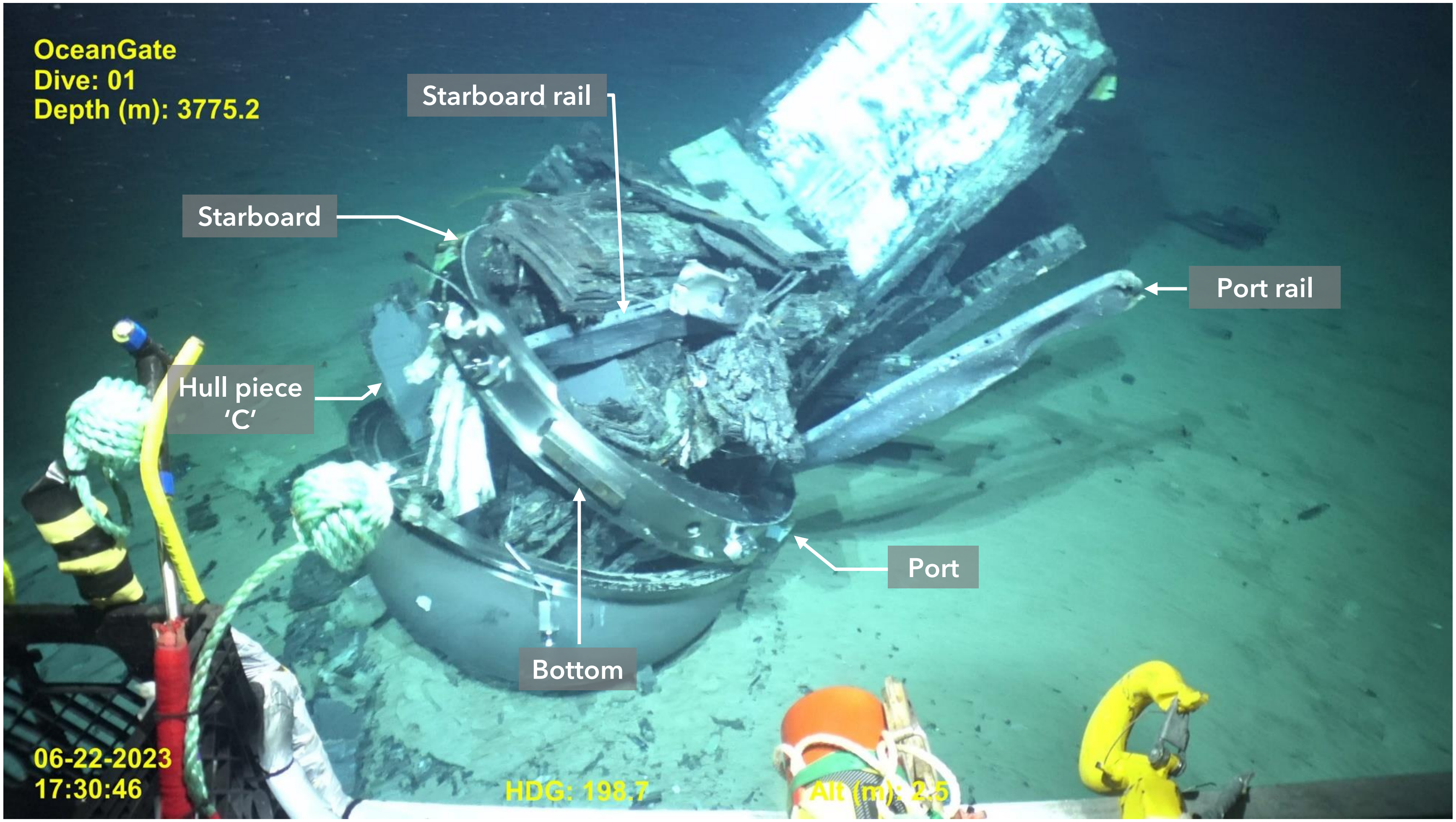


Figure 6. Main wreckage viewed from bottom side.

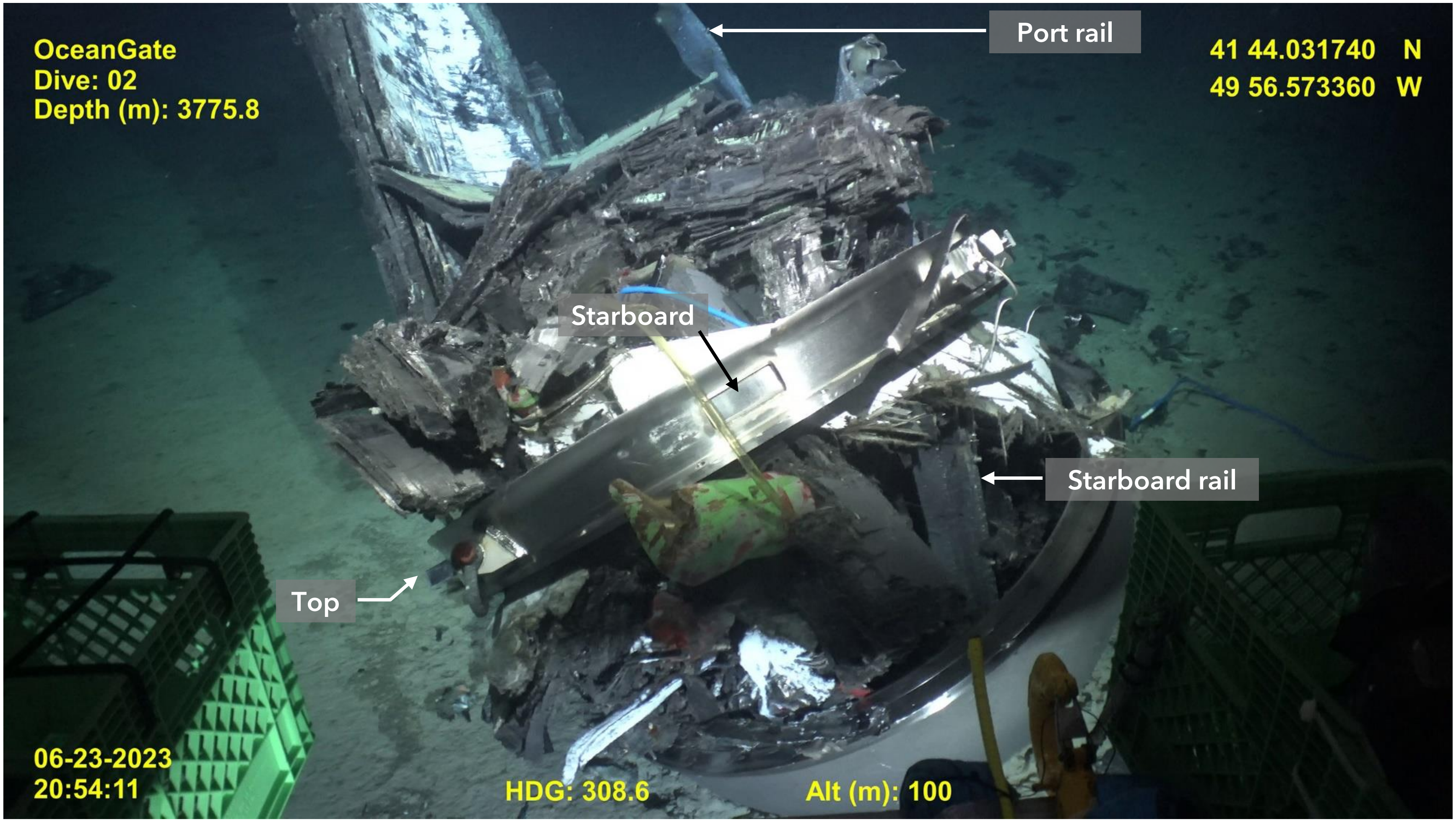


Figure 7. Main wreckage viewed starboard side.

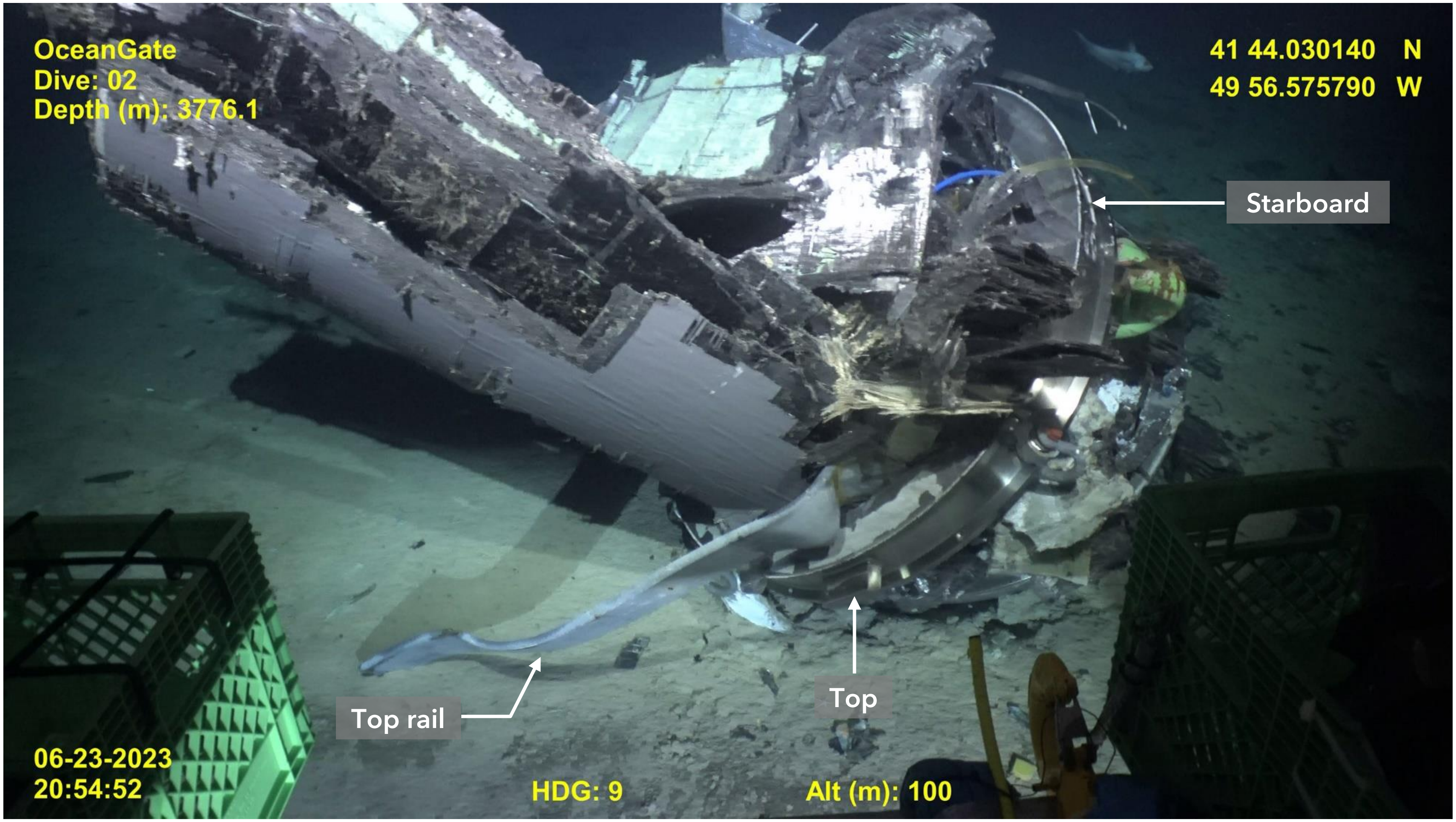


Figure 8. Main wreckage viewed from top side.

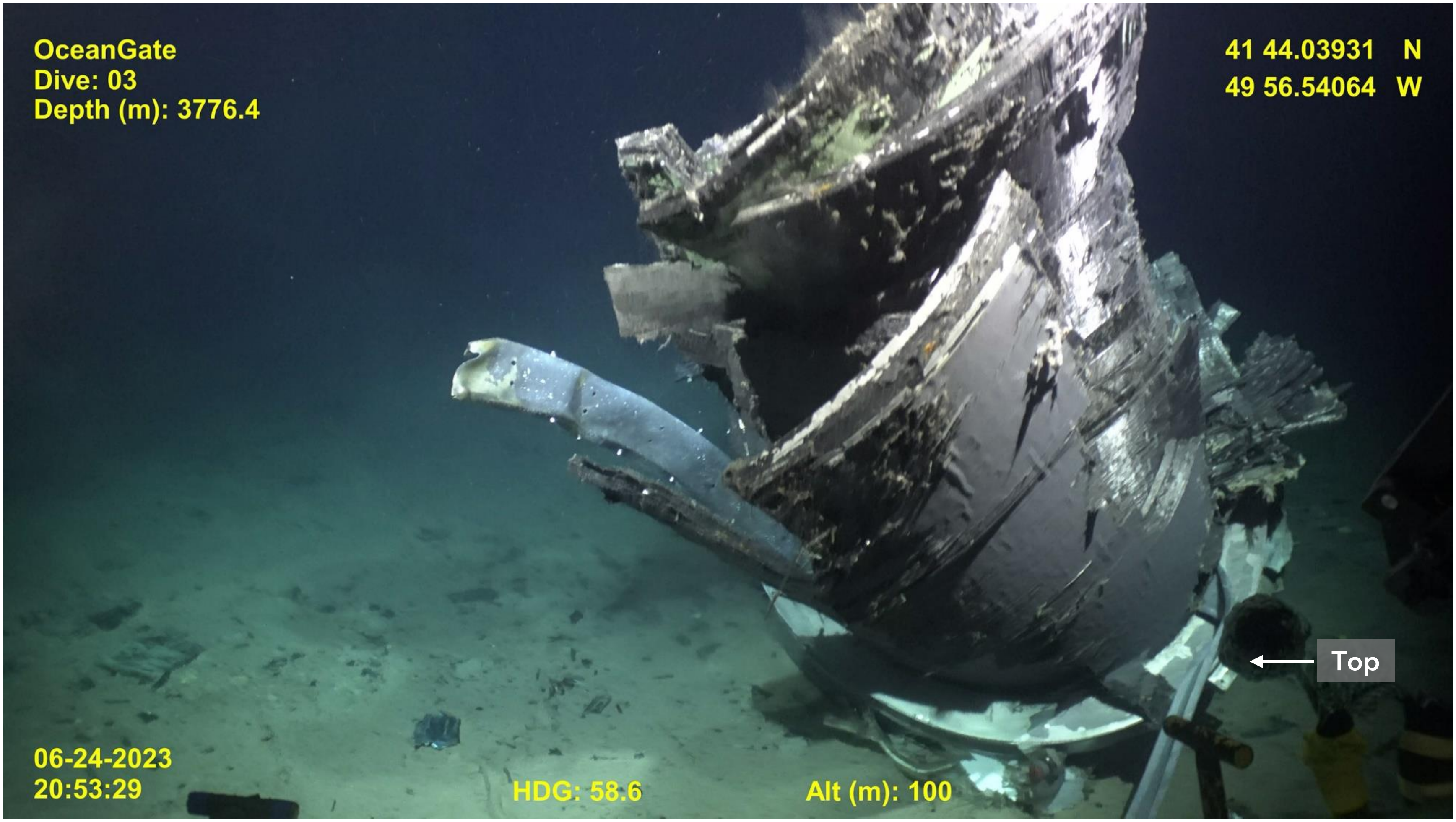


Figure 9. Main wreckage viewed from forward end and top side.

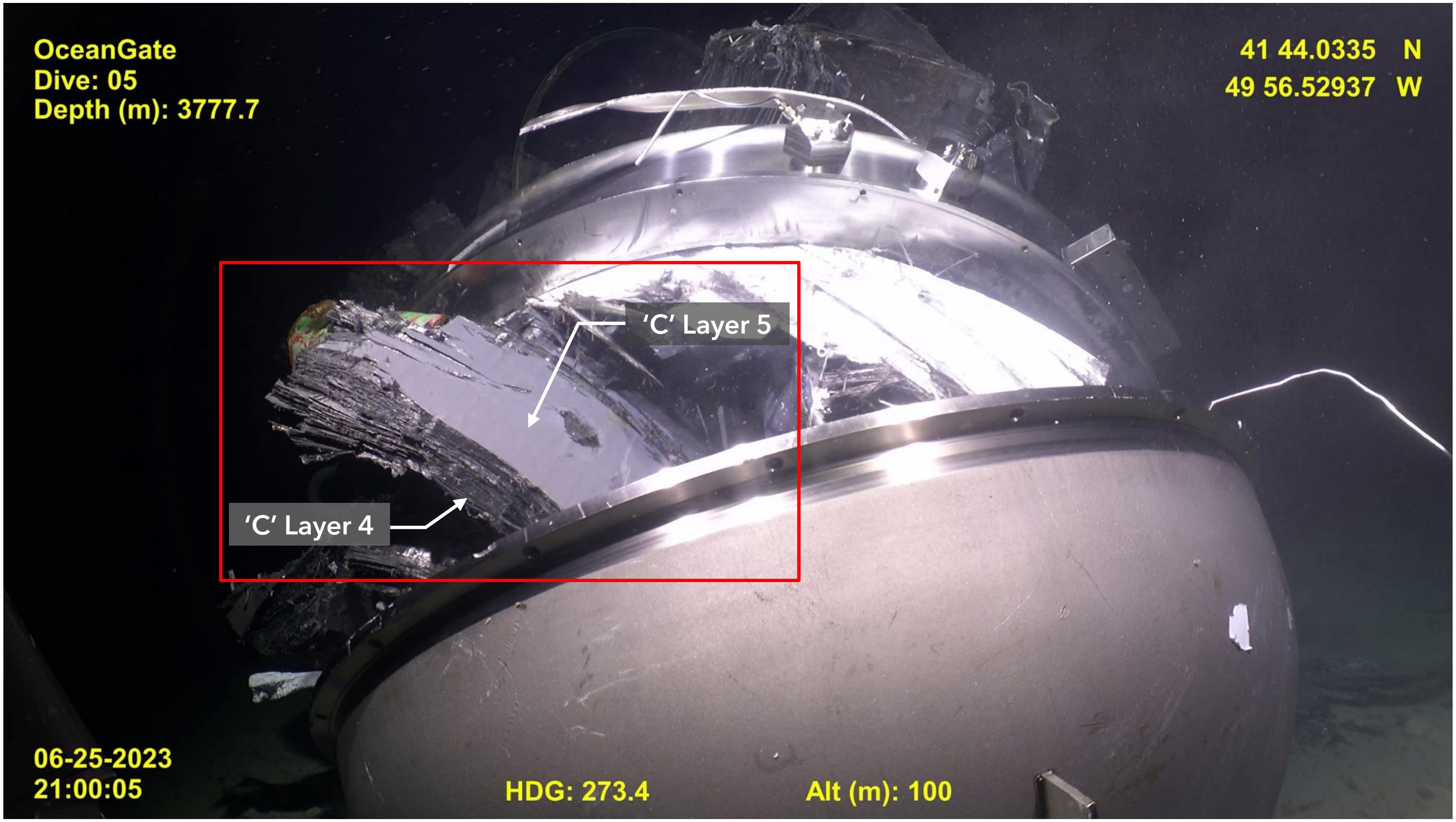


Figure 10. Piece of hull with rubber coating on the outside and the thickness of two co-bonded layers, consistent with layers 4 and 5.

