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Opinion paper

Comprehensive assessment of deep-water vessel implosion mechanisms: OceanGate's Titan submersible failure sequence explained

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ABSTRACT

This study outlines the physical mechanisms involved in a submersible implosion and analyzes the loss of the Titan submersible ('sub') that occurred on June 18, 2023 during a mission to visit the wreck of the Titanic. Titan's collapse mechanisms at the moment of implosion are described in detail and outer hull fracturing rate, subsequent implosion rate, accompanying heat release and other key processes are quantified. Plausible causes of the hull's leak leading up to critical loss of the sub's hermetic closure are reviewed using test results made publicly available by the U.S. Marine Board of Investigation. Their data indicated that the bond interfaces between the individual layers of the carbon fiber hull (Hull V2) were critically compromised due to manufacturing defects, voids, porosity, and inadequate adhesive integrity, resulting in significant delamination. Analysis of data from the real-time hull health monitoring system, revealed acoustic anomalies and strain shifts, pointing toward increasing structural fatigue, which went unaddressed prior to the fatal dive. The implosion process can be characterized by an instantaneous collapse of the air volume within the hull under extreme external pressure: even the tiniest leak would lead to destruction of the vessel's structural integrity. The destruction was the more devastating, because it was accompanied by a secondary explosion due to the heat exchange between the collapsing air volume and the ambient sea water. While the collapsing air was phase-changed into a supercritical state, the generated heat caused the adjacent seawater to evaporate and expand. Hull pieces fragmented by the initial implosion were strewn around during the secondary explosion phase, which ceased rapidly as the steam condensed back into seawater once again. The Titan incident underscores the urgent need for improved design standards, rigorous quality control in manufacturing, and enhanced real-time monitoring to prevent similar failures of future deep-sea exploration vehicles.

1. Introduction

Engineering designs are rarely perfect and never foolproof, because the occurrence of an extreme set of unanticipated circumstances may result in structural damage [1]. This applies especially to vessels purpose-built for the harsh environment of our oceans. In spite of all our efforts to keep surface vessels afloat and submarine vessels dry (on the inside), an estimated 1–3 million wrecks presently litter the sea floor [2]. These wrecks serve as grim reminders of how a combination of engineering limitations, navigation errors, bad weather and warfare may prematurely terminate the useful life of state-of-the-art vessels. In order to avoid the recurrence of engineering flaws, we commonly try to reconstruct the possible causes of marine vessel loss [3].

For example, one such failure, the sinking of the Titanic on April 15, 1912, received an astonishing amount of world attention, and became legendary [4]. Arguably, the failure of a state-of-the-art structure like the Titanic is experienced by the global community — in spite of all our marvelous inventions, science and engineering — as a stark reminder of our human vulnerability. The ship's legacy solidified in the mind of many when the wreck was located in 1985 [5].

Impressive visual imagery — augmented by digital means — shows in great detail what remains of the ship [6]. The stern section (Fig. 1a and b) lies 600 m away from the bow section (Fig. 1c and d) in a nearly 4 km deep part of the North Atlantic. The Titanic's cause of sinking has been analyzed in great detail [7]. Bolted hull plates came loose when dented by collision with an iceberg [8]. Sheared rivets and tears in the

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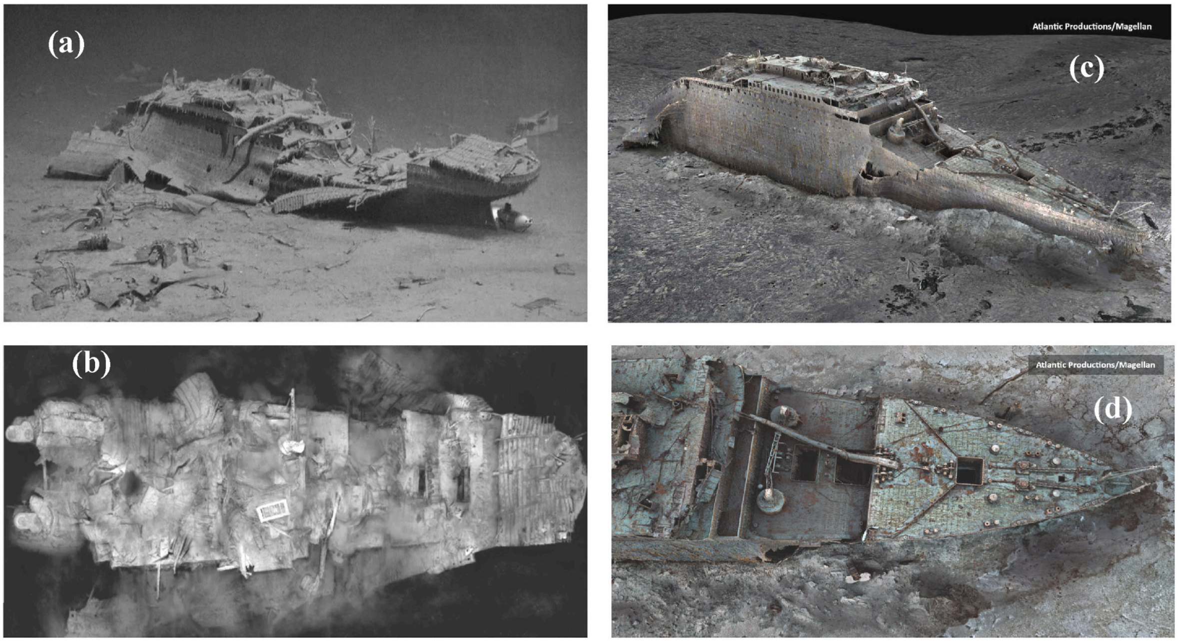