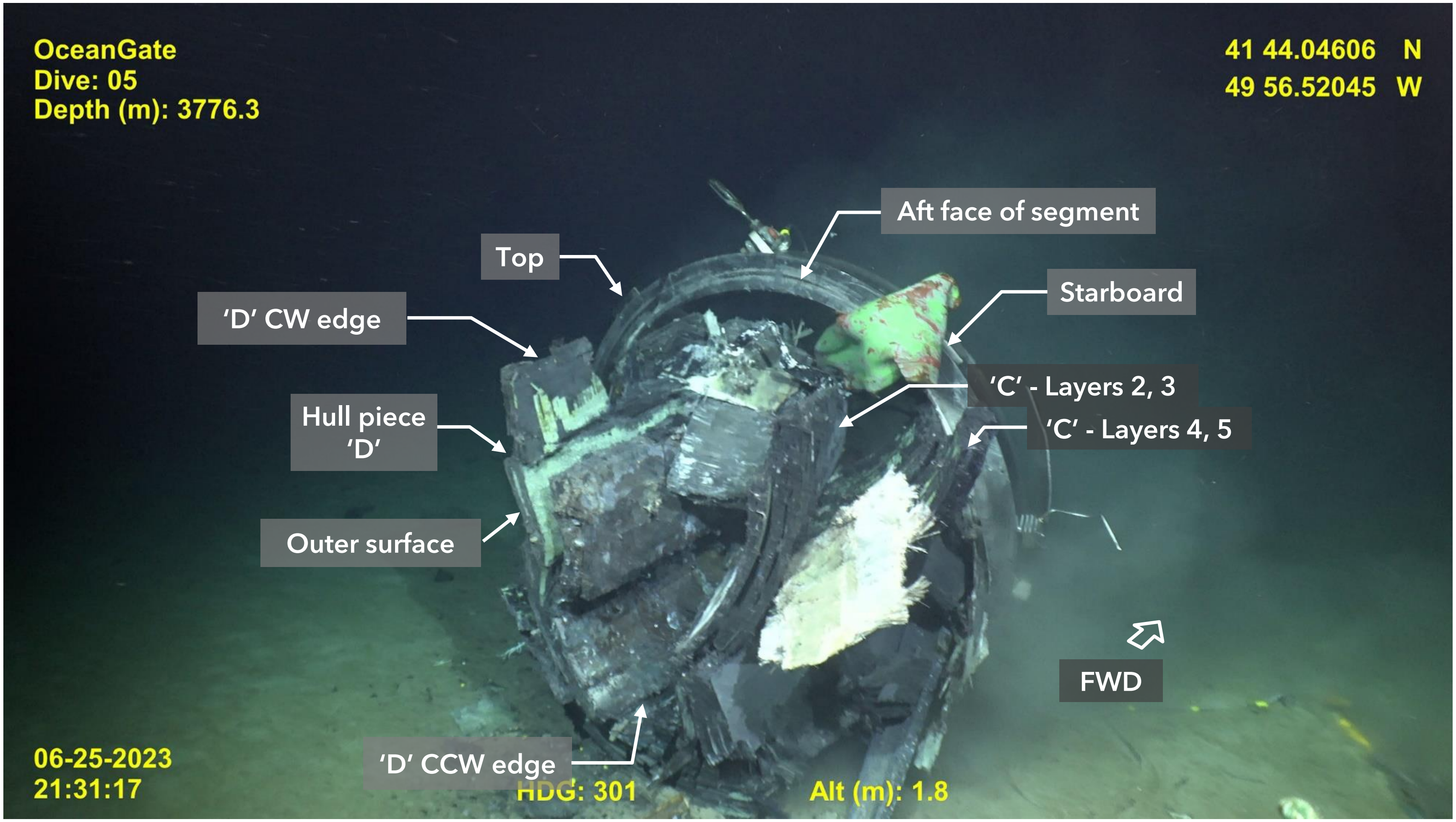


Figure 11. Aft segment and aft end of aft hull pieces after the segment was removed from the aft dome.

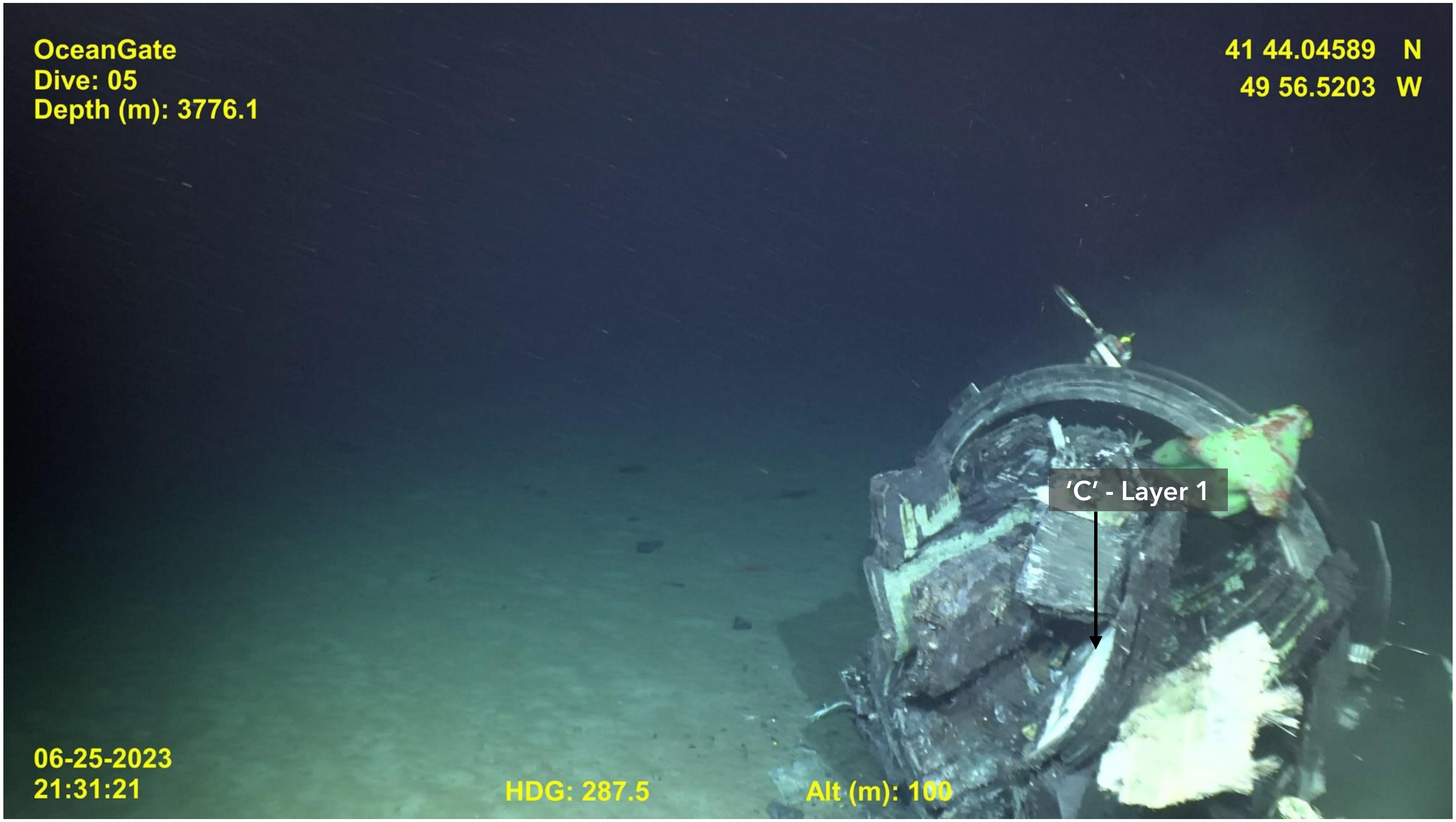


Figure 12. Similar image as figure 11 but at a slightly different angle to show the white paint on the inner surface hull piece 'C' layer 1.

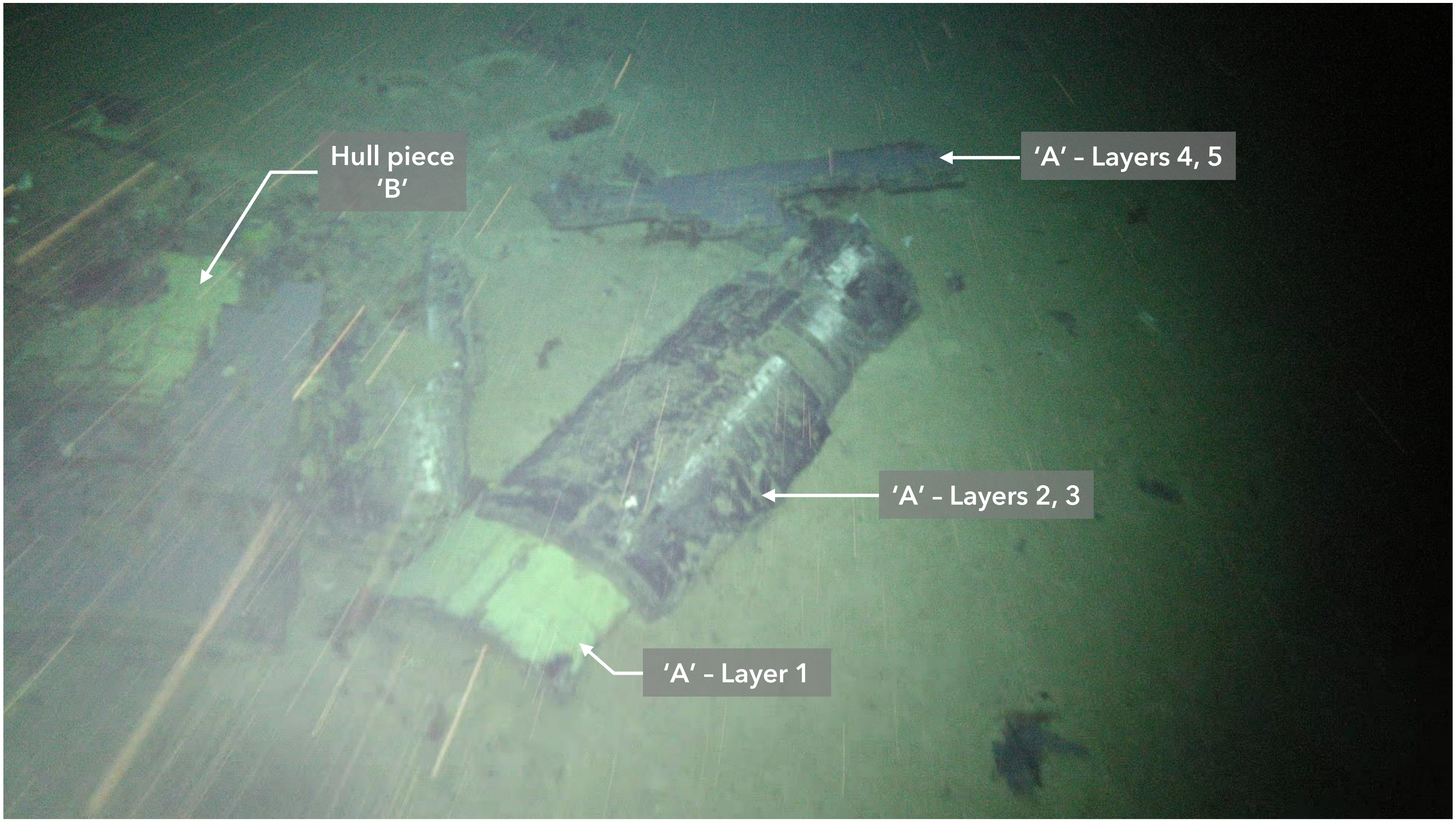


Figure 13. Image of hull piece 'A' after disentanglement from the aft segment.

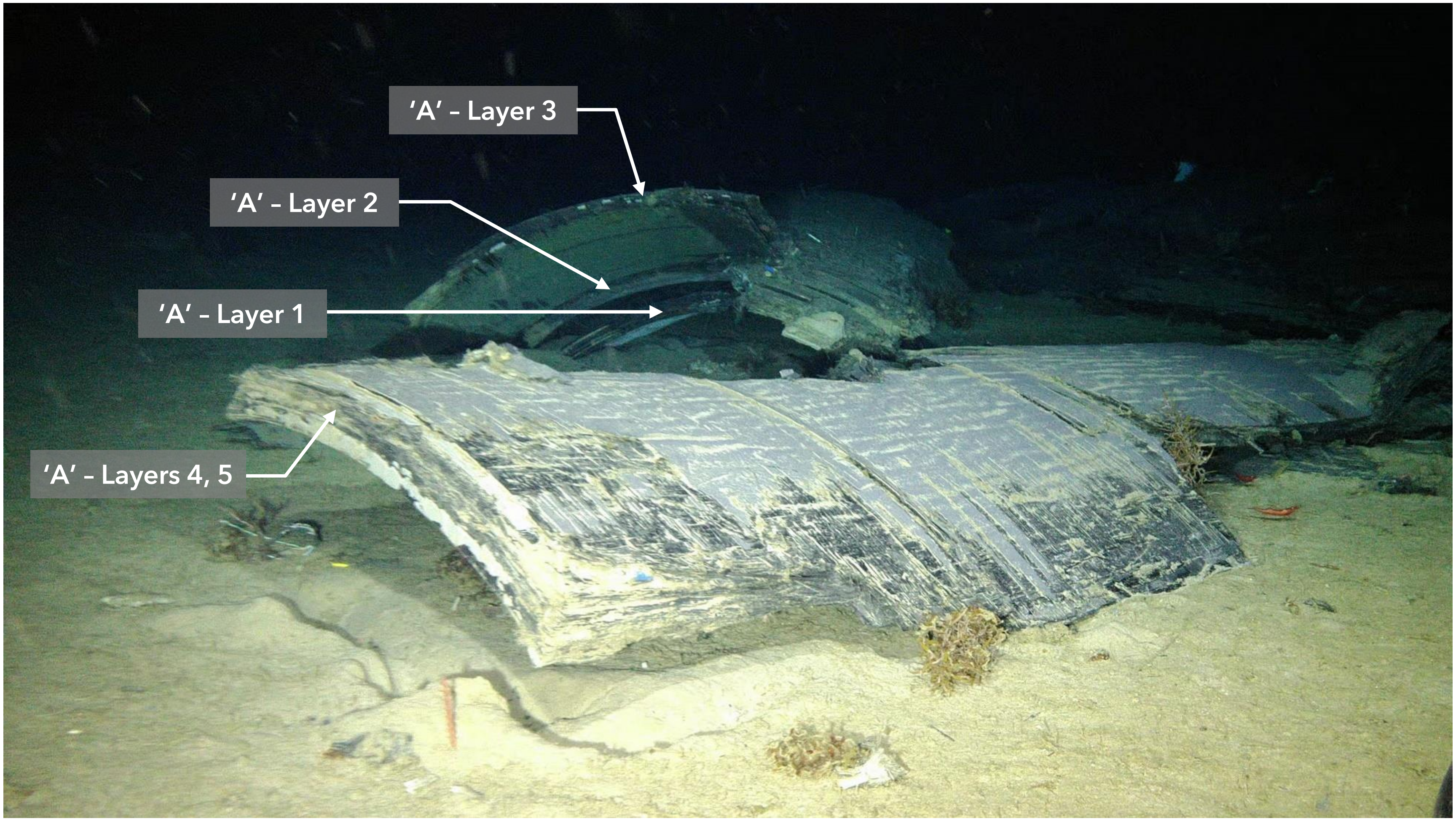


Figure 14. View of the forward ends of hull piece 'A' with the individual co-bonded layer labelled.

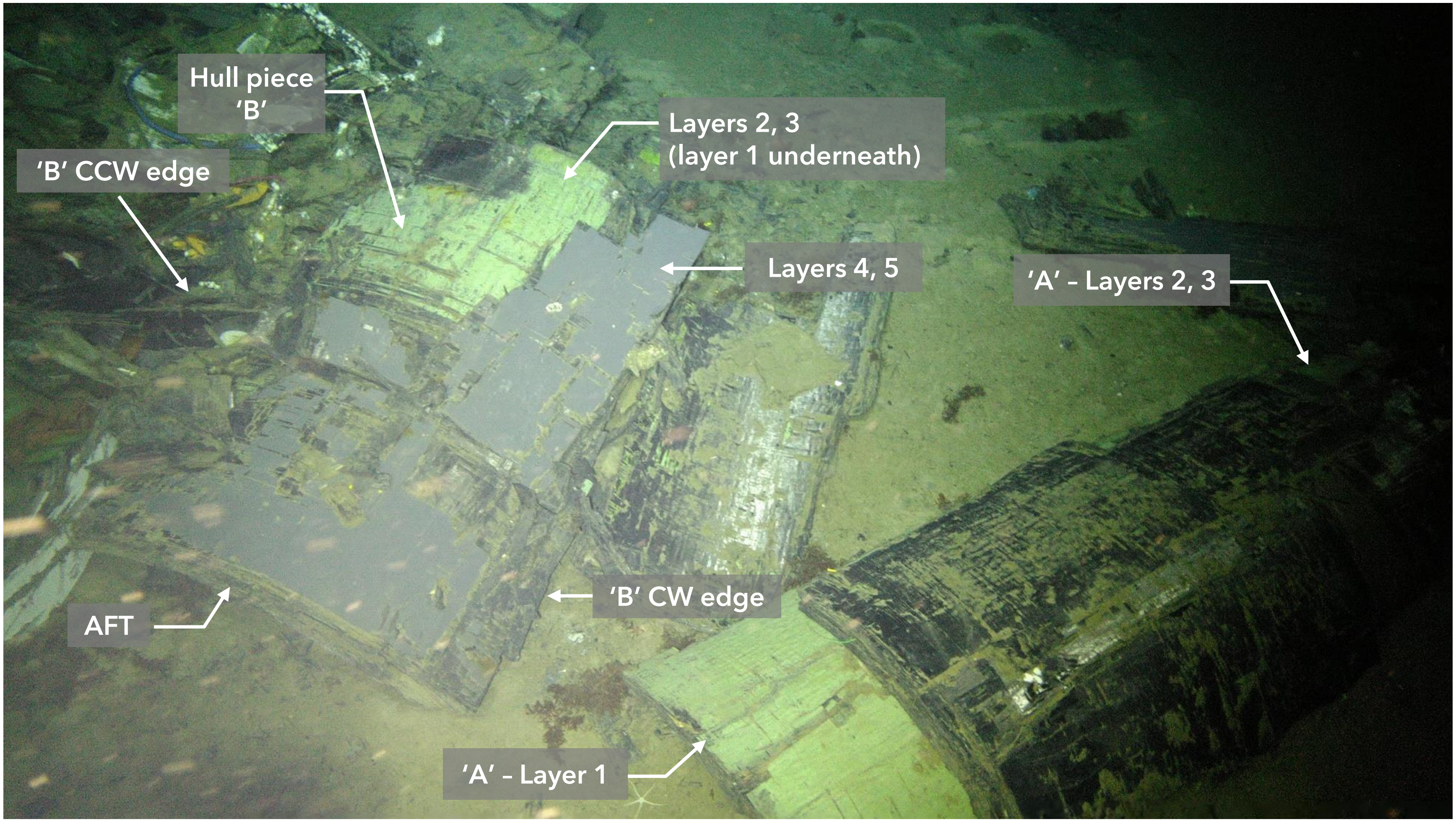


Figure 15. View of hull piece 'B' with the layers labelled. Portions of piece 'A' visible on the right side of the image.