Fig. 1. (a)–(d) 3D views of Titanic's two main wrecks, comprised of its stern section (left images) and its bow section (right images). The images were rendered based on digital reconstruction by specialized artists and companies. Top row shows oblique views, bottom row shows top down views. Courtesy Atlantic Productions/Magellan.

hull below the waterline caused the ship's first five bow compartments to flood and a sixth compartment flooded partially, controlled by pumps [9]. However, the Titanic was designed to stay afloat only with a maximum of four compartments flooded, and therefore sank 2 hours and 40 minutes after the collision.

In fact, hull damage similar to that inflicted on the Titanic in 1912 had already occurred to its almost identical sister ship (one of two), the RMS Olympic. The Olympic nearly sank on September 20, 1911, when it

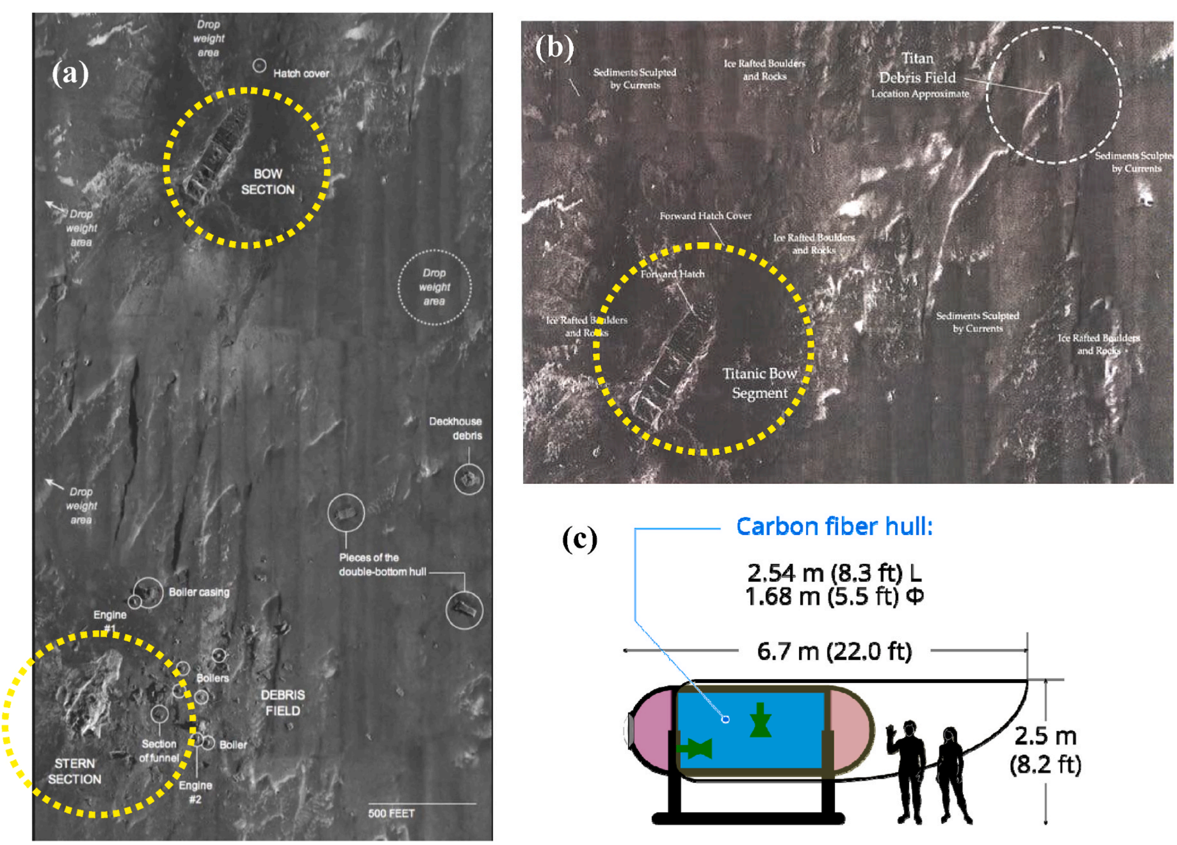


Fig. 2. (a) Left map: Wreckage and debris field showing the final resting place of Titanic's stern and bow sections [17]. (b) Upper map detail with position of Titan sub's debris field relative to the Titanic's bow section wreck [17]. (c). Schematic of the Titan submersible, with dimensions [18].

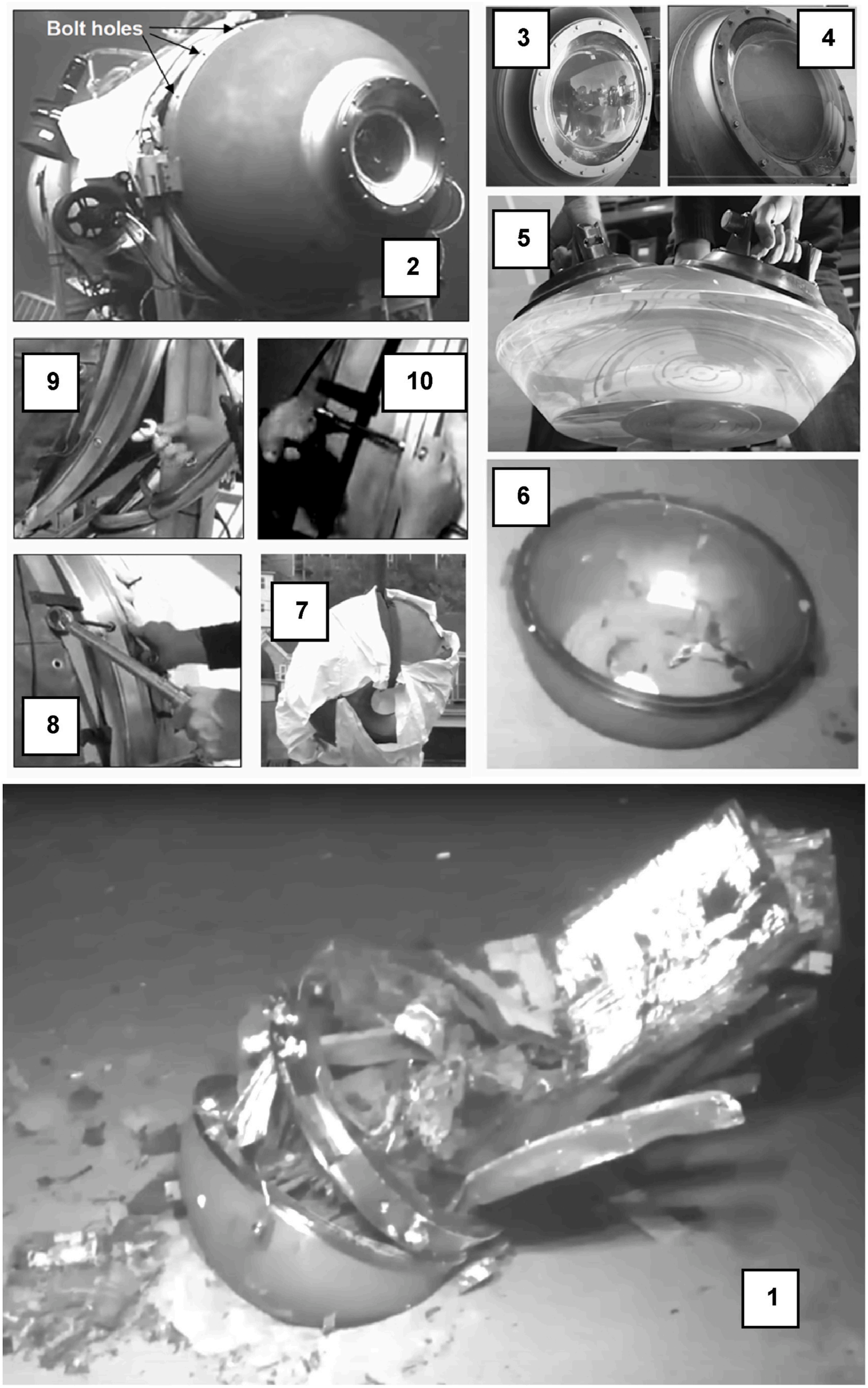


Fig. 3. Video stills from Titan parts before and after implosion [14–16]. Image 1: Imploded rear part of the sub. Images 2–4: Pre-accident front cone. Image 5: Perspex lens before assembly. Image 6: Titanium front cone after implosion; Perspex lens is missing. Image 7: Salvaged front cone lifted ashore. Images 8–10: Bolting of front cone hatch door.

collided with a cruiser (HMS Hawke) in the port of Southampton [10]. The ship made it safely to port for hull repairs and served until 1935, and was then scrapped. The Brittanic — Titanic's youngest sister ship — served as a hospital ship in WWI, and sank in 1916, after striking a sea mine in Greece [11].

The Titanic's wreck has proven to be a magnet for further studies, artifact salvaging, subsea tourism and the entertainment industry [12]. Ultimately, this led to the unfortunate loss of an experimental sub developed by OceanGate for tourist trips to the wreckage of the Titanic. The nimble sub, named Titan, was manned by a pilot and four tourists on board, all of whom died instantly when the vessel imploded during its last diving trip to the Titanic [13].

The present paper reconstructs the implosion event, based on (1) visual inspection of the very detailed imagery of the Titan's wreckage (Sections 2 and 3), (2) sensor data from dives immediately prior to the fatal dive (Section 5.1), and (3) material analyses (Section 5.2), combined with (4) fundamental physics (Section 4 and Appendix A) and (5) logical deduction (Section 6). The data used are selected from what was made public by the US Marine Board of Investigation during hearings 16–27 September 2024 [14]. These hearings covered a wide range of topics, including company culture and expert testimony on technical findings.