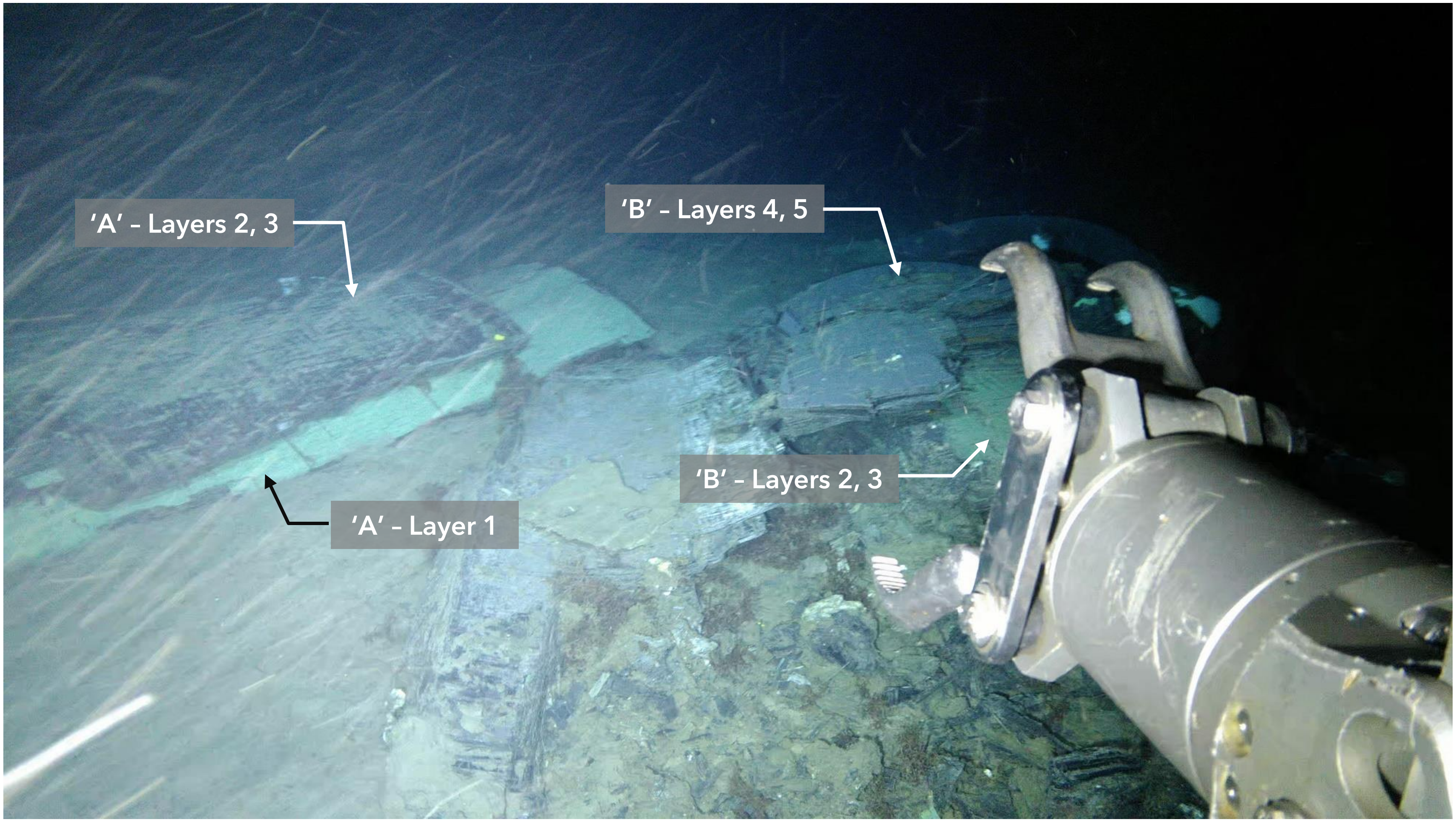


Figure 16. Pieces 'A' and 'B' from a different point of view.

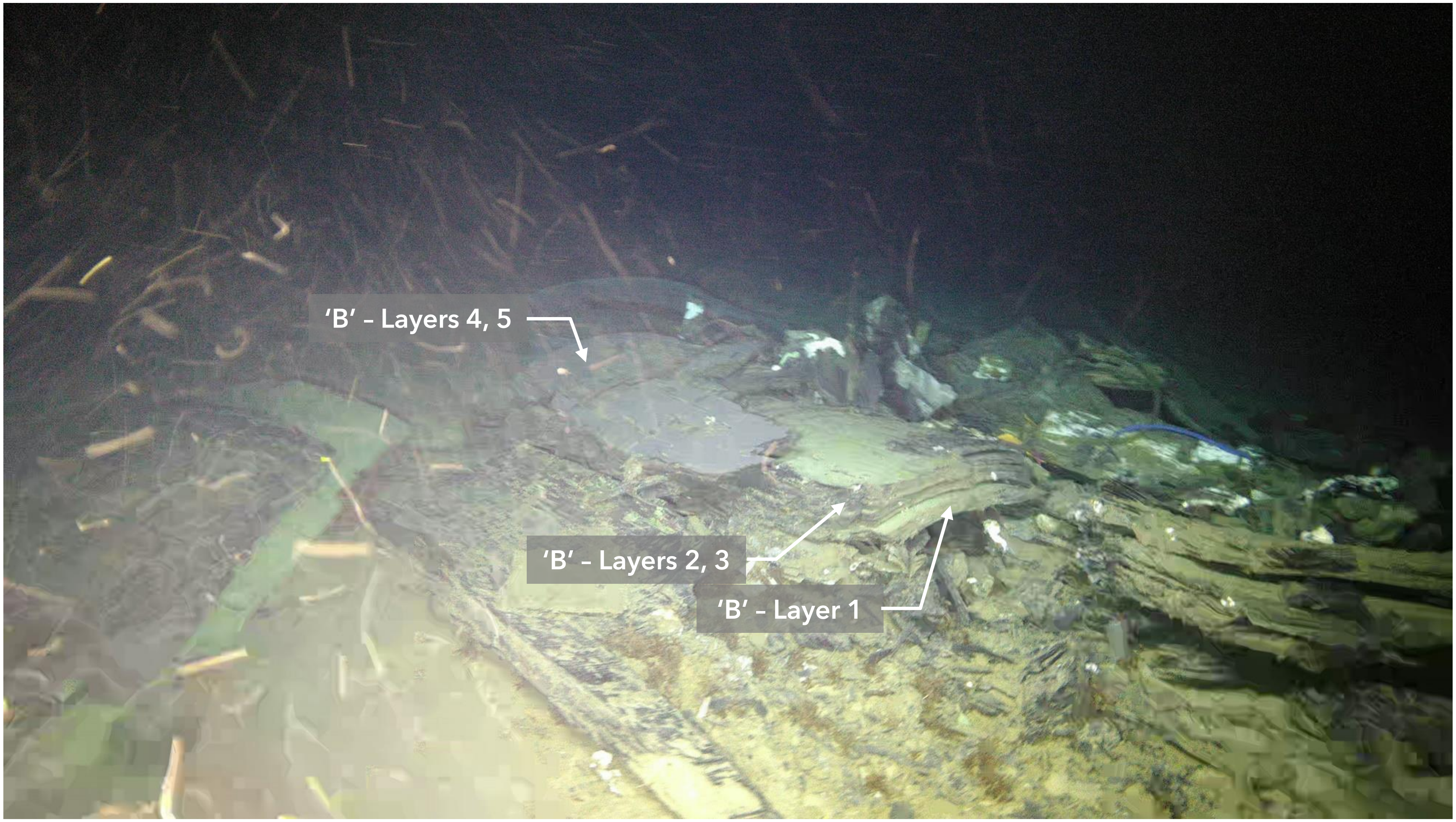


Figure 17. Image of piece ‘B’ with the layer pieces labelled.

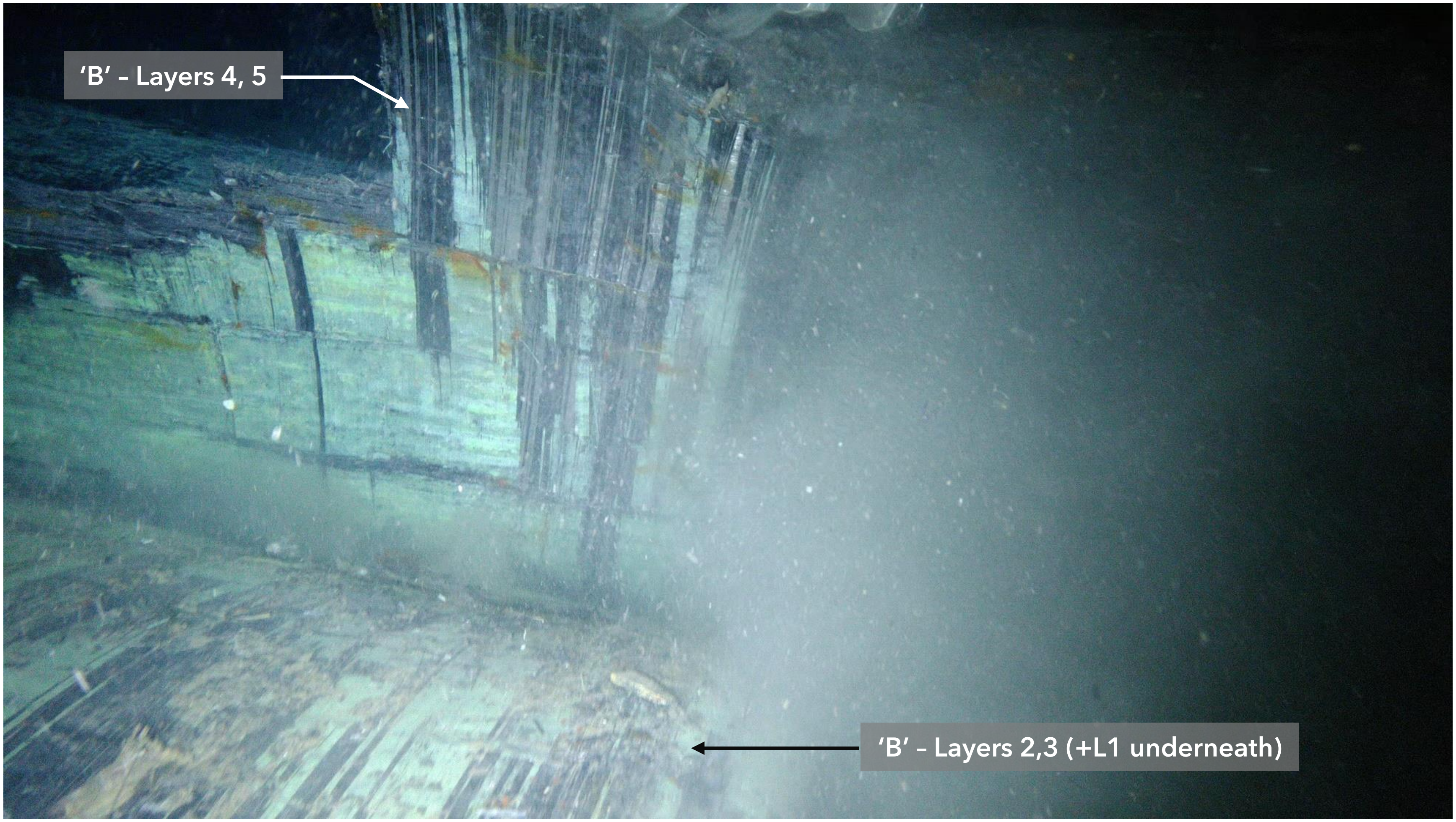


Figure 18. Piece 'B' layer 3/4 interface showing period light dark pattern in the adhesive.

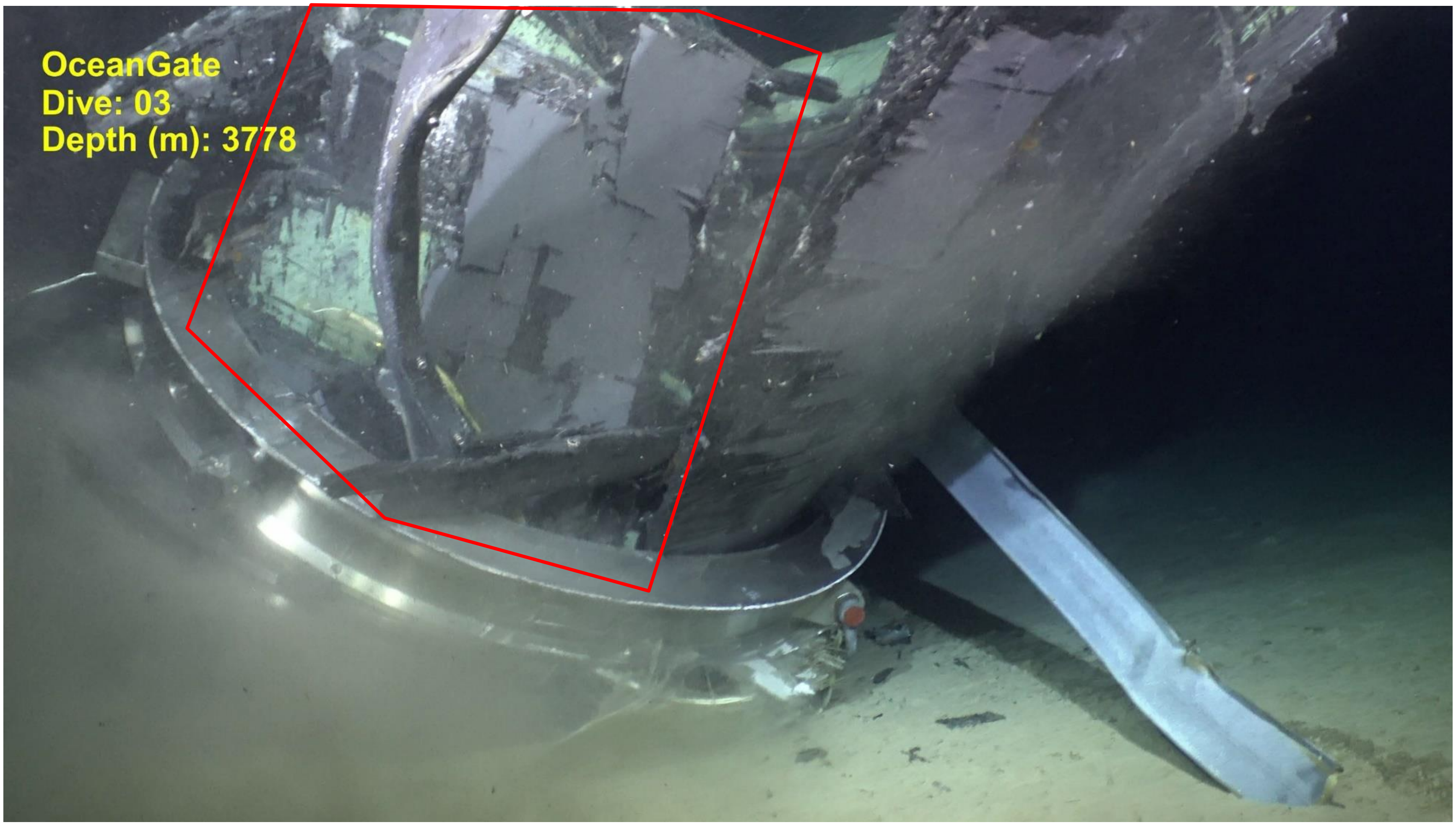


Figure 19. Image of piece 'B' showing cracking on the surface.

Figure 20. View of piece 'B' after removal of layers 4 and 5. The fracture along the CCW edge was irregular.

Figure 21. Piece 'B' after removal of layers 4 and 5 from a different point of view.

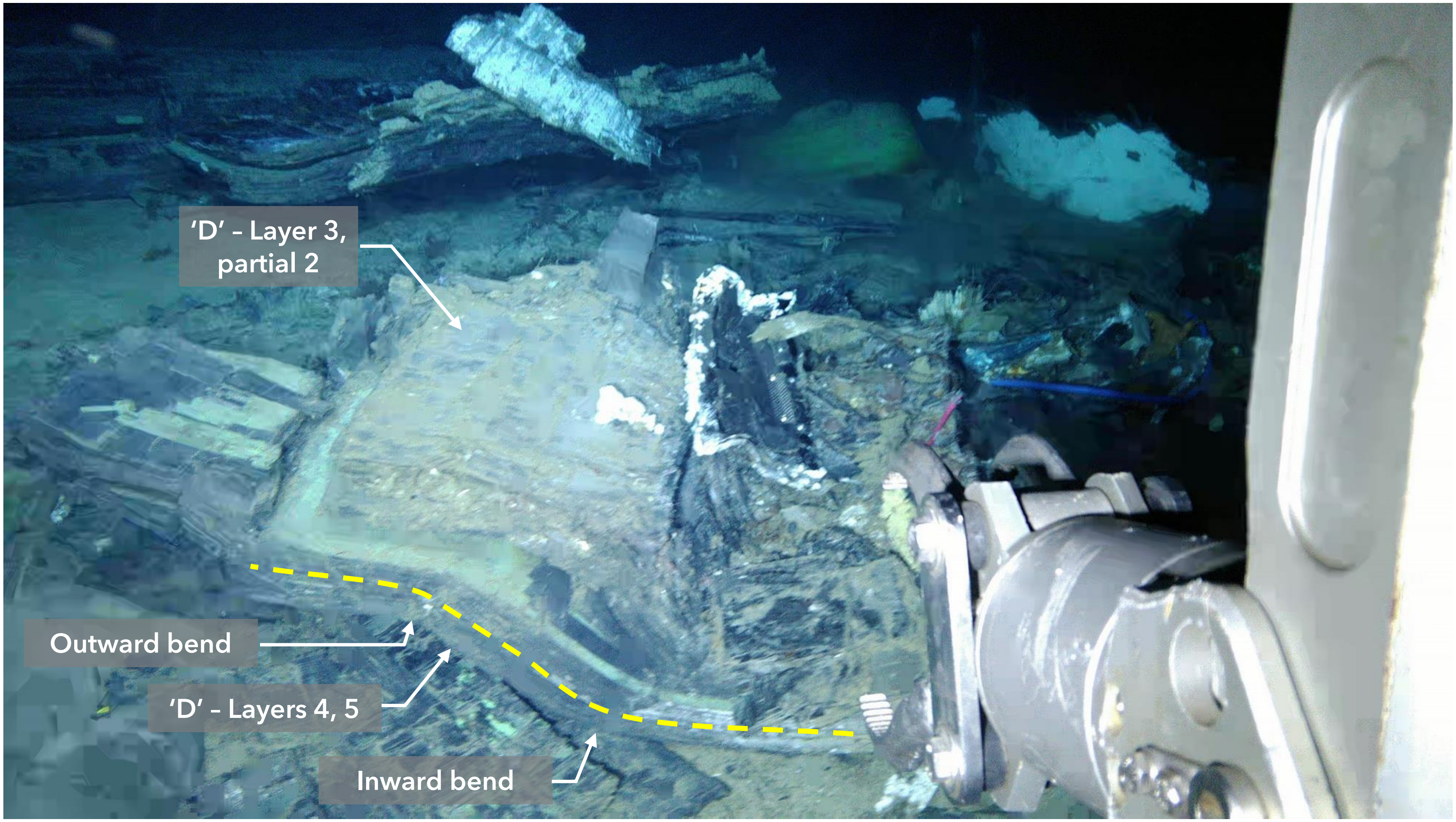


Figure 22. Image of piece 'D' showing the sigmoidal buckle as a yellow dashed line.

Figure 23. Piece 'D' from another point of view.

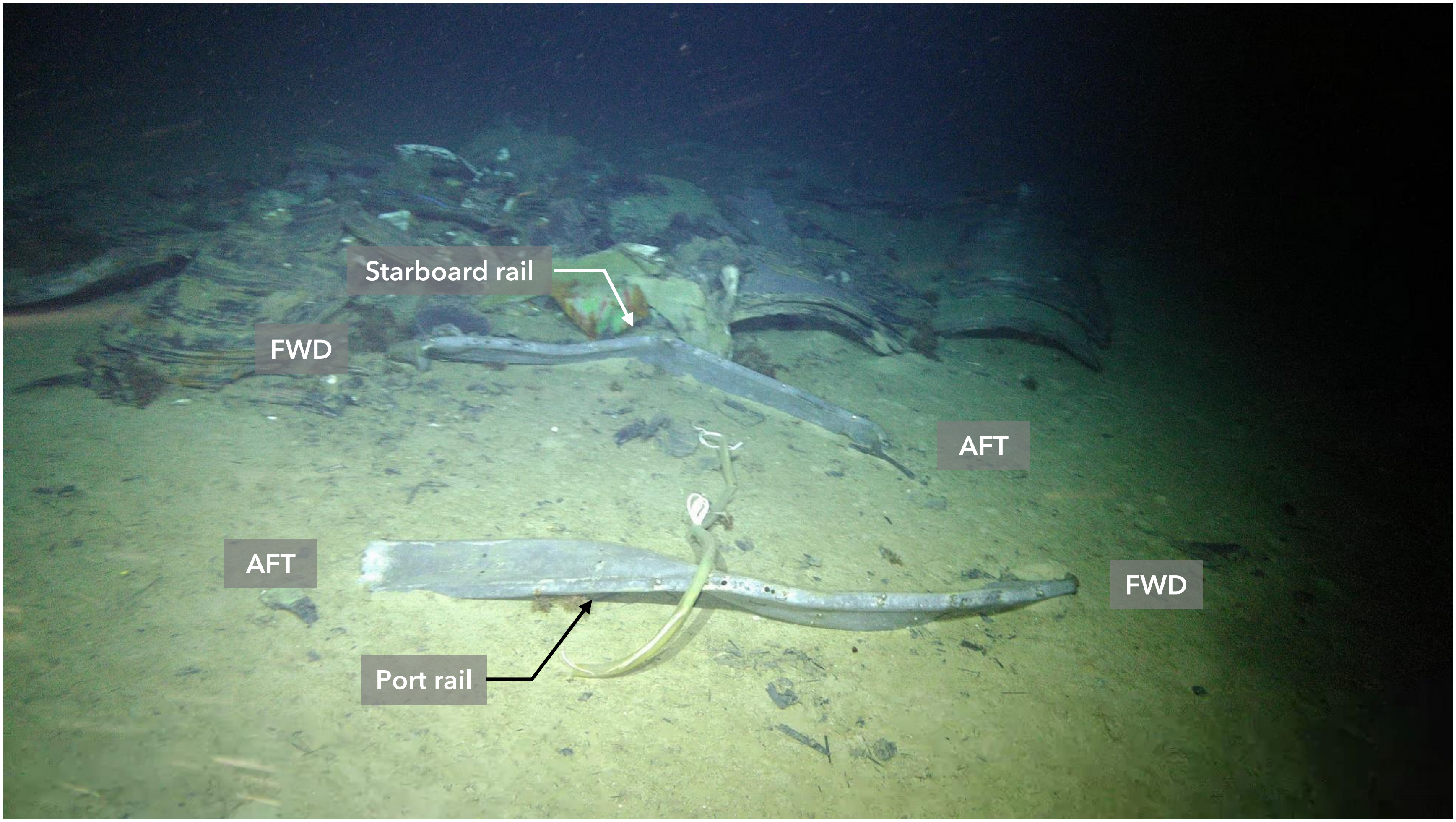
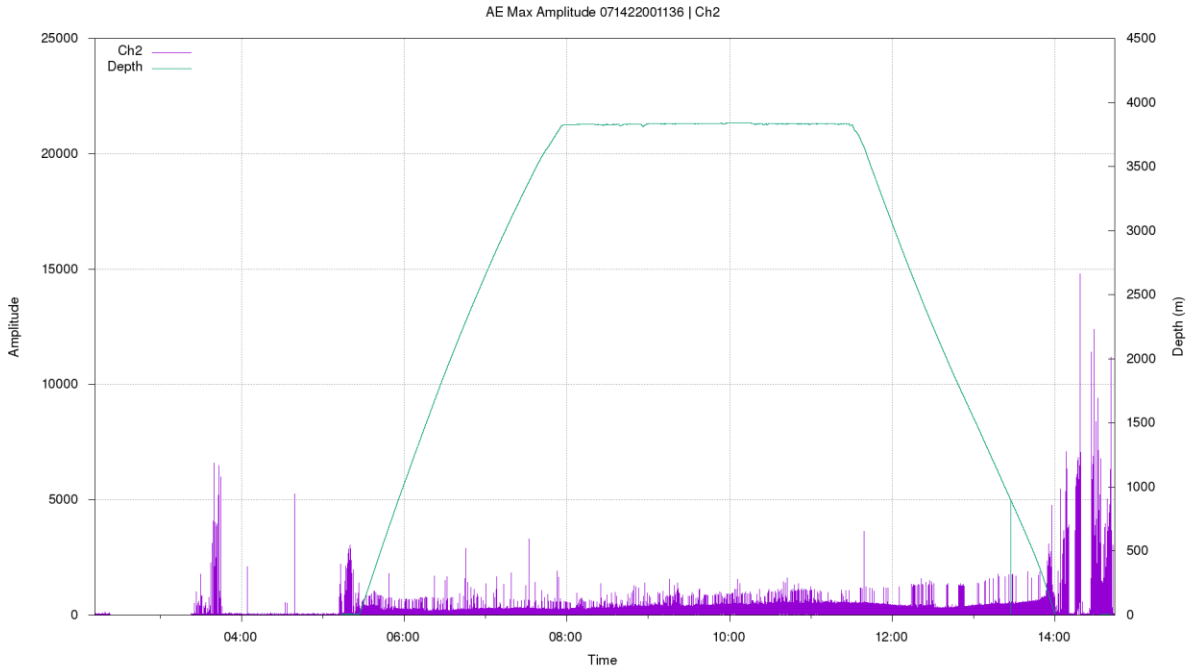
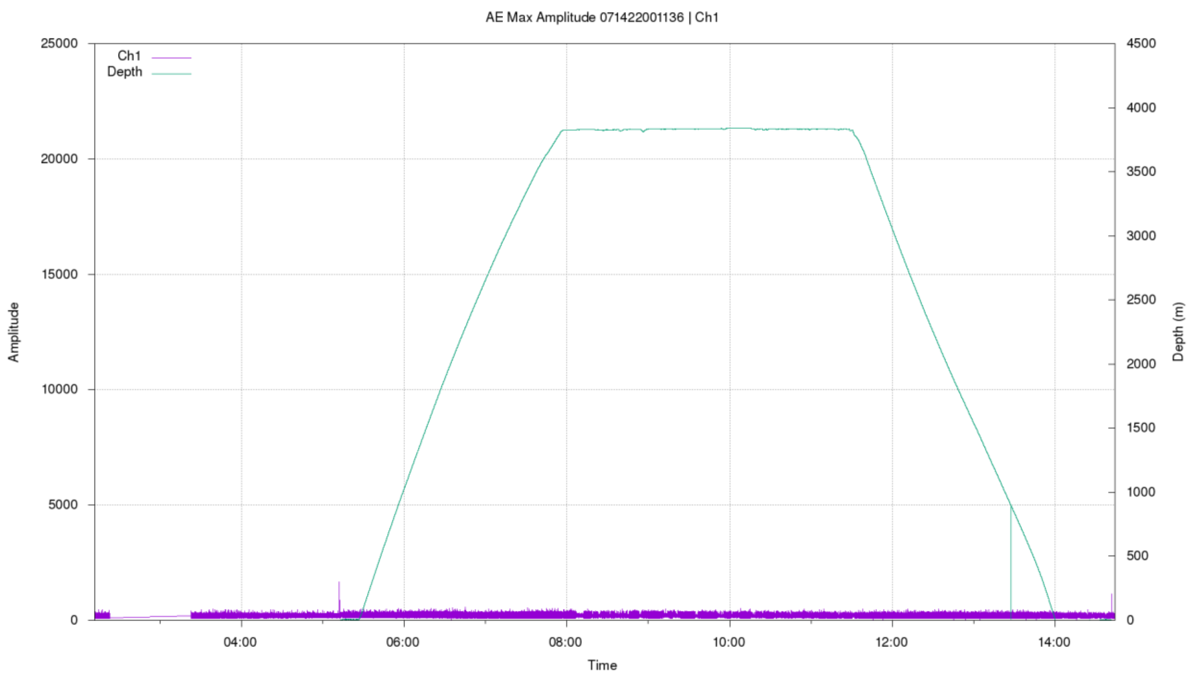


Figure 24. Port and starboard rails. The short sides of the rails in view are most likely the lower sides, based on residual marks left by the drop weight assembly attachment brackets.

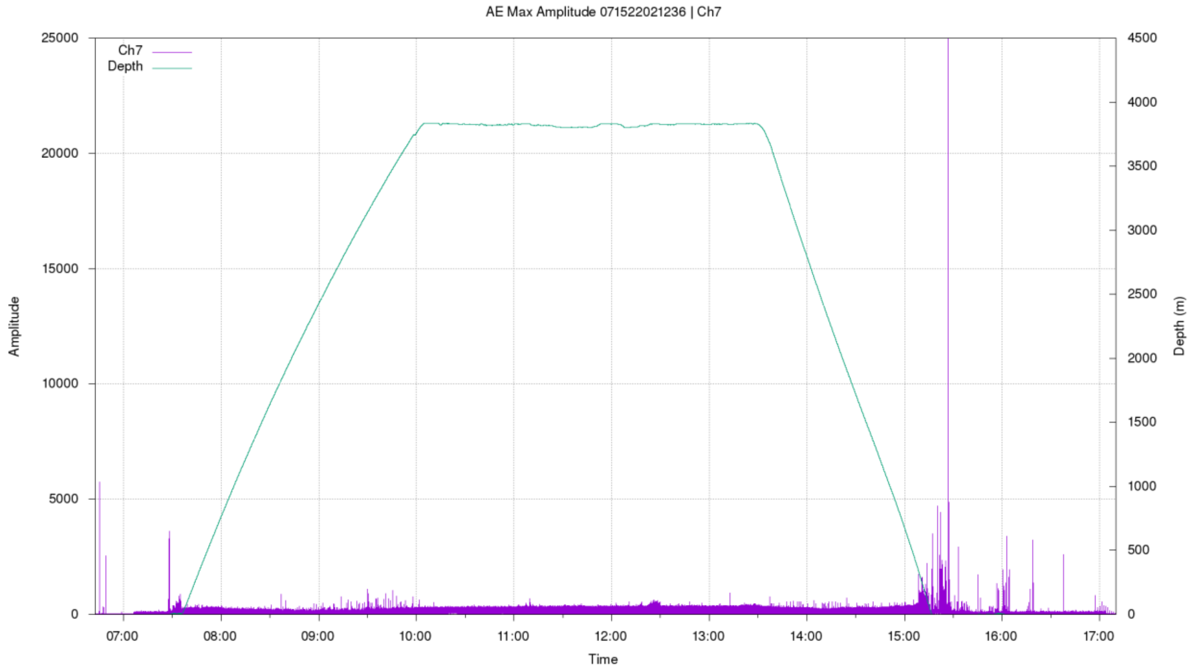


a)

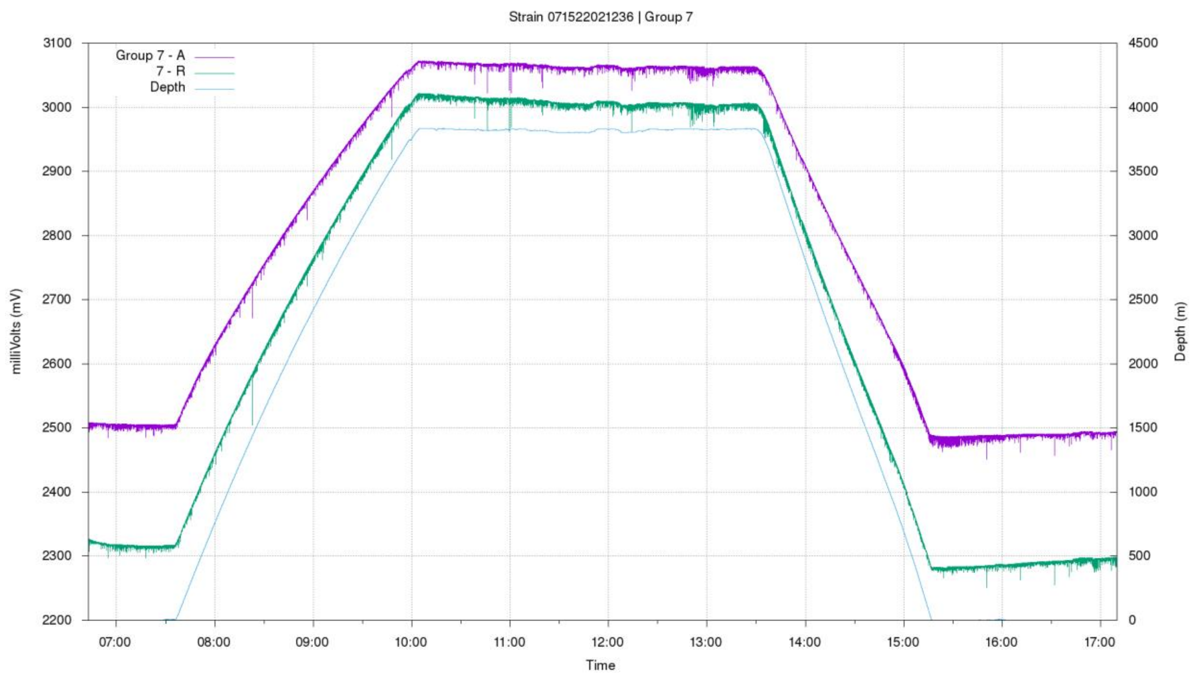


b)

Figure 25. Time plots of acoustic events detected by acoustic emission detector for Dive 76: a) Channel 2 showing detected event and b) channel 1 showing no indication of event detection.

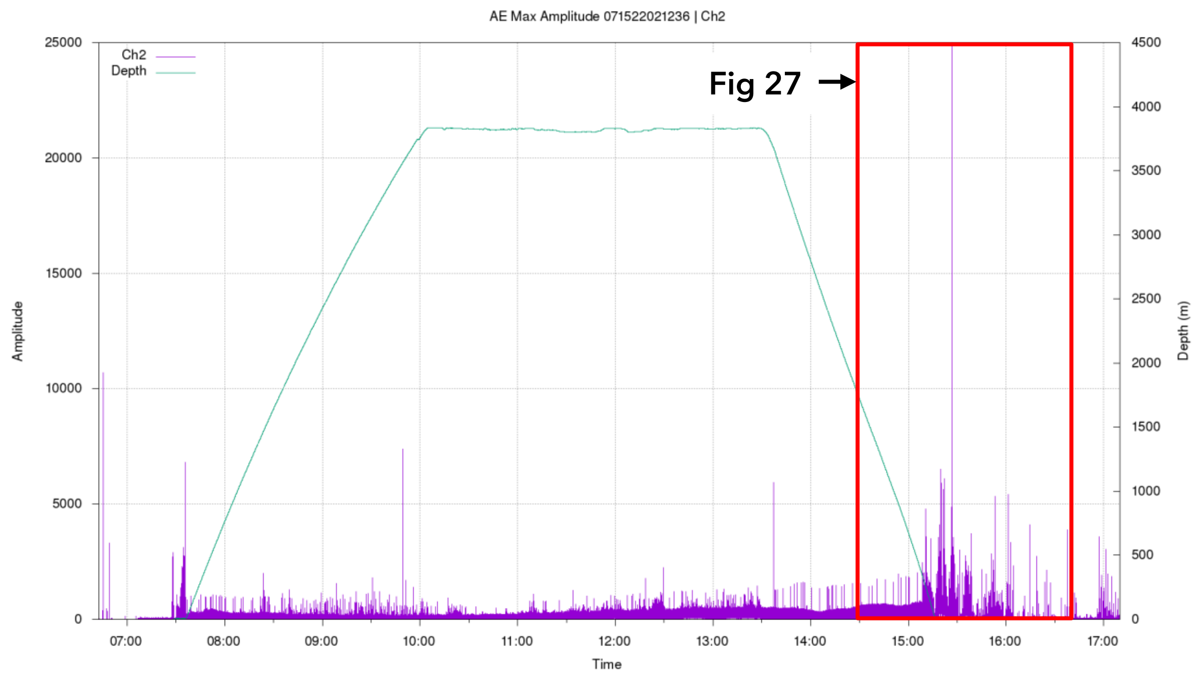


a)

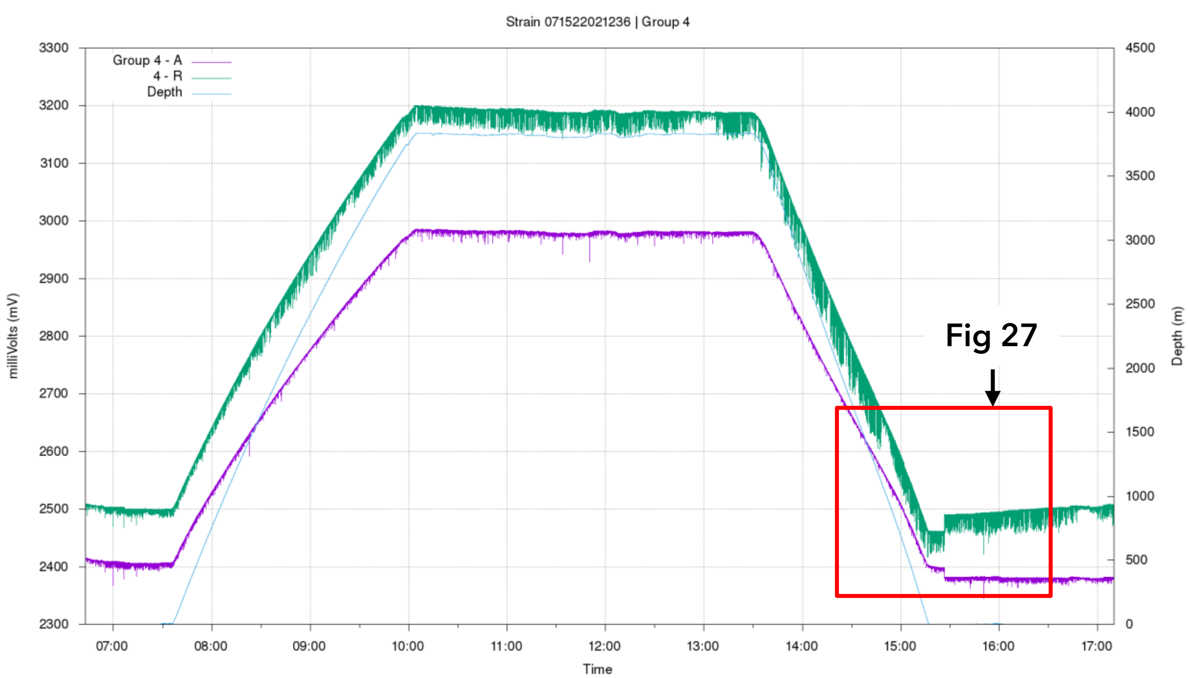


b)

Figure 26. Time plots from Dive 80. Time of day is reported in Newfoundland Daylight Time (UTC – 2:30): a) acoustic activity from channel 7; b) strain gage output from group 7 showing hoop strain (R) and longitudinal strain (A);



c)



d)

Figure 26 (cont.). c) acoustic activity from channel 2 and d) strain gage output from group 4 showing hoop strain (R) and longitudinal strain (A).