Key data have been selected for this study to support a fairly conclusive reconstruction of events, shedding new light on what may have actually occurred at the moment of failure. This study goes beyond the evidence presented during the hearing by highlighting that a submersible implosion is primarily driven by air collapse, which generates heat and leads to a secondary steam-driven explosion, ejecting imploded elements into the surrounding water. The current analysis in no way aims to undermine the ongoing investigation, but may provide critical new insights that could either be corroborated or refuted by future research.

2. Titan wreckage location

An enormous volume of speculative theories has circulated online and continues to develop regarding the causes of the loss of the Titan [15,16]. This study does not enter into character analysis of the company owner, lack of safety certification, and many of the iconoclastic design choices made in the construction of what was in essence an experimental vehicle. Instead, the focus will be on the physical processes occurring at the moment of implosion and how sub-implosion works in the first place.

The principal physical mechanism of imploding subs is that the volume of a certain air mass enclosed in the pressure chamber at the surface will not be able to maintain the same volume at depth unless protected by an elastic hull. The elastic hull must absorb and withstand all the stresses caused by the pressure difference between the inside fluid and the fluid outside of the sub. If even the tiniest flow path were to occur by connecting a sub's air space (which is effectively at near-surface pressure) with the outside water body (at immense pressure), then the air volume in the sub will instantaneously collapse in a violent manner, known as an implosion. In the same instant, the elastic hull will collapse due to the additional stresses caused by the collapsing air volume.

This tragic fate of implosion befell the manned Titan sub on June 18, 2023 [14–16], with paying passengers eager to take a direct look at the wreck of the Titanic, which had sunk over a century earlier. The wreckage of the imploded Titan was located later in June 2023 by remotely controlled vehicles, which collected high-resolution video footage of the debris parts in place. The Titan's debris field lies directly northeast of the Titanics' debris field (Fig. 2a), and occurs about 200 m northeast of the Titanic's bow section (Fig. 2b). Key parts of the sub's wreckage were hauled to the surface for further inspection. Essential stills from the salvaged footage, and screen grabs from intact sub parts prior to the accident, are used (public data) to analyze what may have caused the Titan's hull breach. The visual scenery of the crash site and recovered items are combined with selected sensor data results and material analyses released during the September 2024 hearings of the U. S. Marine Board of Investigation (MBI [14]).

The hull of the Titan (Fig. 2c) was comprised of a cylinder made of carbon fiber (blue segment) capped at either side by Titanium domes (magenta). It has been posited that the Titanium rings glue-bonds to the carbon fiber was the first cause of failure. However, we will see that Titan's destruction involved the following principal mechanisms: *(A) Primary Implosion Triggers*, given here in arbitrary sequence: (1) viewport collapse, (2) hull collapse, (3) bonding failure between the Titanium rings and the carbon fiber hull, and (4) failure of bolts that connected the two end caps to the Titanium rings mentioned under (3), and *(B) Secondary Explosion*. Based on inspection of the evidence it seems possible to sequence the failure of structural elements, and reconstruct how this cascaded, instantly, into total loss of the engineered structure.

For clarity, it must be stated that the outer, insect-like wings of the Titan (yellow in Fig. 2c) were mainly hydrodynamic design esthetics, and have little bearing on pressure-withstanding of the functional hull; the pressure chamber segment is the blue cylinder with its Titanium end caps.

3. Visual inspection

Key elements of the Titan's pressure chamber are depicted in Fig. 3, which includes before and after implosion images. The most straightforward line of reasoning inferred from only visually inspecting key parts is as follows. The rear cone is after implosion seen sitting in dog-like position on the seafloor (Fig. 3, Image 1), not deeply buried, and evidently landed there without bouncing; the heaviest part is the rear, which is filled with all debris of the collapsed carbon fiber hull. Importantly, the rear cone was still partly connected to the Titanium ring that was initially glued to the carbon fiber cylinder hull part. And some carbon fiber slabbing was found still bonded to the titanium ring, and was sticking upward. A rectangular white hull segment remained largely intact. The heap of carbon fiber seen crumpled in the rear cone, suggest that the collapsing air volume ended up concentrated in that rear end. We will compute in Section 4 what was the remaining volume of the collapsed air after the implosion.

The front cone with its view port hatch is seen attached intact in the pre-accident Image 2 (Fig. 3). The front cone was bolted via 18 tiny holes onto the Titanium ring that in turn was glue-bonded to the carbon fiber cylinder. The 'eye' of the viewport is made up of a thick Perspex lens (Image 3) sitting at the apex of the front cone in a bowl-shaped depression and was held in placed with a frontal ring bolted onto the Titanium cone with 16 bolts (Images 4 and 5).

The salvaged Titanium frontal port hatch (seen dangling from a crane in Image 6) has the lens missing. This can also be seen when the port hatch was retrieved from the ocean floor (Image 7). Apparently, the front cone blew off and the lens fell out. But, what is absolutely crucial to note is that the front cone, as it rest upside down on the seafloor, has no longer its Titanium base ring with flange connection to it.