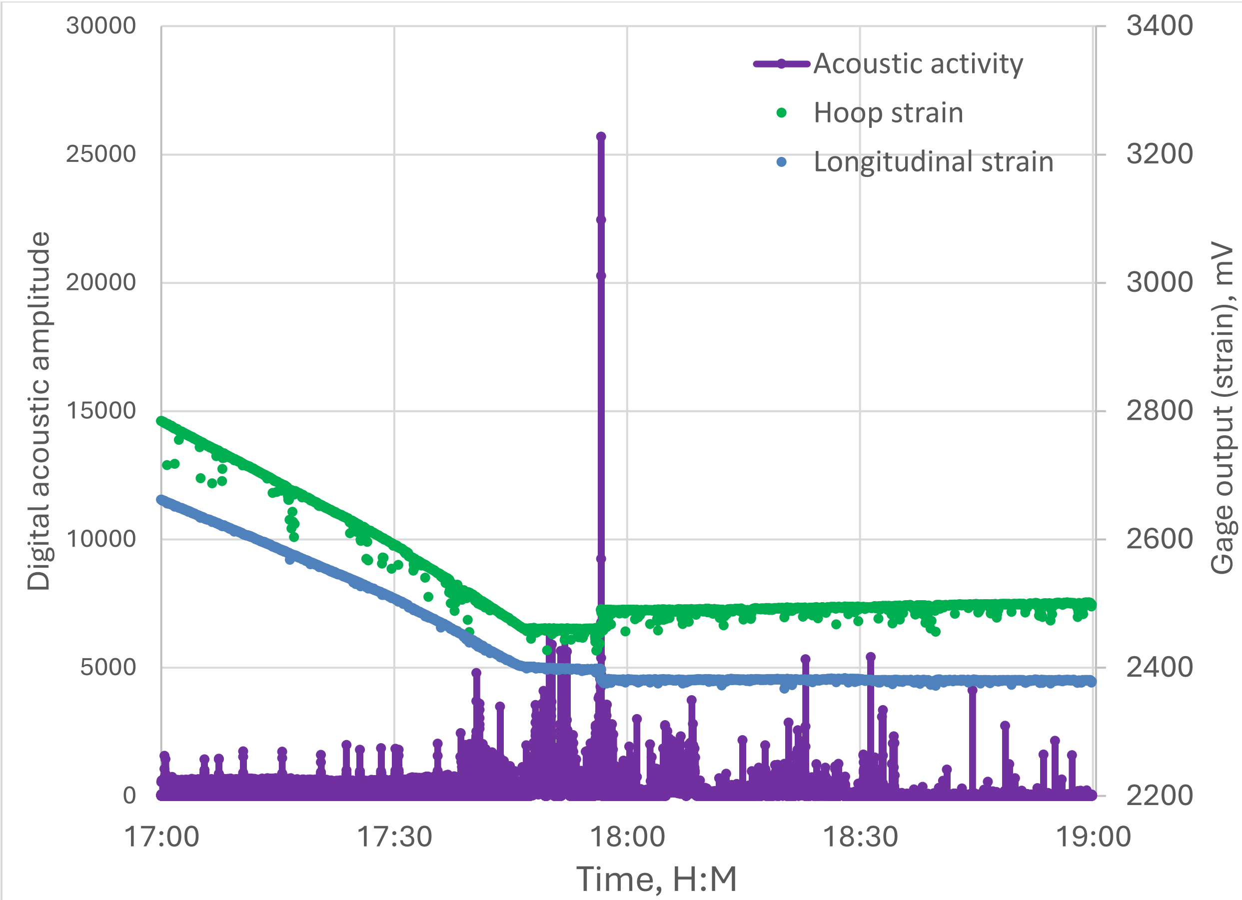


Figure 27. Time plot of channel 2 acoustic activity, hoop strain, and longitudinal strain from group 4 for the Dive 80 2-hour interval after surfacing. Time is reported in UTC.

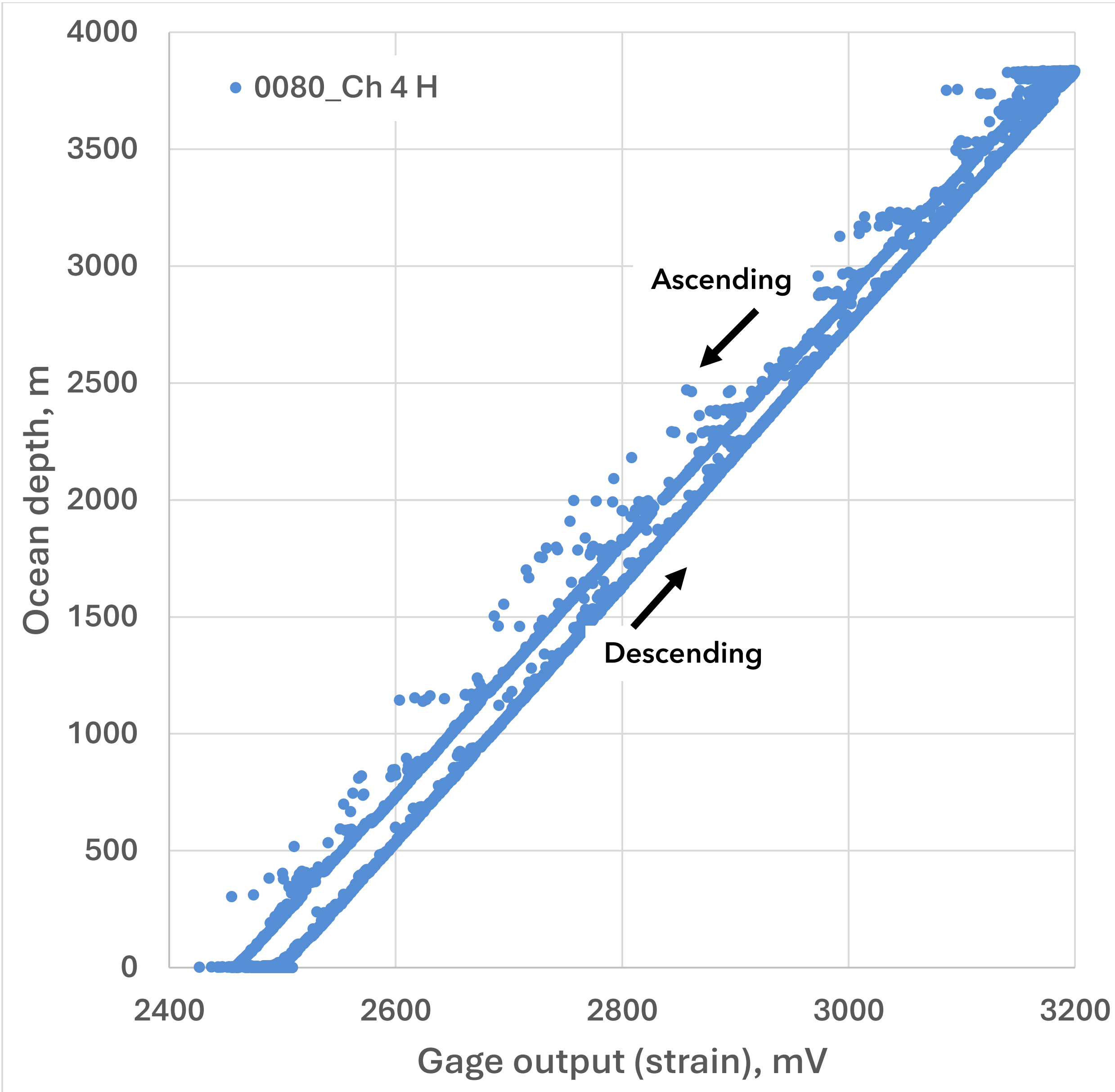


Figure 28. Plot of dive depth as a function of strain gage output for Dive 80 – Gage group 4 – hoop strain gage. The reduction of gage output while at the ocean bottom results in lower gage output for the ascent phase of the trip.

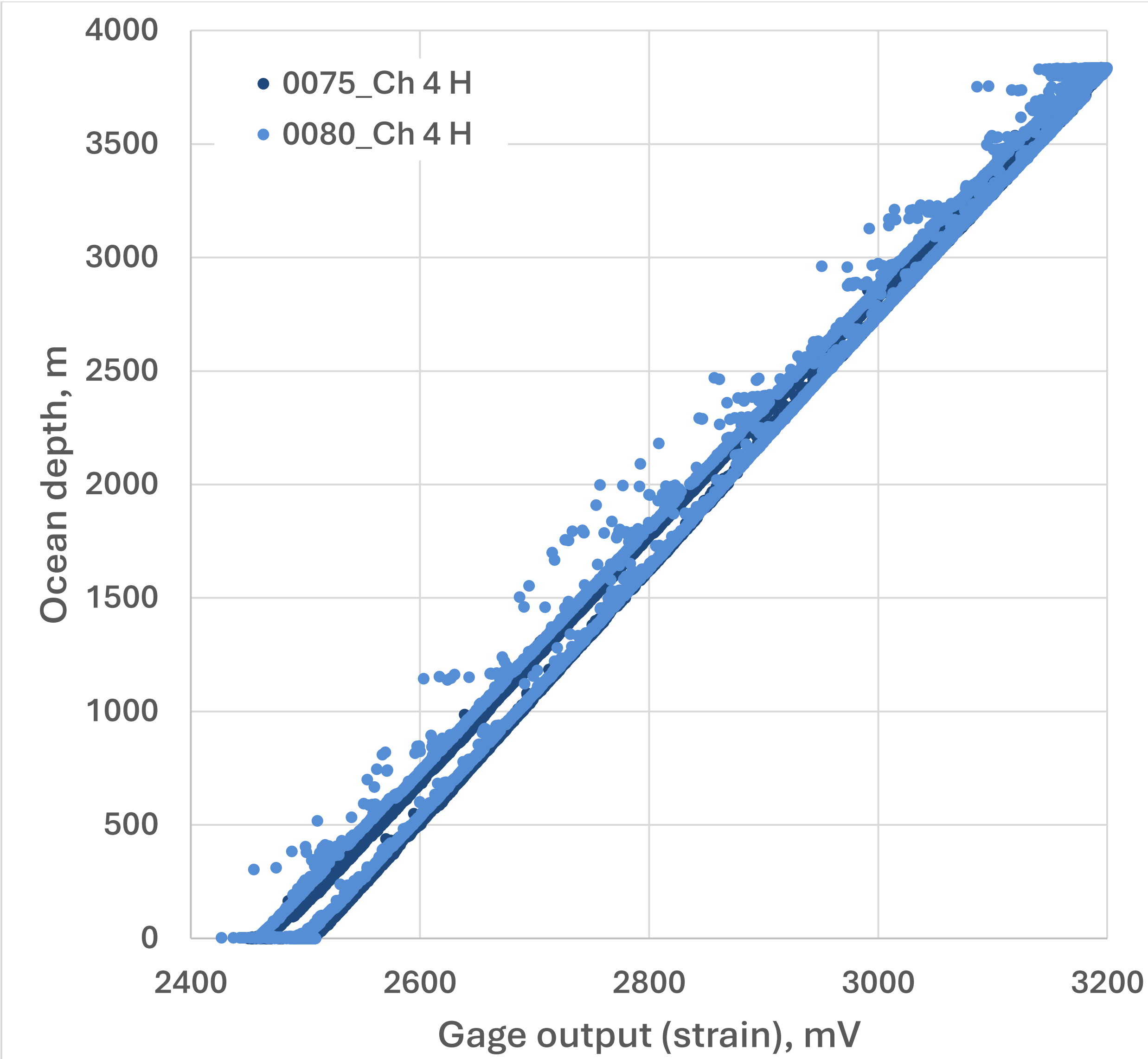


Figure 29. Plot of dive depth as a function of strain gage output for Dives 75 and 80 – Gage group 4 – hoop strain gage. The curves have been aligned using the linear portion of the descent phase of the trip.

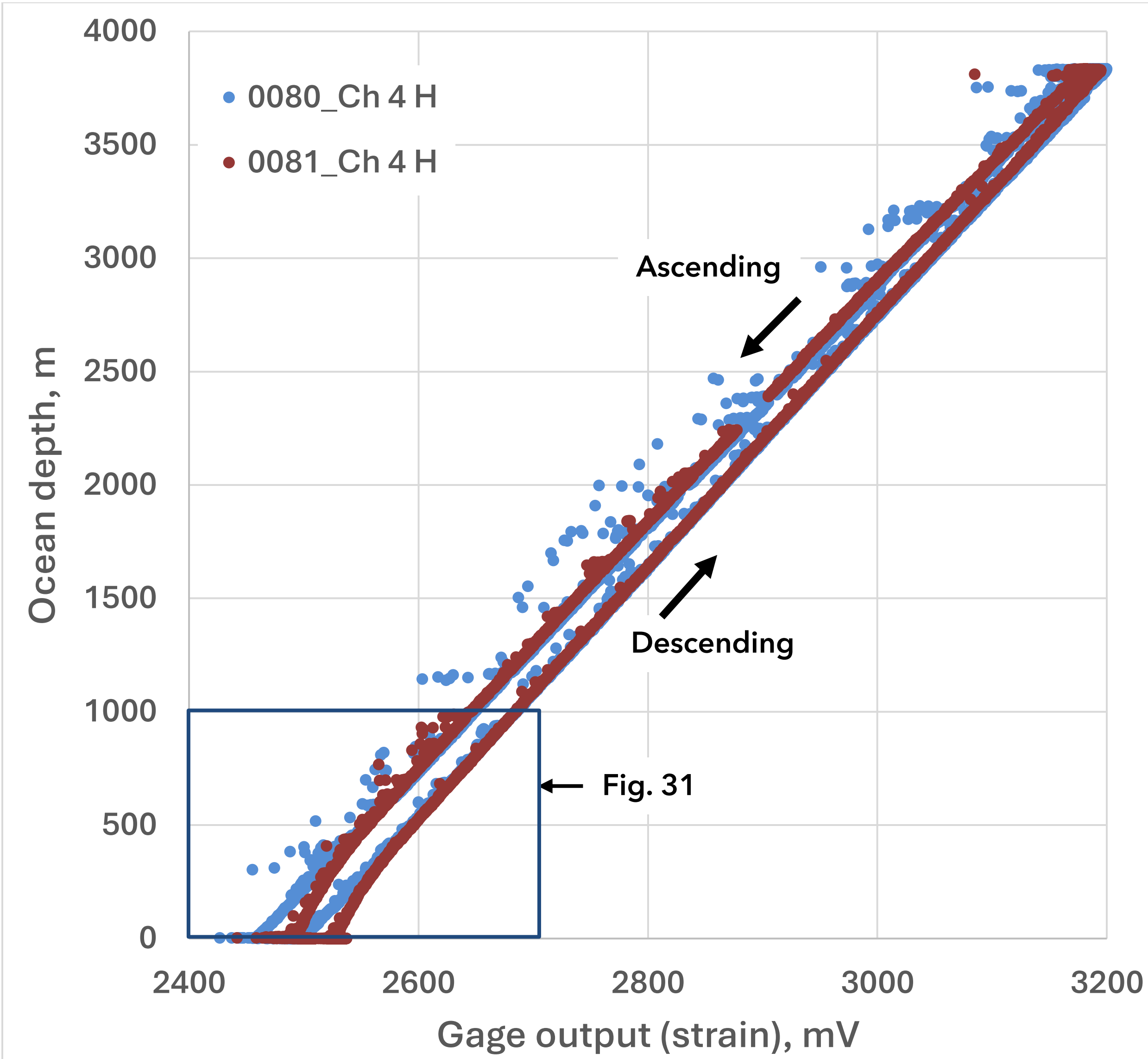


Figure 30. Plot of dive depth as a function of strain gage output for Dives 80 and 81 – Gage group 4 – hoop strain gage. The curves have been aligned using the linear portion of the descent phase of the trip. The strain for Dive 81 shows non-linear behavior between 0 m and 500 m dive depth.

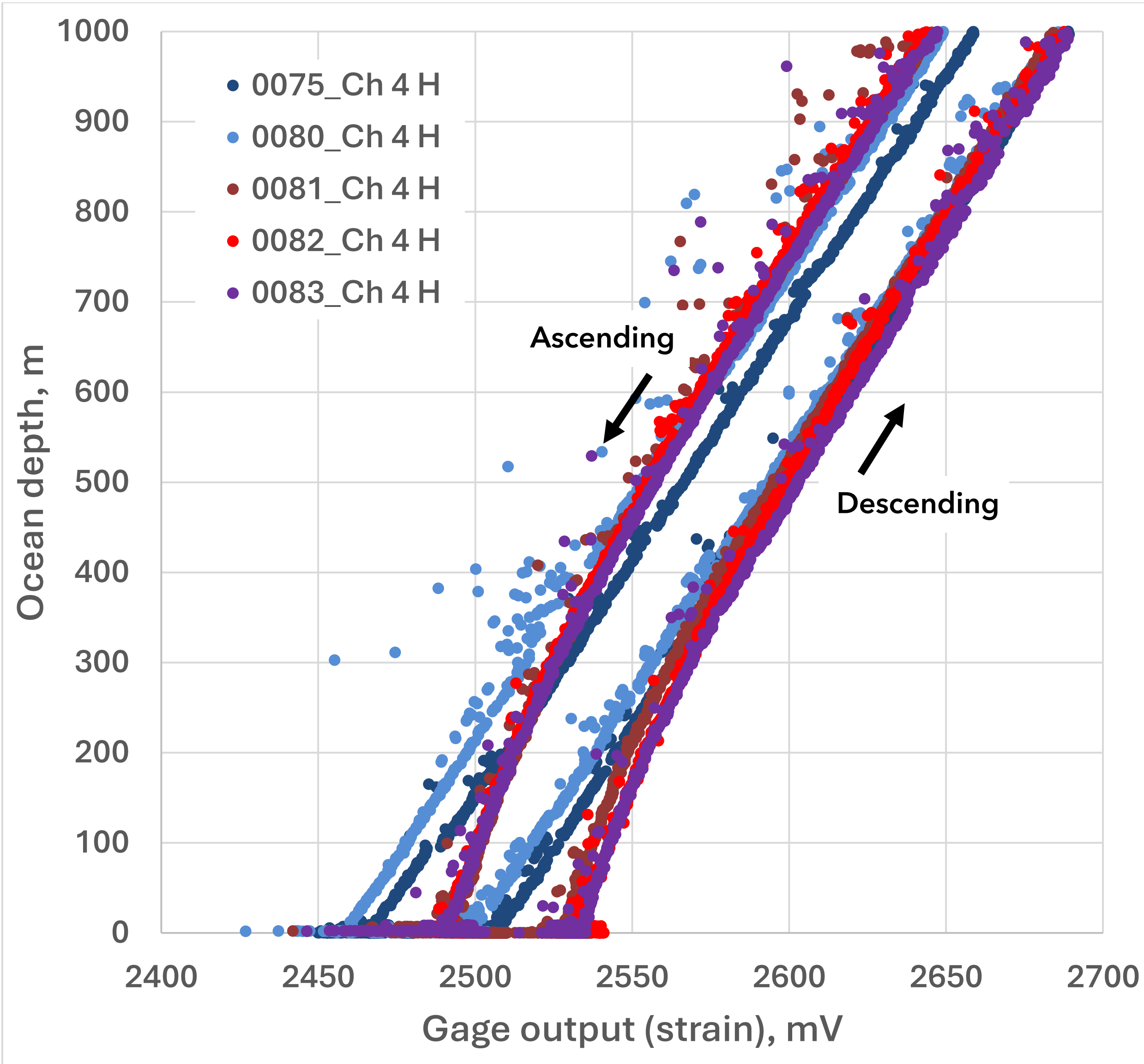


Figure 31. First and last 1000 m of dive depth for Dives 75 and 80 – 83 – Gage group 4 – hoop strain gage. The curves have been aligned using the linear portion of the descent phase of the trip. The strain for Dives 81, 82, and 83 show non-linear behavior between 0 m and 500 m dive depth.