David Pogue, a science correspondent for CBS, who had spent nine days with the sub company, made notion of the fact that there were 18 bolt holes around the hatch, but the crew only used 17 bolts, dismissing the 18th bolt claiming it made no difference [19]. Another know fact is that on a trip prior to the disaster, only 4 bolts were left on the port cone, but these bolts sheared off when the submersible was towed onto the salvage platform along the expedition vessel, and the view port hatch tumbled loose onto the same platform and nearly fell into the sea.

The 17 bolts used to fix the hatch to the Titanium ring (which was in turn glued onto the carbon hull), were affixed by hand using a wrench for the nut and a turning wrench to tighten the bolt (Images 8–10 in Fig. 3). The diameter of the bolts is estimated to have been no more than 8 mm, which must be considered undersized for the shear stresses occurring. Separately, the glue bonds of the multi-bonded carbon fiber

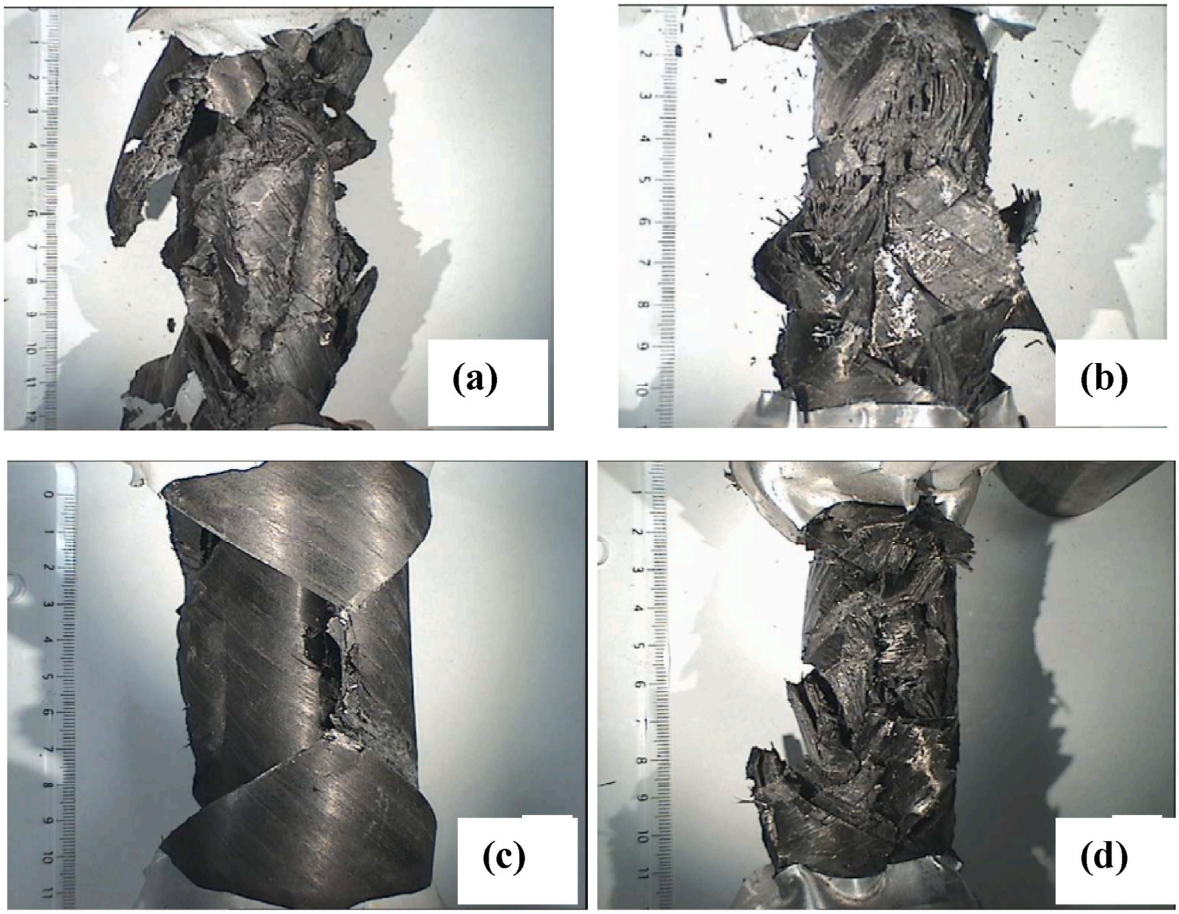


Fig. 4. (a)–(d) Examples of imploded carbon composite tubes from 2005-implosion tests in a 2400 bar pressure vessel [21].

hull and glue bonds to the Titanium flanges were also weak points (see Section 5.2).

4. Computations

4.1. Air and hull implosion process

The volume (V) of the air in the sub's intact compression chamber of length L and finite radius r_e is here approximated by computing the cylinder volume from:

$$V = \pi r_e^{\,2} L \tag{1}$$

Substituting $r_e = 0.84$ m and $L = 2.54$ m, gives V = 5.63 m^3. The density of the air in the chamber at surface condition is $\rho = 1.225$ kg/m^3. A key step now is the computation of the mass (M) of the entrapped air:

$$M = \rho \pi r_e^{\,2} L \tag{2}$$

Using the given numbers indicates $M = 6.897$ kg of air was sitting inside the pressure chamber during each dive. When we now move to the recorded depth of 3777 m (the site of the retrieved cones) and assume that the accident occurred shortly after communication contact with the support vessel was lost, the sub was at about 3500 m below sea level. The density of air if subjected to the pressure of 350 bar at that depth, will be about 416 kg/m^3. This means that if the air mass of 6.897 kg inside the sub was subjected to the ambient water pressure, its final volume can be computed, using $M/\rho = V$, which gives 0.0166 m^3. At the new ambient temperature and pressure, commonly available phase diagrams for air reveal the collapsed air would be in supercritical state [20].

4.2. Hull collapse modes

The implosion process of the sub is led by the air volume collapsing from $V = 5.63$ m^3 to just 0.0166 m^3 or 16.6 L, a 99.7 % reduction of the original air volume (Section 4.1). As the air collapse occurs, the hull will buckle due to the compounded effect of the external positive pressure on the hull and the negative pressure due to air collapse inside. In fact, scaled implosion tests on carbon fiber tubes were originally published in 2005 [21] (many years prior to the Titan development), shown here in Fig. 4.

The experiments of Fig. 4 showed relatively thick-skinned tubes (which are stronger than thin-skinned ones), which develop primarily shear-like fractures created by the large differential between the hoop and the longitudinal stresses when implosion occurs. In contrast, many rectangular hull panel fragments (Fig. 5a) were found at the Titan debris field location. These panels came off the tubular hull via large longitudinal tear fractures. Such fractures are consistent with inward buckling and failure of tubes with relatively thin skins during an implosion [22, 23].

One may now wonder, was the Titan thin-skinned? The answer is, yes, in a way, as explained first here. At the Titan crash site, many signs were observed of delamination or unbonding between the 1-inch thick layers of the 5 layer thick multi-layered carbon fiber hull. Fig. 5b shows one example, where three inner layers of the hull became unbonded, and layers 4 and 5 are outside the field of view, also delaminated. This is very precious diagnostic information, telling us that the delamination process facilitated the inward buckling of panels already thinned by delamination due to cyclic loading during prior dives (see evidence in Section 5.1), actively delaminating as the implosion occurred. If delamination had not happened, the failure would have need to occur in the shear

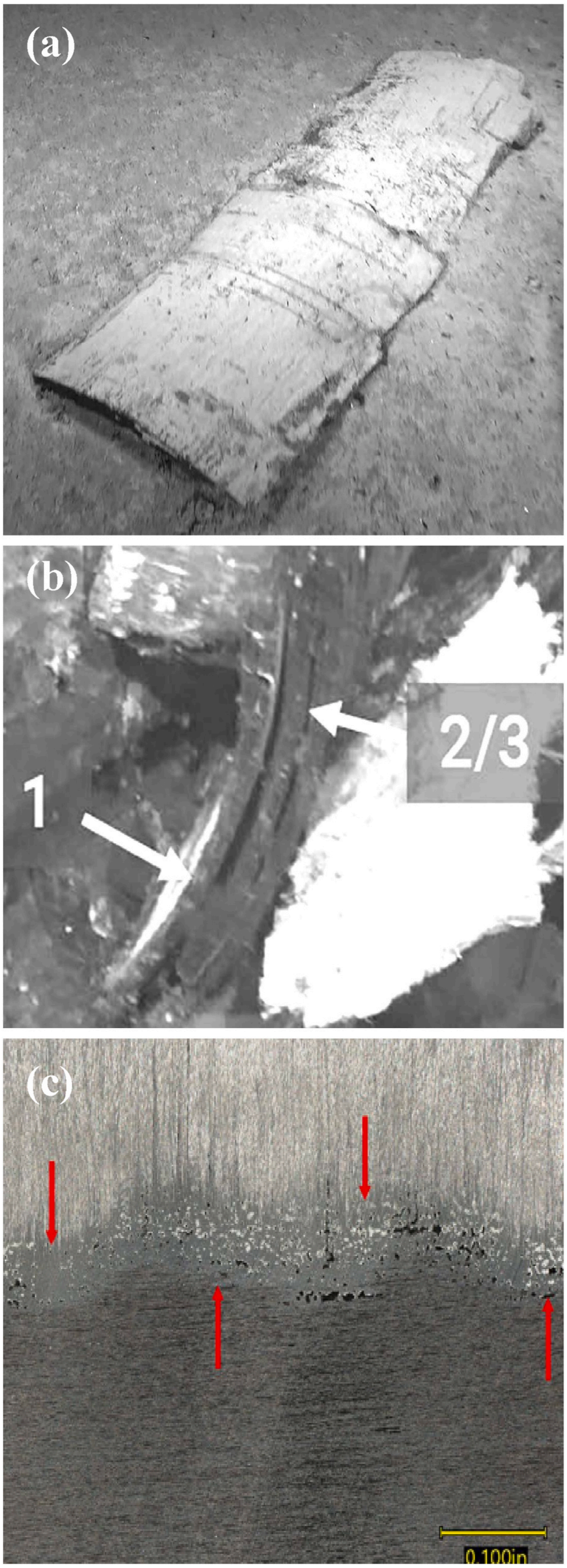


Fig. 5. (a) Hull fragment (about 2 × 6 ft) is a delaminated slab, inner layer 1 of the carbon fiber hull, which tore along two longitudinal fractures which are known to develop when cylinders buckle inward and reach the failure limit. (b) Extensive delamination was observed of hull slabs retrieved from Titan's debris field (c) Evidence of micro-pores in hull material [14].