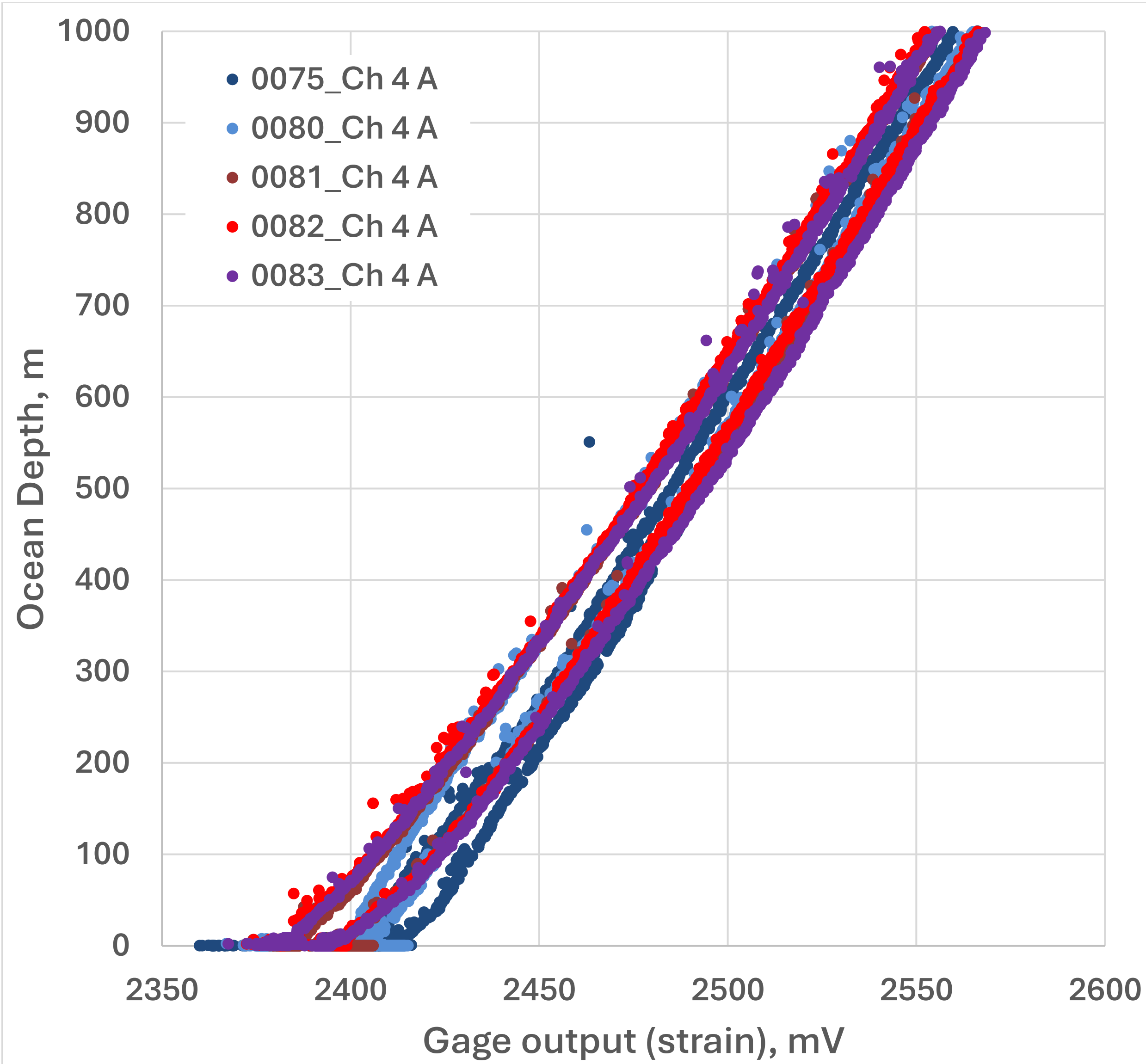


Figure 32. First and last 1000 m of dive depth for Dives 75 and 80 – 83 – Gage group 4 – longitudinal strain gage. The curves have been aligned using the linear portion of the descent phase of the trip. The strain for Dives 81, 82, and 83 show non-linear behavior and reduced apparent stiffness between 0 m and 500 m dive depth.

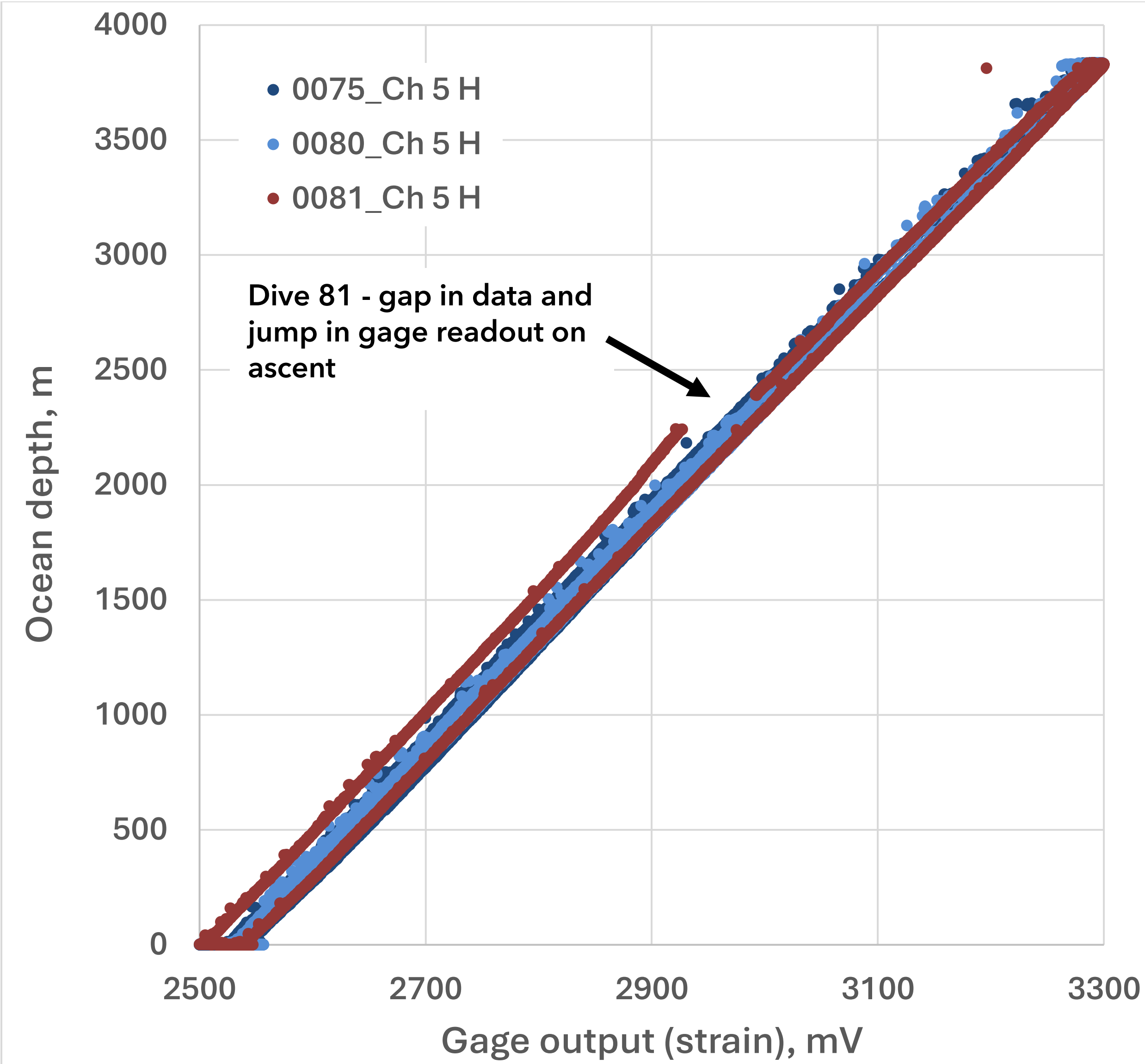


Figure 33. Plot of dive depth as a function of strain gage output for Dives 75, 80 and 81 – Gage group 5 – hoop strain gage. The curves have been aligned using the linear portion of the descent phase of the trip. On the ascent phase of the trip there is an approximately 6 minute and 27 second gap in recorded data between 2389.7 m and 2242.5 m. When recording resumes, the gage output has shifted to a lower voltage.

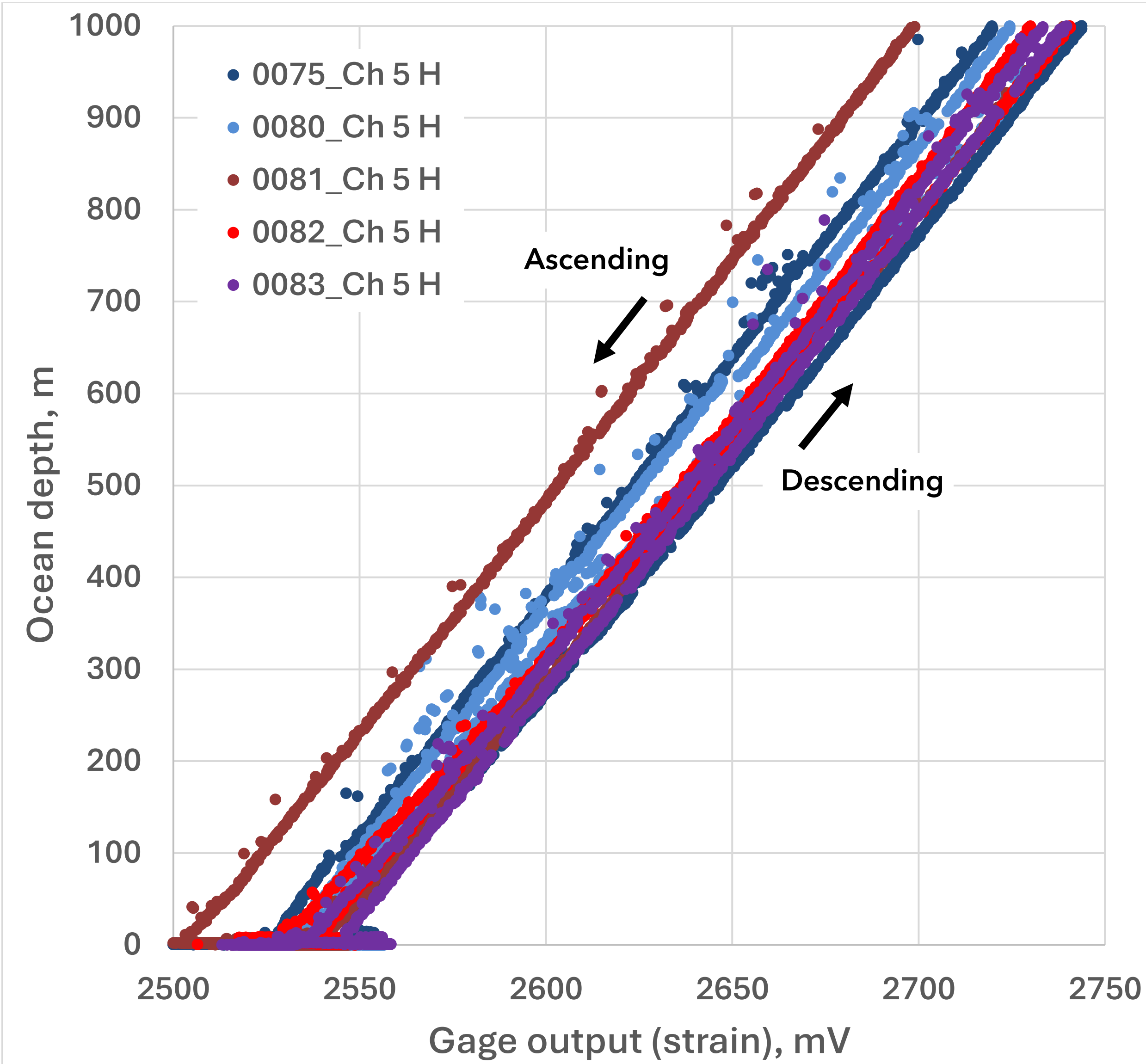


Figure 34. First and last 1000 m of dive depth for Dives 75 and 80 – 83 – Gage group 5 – hoop strain gage. The curves have been aligned using the linear portion of the descent phase of the trip.

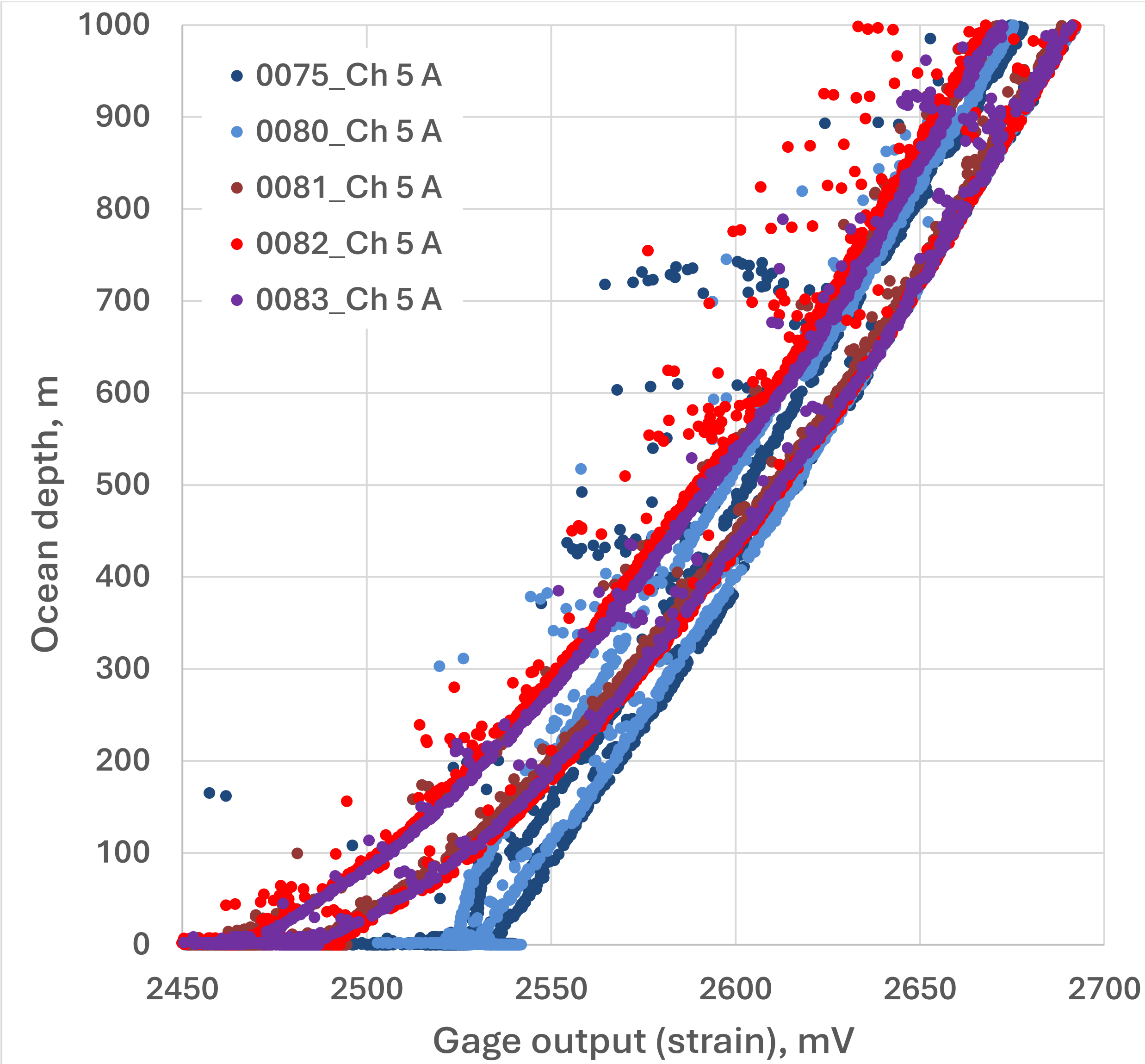


Figure 35. First and last 1000 m of dive depth for Dives 75 and 80 – 83 – Gage group 5 – longitudinal strain gage. The curves have been aligned using the linear portion of the descent phase of the trip. The strain for Dives 81, 82, and 83 show non-linear behavior and reduced apparent stiffness between 0 m and 800 m dive depth.

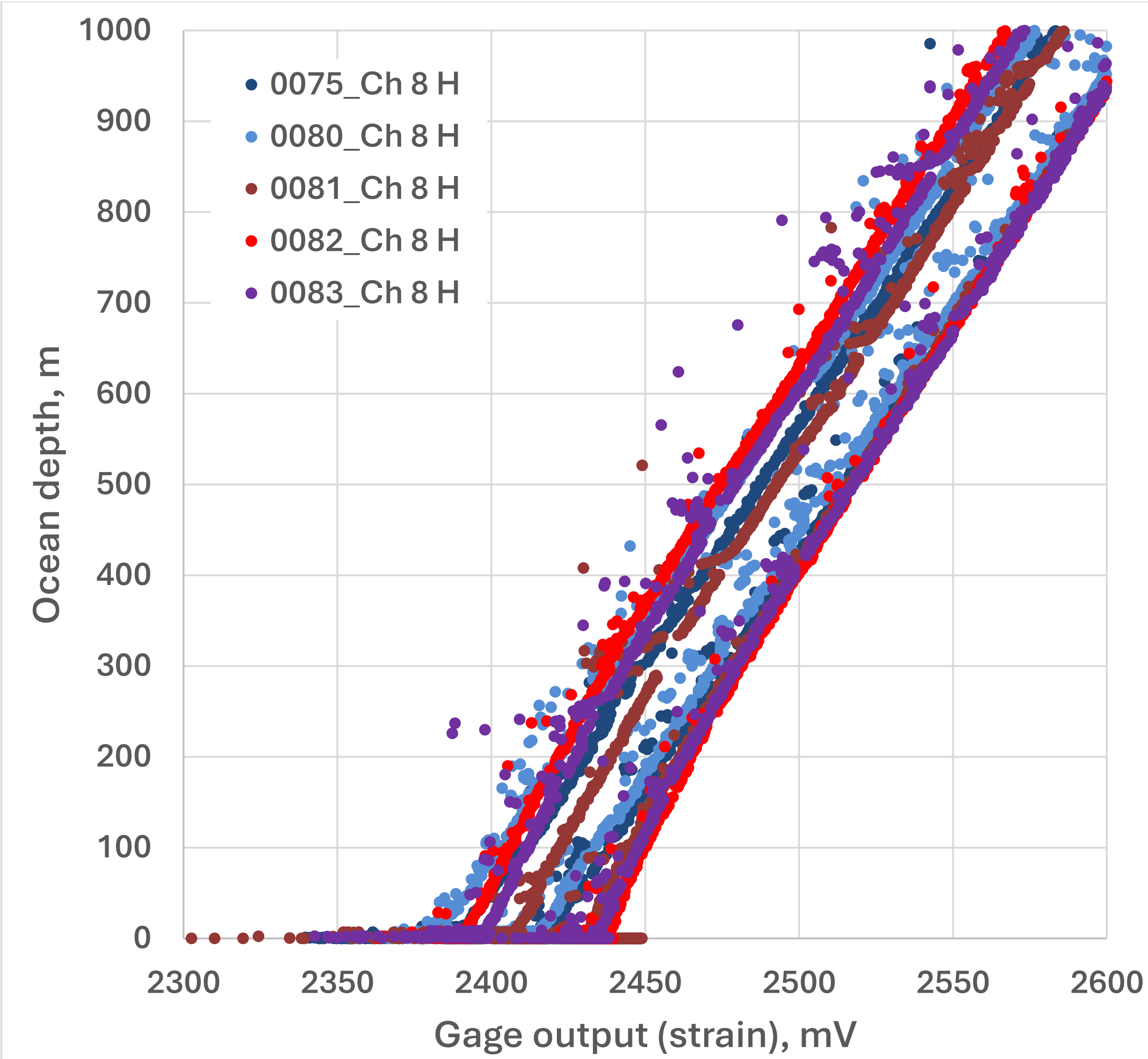


Figure 36. First and last 1000 m of dive depth for Dives 75 and 80 – 83 – Gage group 8 – hoop strain gage. The curves have been aligned using the linear portion of the descent phase of the trip. The strain for Dives 81, 82, and 83 show non-linear behavior between 0 m and 400 m dive depth.

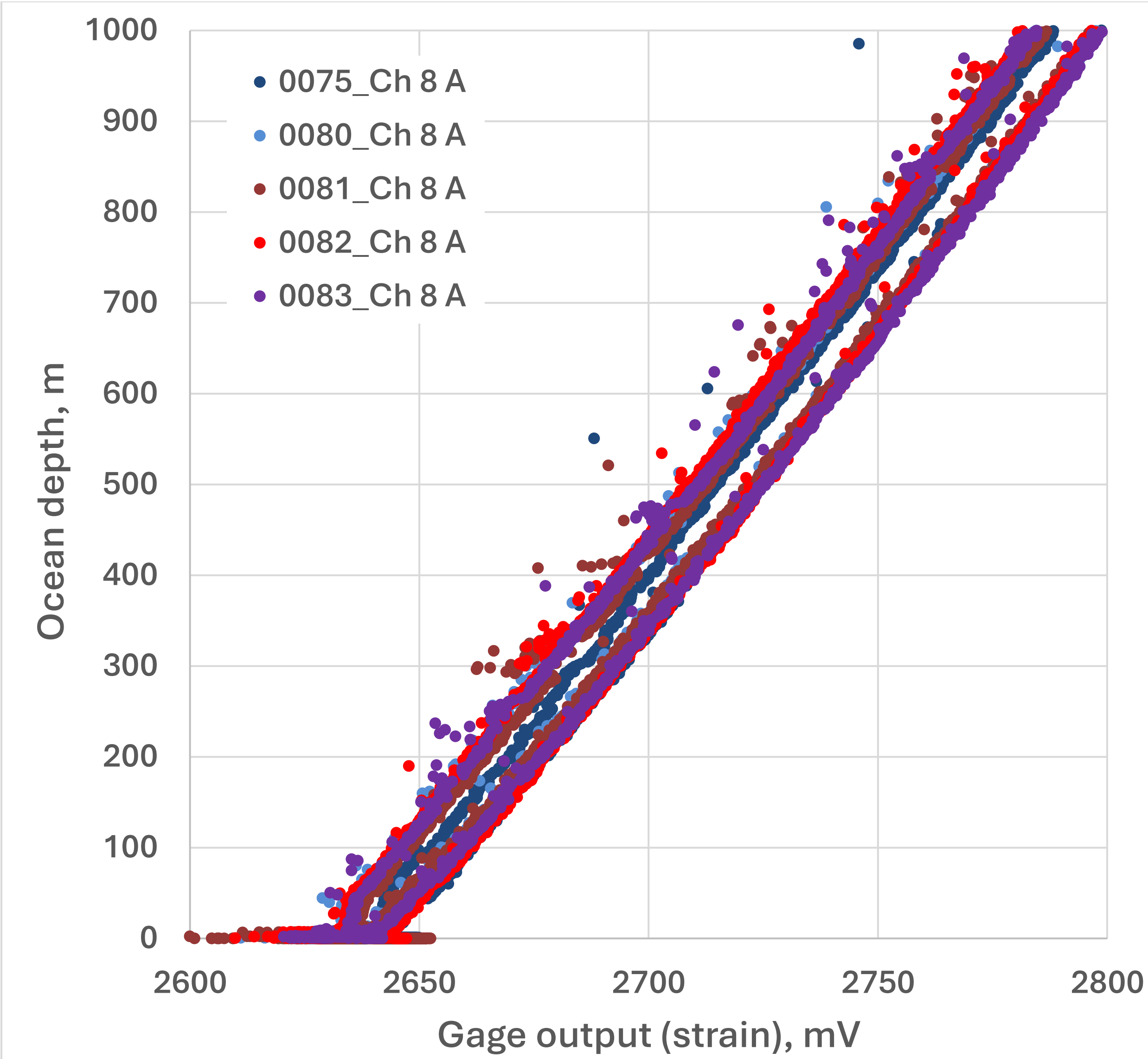


Figure 37. First and last 1000 m of dive depth for Dives 75 and 80 – 83 – Gage group 8 – longitudinal strain gage. The curves have been aligned using the linear portion of the descent phase of the trip.

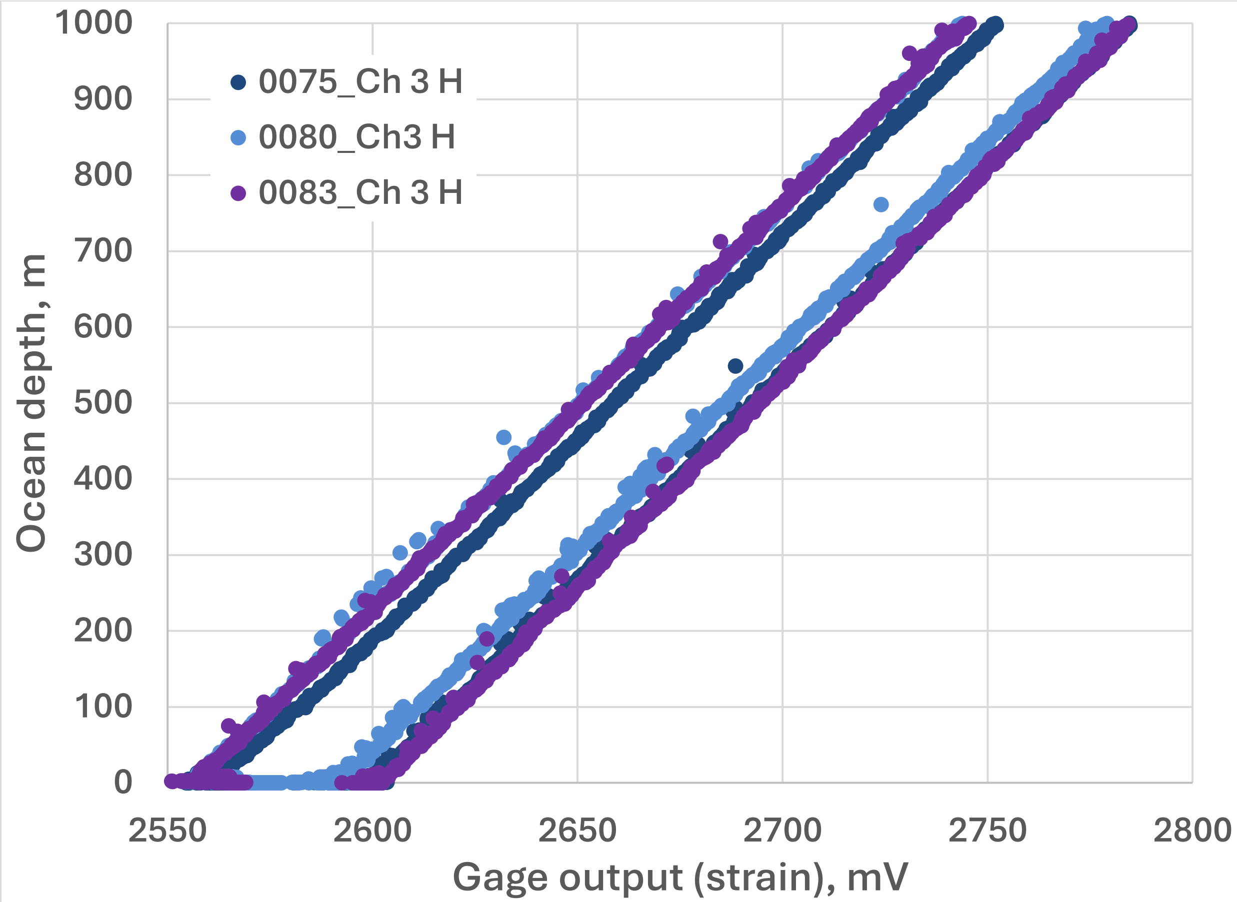
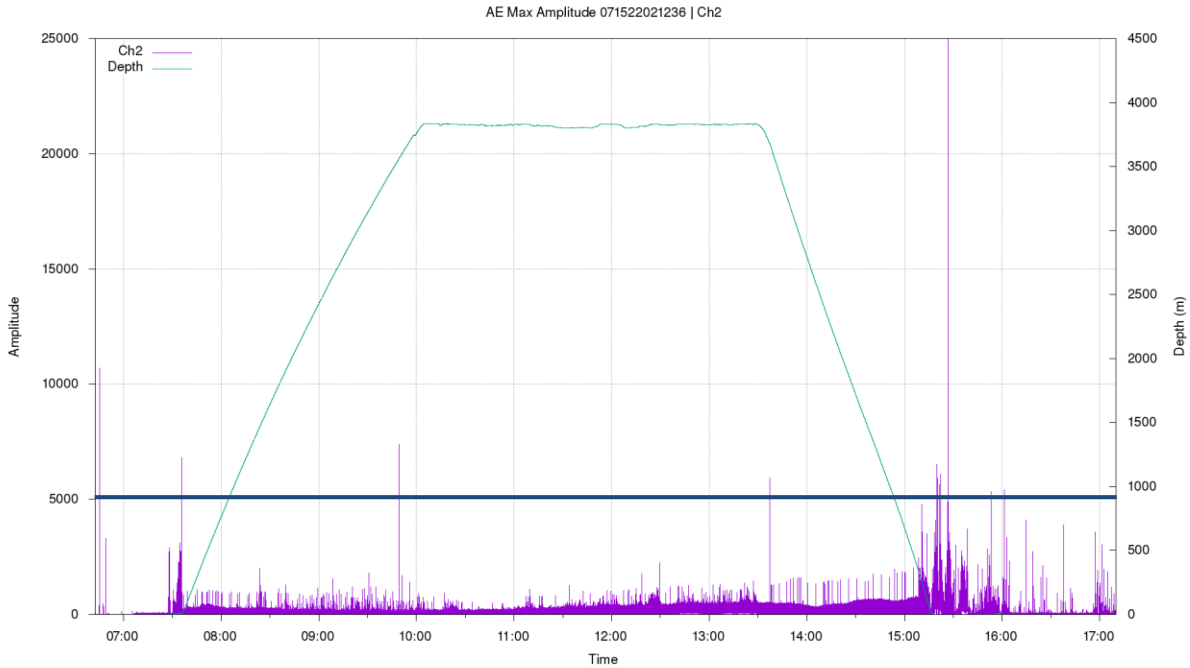
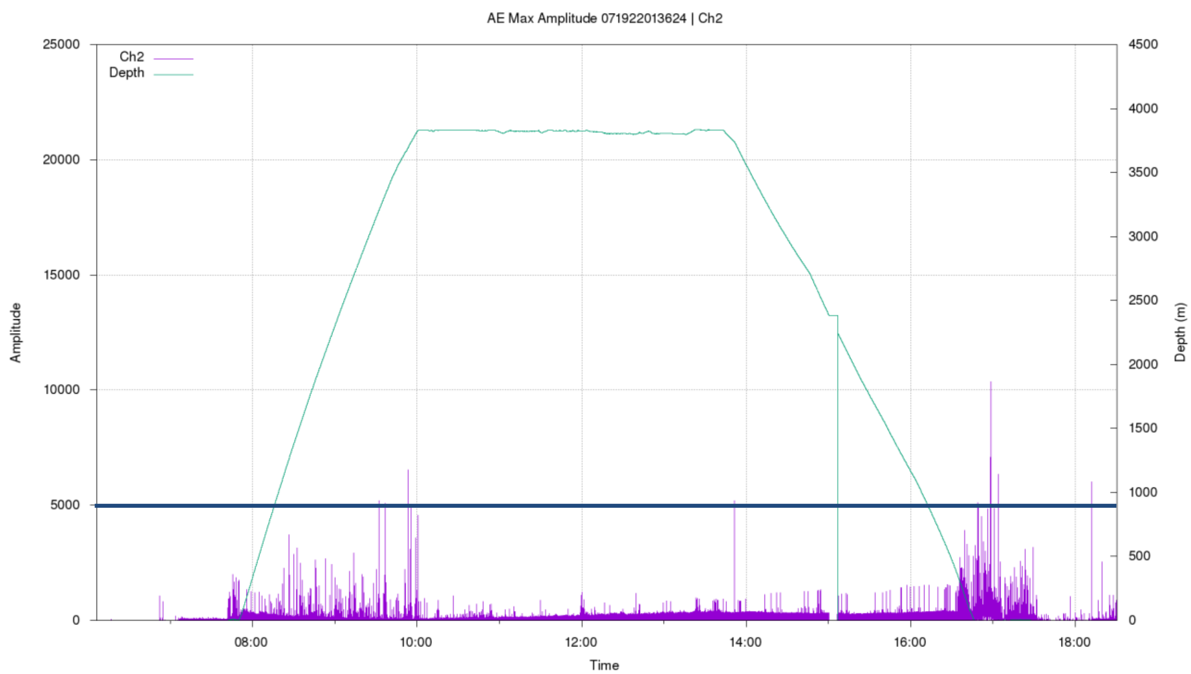


Figure 38. First and last 1000 m of dive depth for Dives 75, 80, and 83 – Gage group 3 – hoop strain gage. The curves have been aligned using the linear portion of the descent phase of the trip. The strain response was linear for all dives.

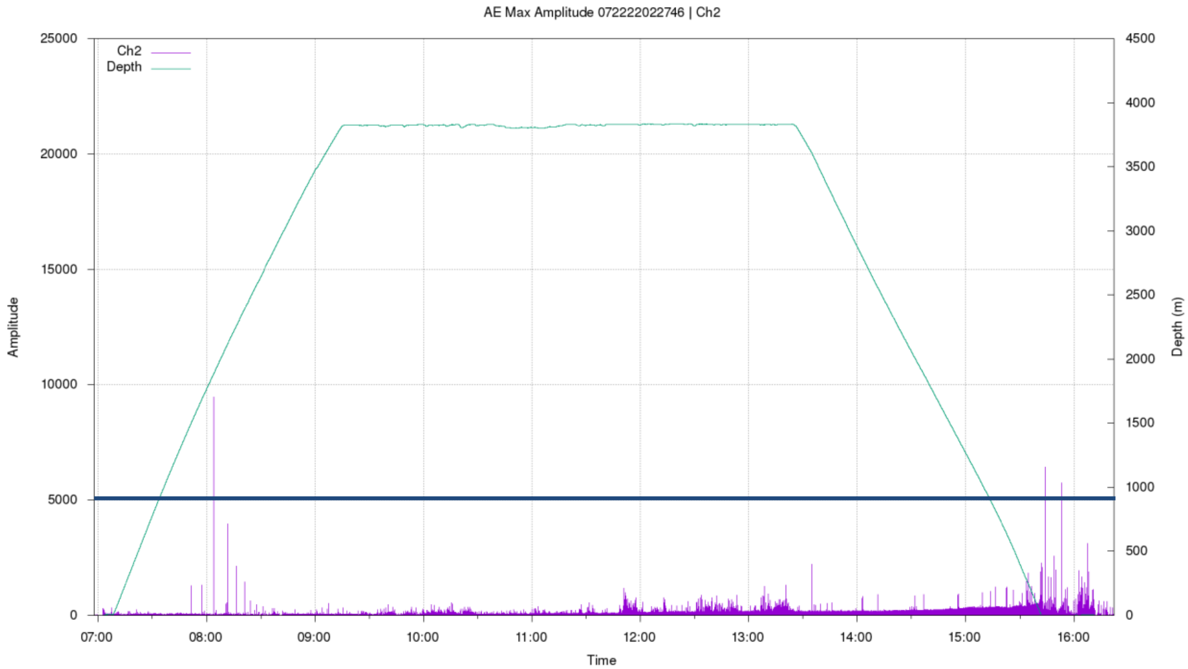


a)

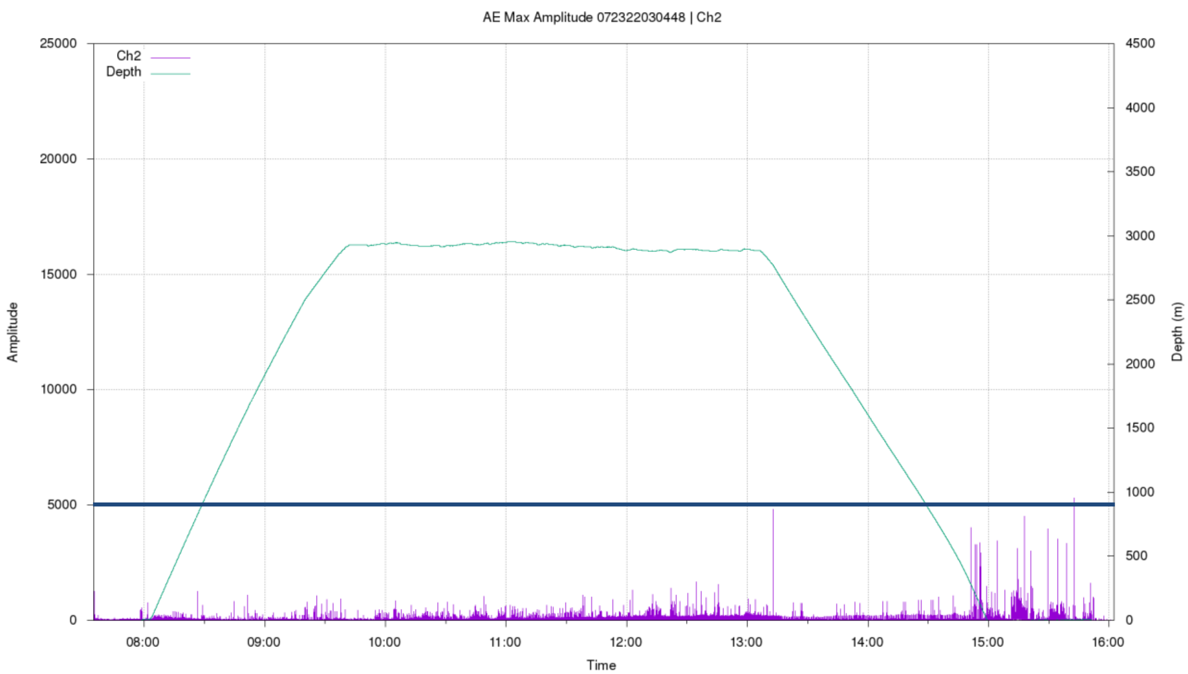


b)