mode of thick-skinned tubes, which requires higher stresses (and thus greater depths) than for the occurrence of longitudinal fractures associated with inward buckling. Without the delamination, the Titan sub might have been able to withstand the pressures at the depth of the Titanic wreck (as it had on previous dives). Unfortunately, there was ample evidence of advancing delamination as will be discussed later (Section 5).

There was no mention of heat-induced damage in the material analysis report published by the MBI. However, it is postulated here that a line of pores is seen on the surface of a carbon fiber hull fragment (Fig. 5c), assumedly retrieved from the sea floor, has a toasted appearance. These were simply called pores by the ISB, but are here considered possible degassing pores, created along the contact line of heated (dark portion) of the hull fragment and colder portion (lighter zone) of the hull. In fact, there are dark, scratch like features above the porous degassing zone, which are interpreted here as heat blast markings. However, this is only a speculative observation at this stage.

4.3. Thermodynamic effects

Thermodynamic effects were ignored in the above analysis, and the physical process of implosion can be nuanced by briefly considering these effects as well. Heat exchanges and phase changes were not considered in the simple analysis of Section 4.1. However, the imploding air volume will heat up during its adiabatic compression in a way described by the gas law:

$$T_I = T_a \left(\frac{P_I}{P_a}\right)^{\frac{\gamma-1}{\gamma}} \tag{3}$$

Using an initial air temperature $T_a = 300$ K, pressure ratio $\frac{P_I}{P_a} = 350$ and heat capacity ratio $\gamma = 1.4$, the estimated implosion temperature is $T_I = 1600$ K. Therefore, the temperature of the 16 L of compressed air inside the imploding hull briefly scorched the hull fragments imploding around it. Also, an instantaneous phase-change of seawater to steam was triggered by the heat generated during the implosion of the air, which in turn caused an explosive event as a secondary effect, superseding the initial hull implosion. While the collapsing air was transformed into a supercritical state, the generated heat would cause adjacent seawater to evaporate and expand. Hull pieces fragmented by the initial implosion were subsequently strewn around during the secondary explosion phase, which ceased rapidly as the steam condensed into seawater once again.

4.4. Implosion rate and acoustic effects

The rate of implosion of the air volume inside a collapsing sub is controlled by a transient jump in the deficient pressure in a finite cylinder space. The travel rate of such a pressure transient is controlled by the pressure difference between the sub's outside and its interior, given the boundary condition of a confined cylindrical space and initial condition of being air-filled. These simple inputs suffice to estimate the time required for the pressure transient to remove the pressure difference between the inside and outside of the cylinder space (see Appendix A1). The analytical solution shows that the Titan's implosion event took a fraction of a millisecond, which therefore can be considered instantaneous; the crew could not have consciously registered the implosion event itself.

However, later sections in this study also infer that longitudinal buckling of the carbon fiber hull resulted in longitudinal fractures which propagated from the front to the back through the outer layer of the carbon fiber hull, before it was eventually breached – as needed for the implosion to occur. Using analogy to a hydraulic fracturing process in rocks, the rate of fracture propagation was estimated to have been rather slow (as detailed in Appendix A2). Based on dimensions of the hull and the estimated rate of fracturing of the hull due to fluid advance between the delaminated Layers 3 and 4 of the hull, it was inferred the crew may