Figure 39. Comparison of acoustic sensor channel 2 activity (forward port side sensor) for: a) Dive 80 and b) Dive 81. The hit threshold is indicated by a horizontal line.



c)



d)

Figure 39 (cont.). c) Channel 2 activity for Dive 82; and d) activity for Dive 83.

a) b)

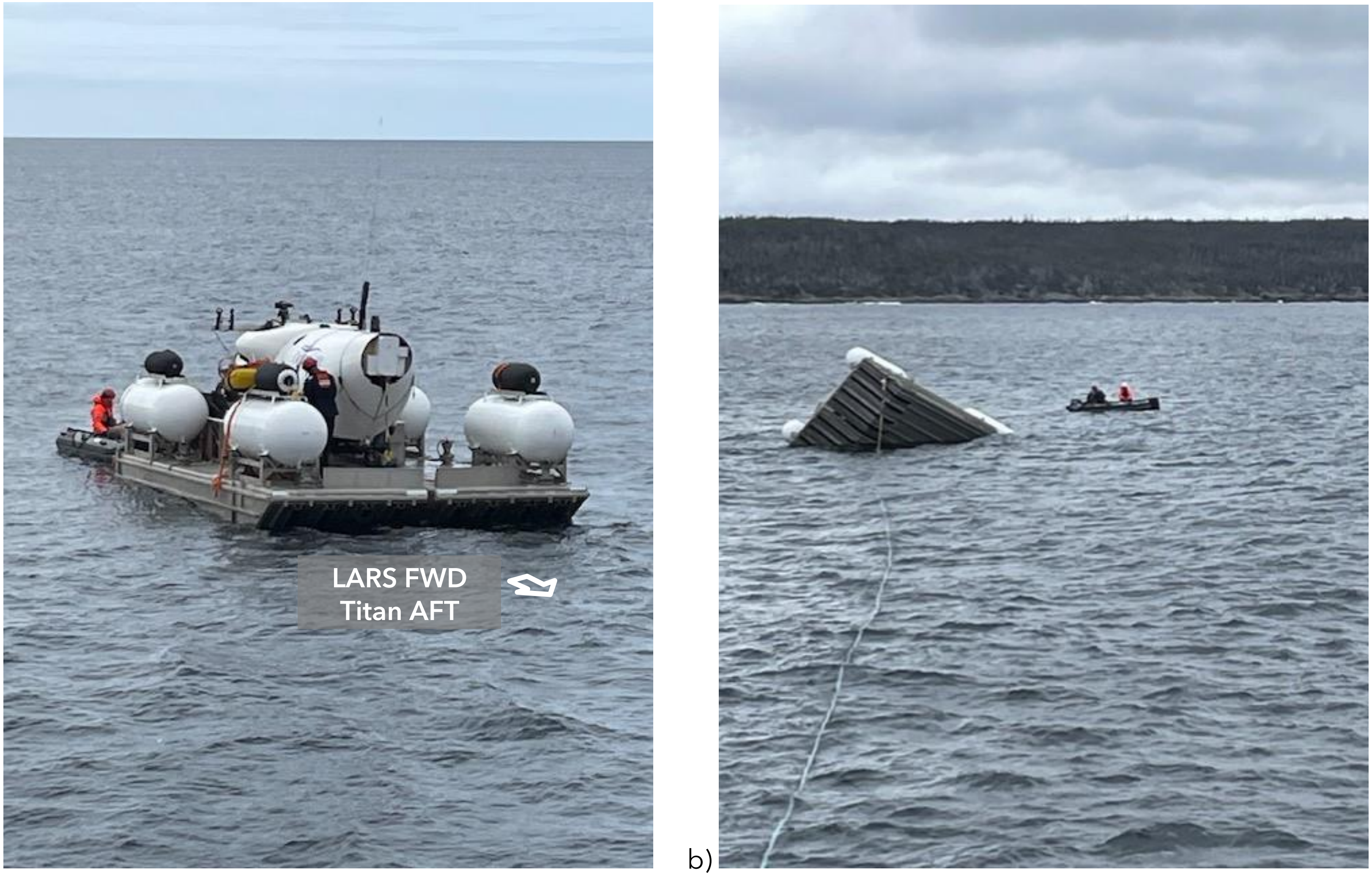


Figure 40. Images of tipping/upset events during 2023 expedition (Source: Steven Taragel): a) Post recovery after the forward end of the LARS (aft end of Titan) tipped downward. The tail cone separated as a result of the mishap; b) tipping event with the aft starboard corner of the LARS tipped downward; and

c) 

Figure 40 (cont.). c) aft end of LARS tipped downward in St. John's.

E. APPENDIX A: Additional strain response curves

The strain response of the forward dome is shown in figure A1. The forward dome was originally equipped with four strain gages: two in the polar orientation and two in the azimuthal orientation. The gages were placed at or near a weld adjacent to the viewport, at a high-stress location. From at least Dive 75 onward, only one polar gage was operational.

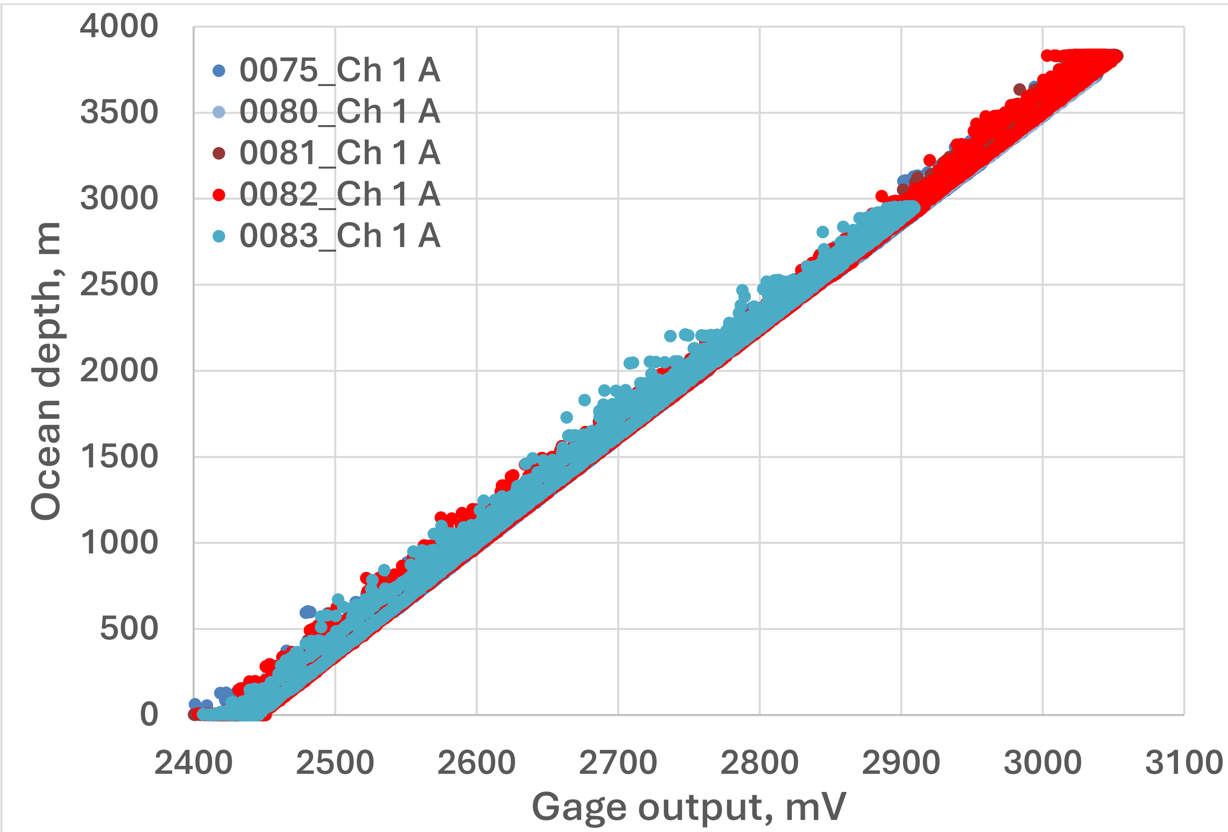
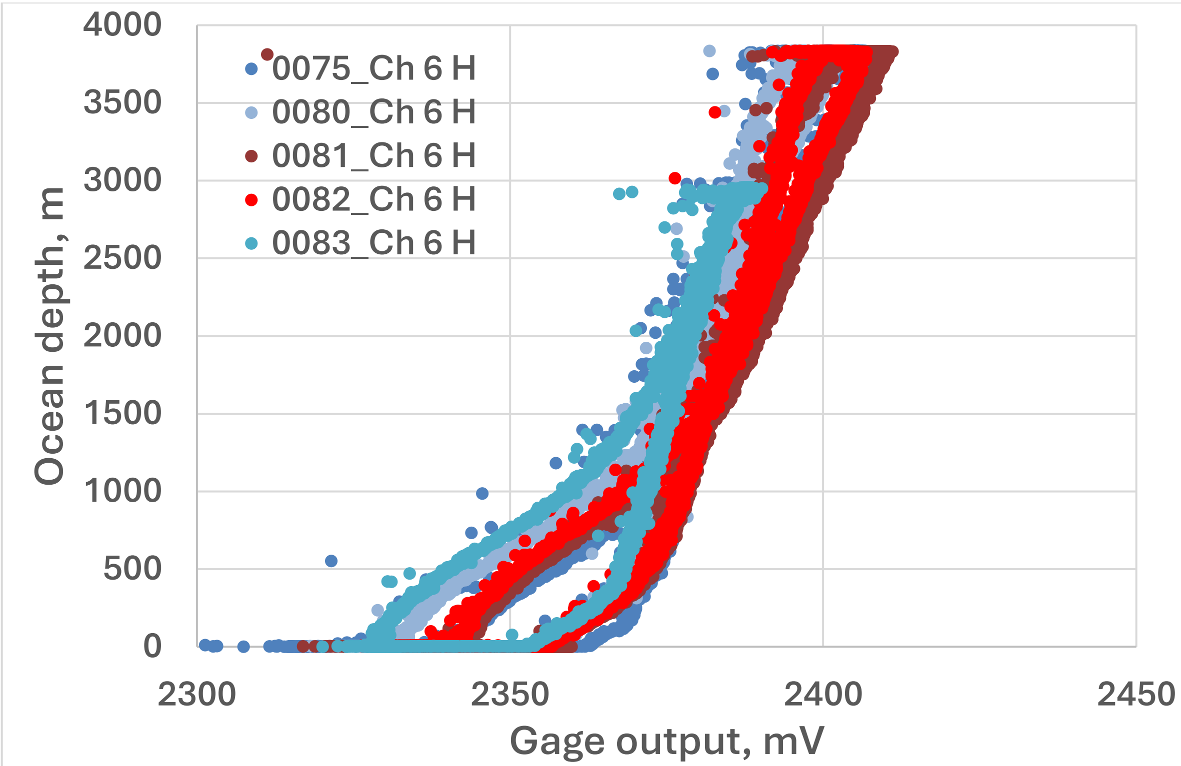
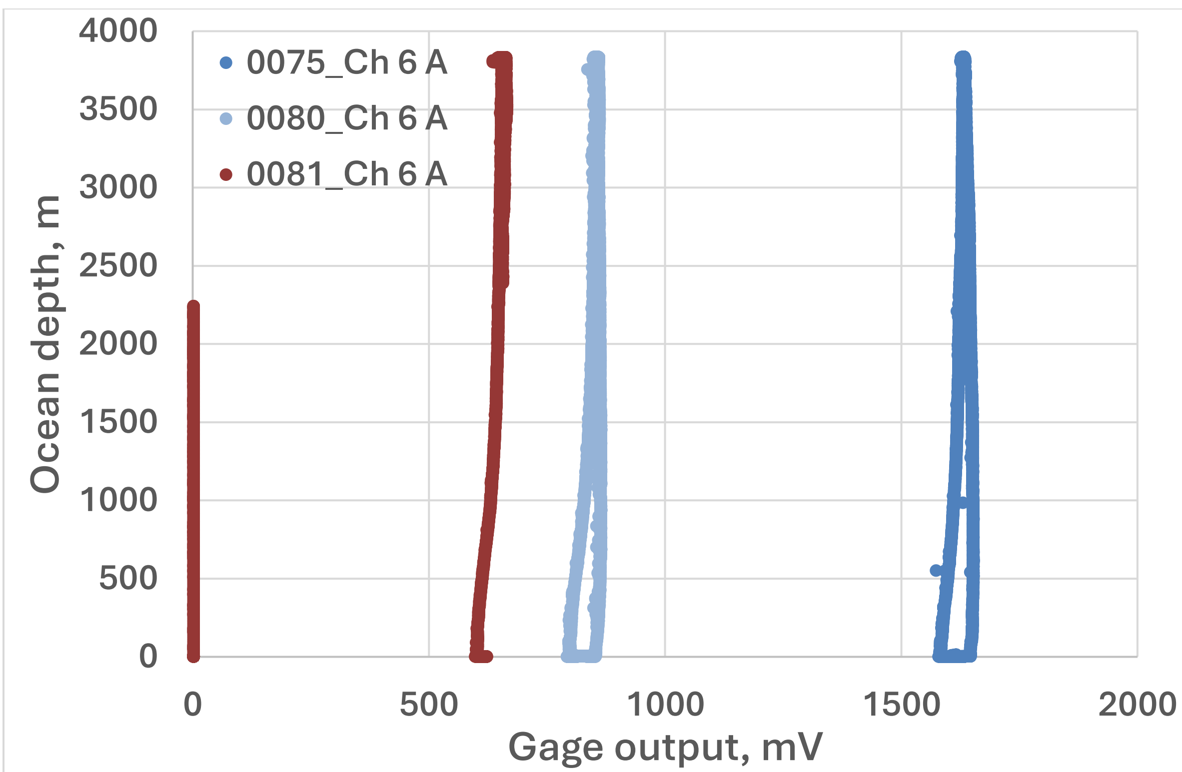


Figure A1. Plot of dive depth as a function of strain gage output for Dives 75 and 80 through 83 – Gage group 1 – "A" strain gage in the polar orientation.

The strain response of the aft titanium segment is shown in figures A2a and A2b for the hoop and longitudinal directions, respectively. Both gages exhibited a non-linear response. The longitudinal gage showed drift from Dives 75 to 80 and from 80 to 81. During the Dive 81 ascent, the longitudinal gage stopped exhibiting a strain response and did not show a strain response on subsequent dives.



a)



b)

Figure A2. a) Plot of dive depth as a function of strain gage output for Dives 75 and 80 through 83 - Gage group 6 – "H" and b) Plot of dive depth as a function of strain gage output for Dives 75, 80, and 81- Gage group 6 – "A".

The group 5 hoop gage output drifted between dives as shown in figure A3. None of the other gages attached to the composite hull showed similar drift from dive to dive.

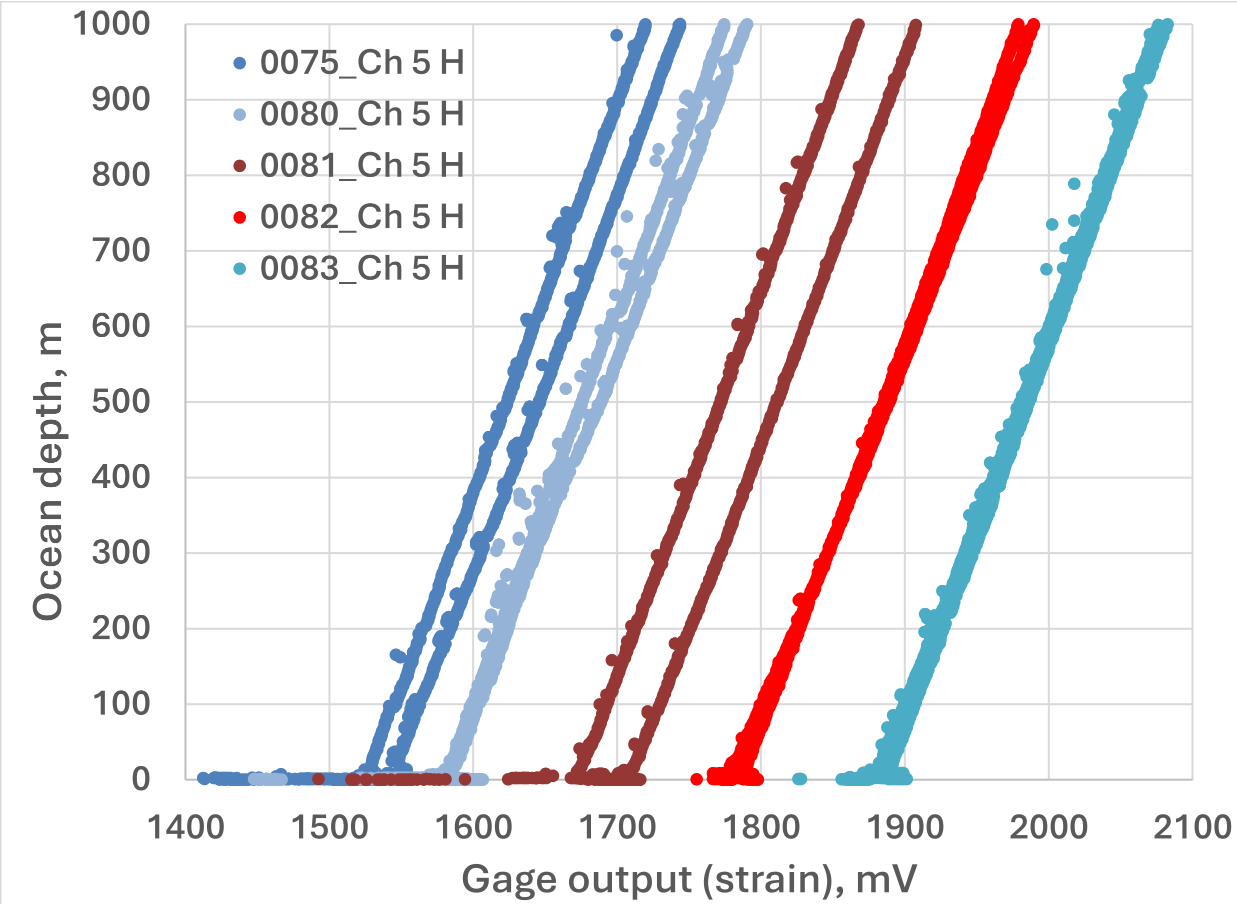


Figure A3. First and last 1000 m of dive depth for Dives 75 and 80 – 83 – Gage group 5 – hoop strain gage. The curves have not been aligned, showing the drift in gage output from dive to dive.