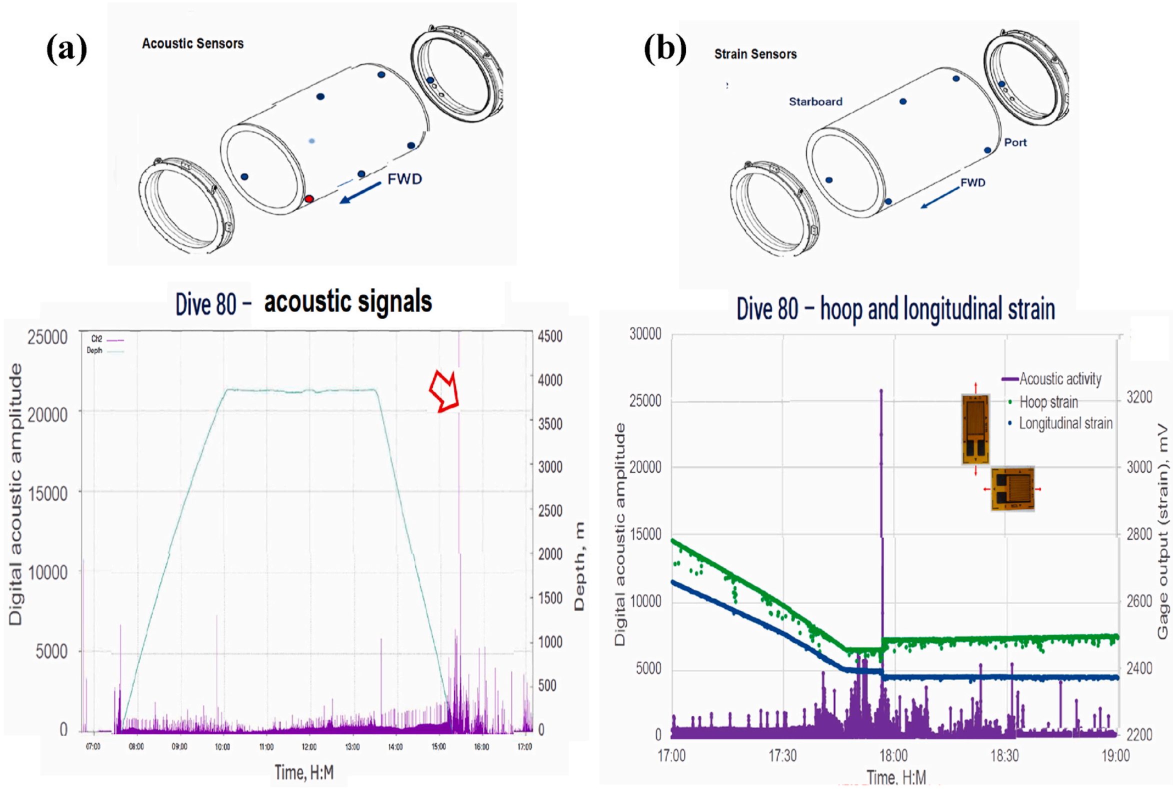


Fig. 6. (a) Dive 80 recording of cracking sounds (purple, amplitude marked on left-hand scale). Green line shows diving depth (marked on right-hand scale). The cracking starts at the beginning of the dive, kicking off with a high amplitude event, returning to lower sounds with a peak amplitude close to arrival at bottom and another peak when the ascend begins. The highest peak occurred after surfacing, a loud 'bang' was heard, marked by the red arrow. (b) Strain gauges (measuring mV) for hoop strain (green) and longitudinal strain (blue), show a distinct shift in mV-magnitude after the occurrence of the 'bang' sound. The increased differential between the hoop and longitudinal strain would persist on future dives.

have heard the advancing fracturing process for nearly a full minute before the actual implosion occurred (Appendix A2).

4.5. Human remains

The implosion of the sub provided a massive squeeze on the humans inside and crushed their bones and tissue to a lump, assumedly in a similar way as their surrounding air volume collapsed (Section 4.1). The density of a human body at the surface is 985 kg/m^3 and assuming an average weight of 75 kg for each of the five men, human volume in the vessel was $375/985 = 0.38$ m^3, which is assumed to match the volume of the hollow cones. The density of the human remains at the implosion depth will be higher than at the surface; assuming it to be 1085 kg/m^3, reduces the heap of crushed bodies to $375/1085 = 0.35$ m^3 or 350 L. As blood and other readily lost human body fluids would be expelled by the squeeze, and lost to the sea water, a further reduction of the volume of human remains to about 300 L is expected, which (in this purely clinically focused analysis) human debris volume equals one-and-a-half barrels of oil. Although there were discreet reports of some human remains having been recovered, it is obvious that the final explosion may have dispersed these remains over a diffuse region, and little remained to be recovered.

5. Sensor data and material analyses

The Titan reached the depth of the Titanic wreckage 13 out of 90 dives, according to passenger waivers signed by OceanGate customers. When the Titan imploded in 2023, it had its second hull (Hull V2), which was manufactured and made ready for use in 2021. Between 2019 and 2021, all trips were scrapped, the reason being that Titan's first carbon fiber hull (Hull V1) manufactured in 2017 had developed so many cracks, that it was retired in 2019. Hull V1 had made only 50 submersion dives, just three of which were to 4000 m.

A successful dive to the Titanic, with Hull V2, was completed in 2021. The Titan imploded on its 5th mission of 2023. During this final Dive 84, it had come close to the Titanic — moments before its implosion occurred. None of the previous missions in 2023 had succeeded to reach the Titanic depth (3777 m) either due to poor weather conditions or other issues.

This section summarizes some of the key findings regarding Titan's sensor data and material testing as reported by the National Transportation Safety Board and U.S. Marine Board of Investigation in reports released during hearings in September 2024 [14]. A principal conclusion was that, at present, the root cause for the sub's failure is indeterminate. However, post-mortem analysis of Hull V2 fragments revealed the material integrity had significantly deteriorated over its 3-year service period (from 2021 up to its implosion dive in 2023). The hull showed signs of significant cyclic fatigue. And there was acoustic and strain sensor data which had already shown, even before the fatal dive, that structural changes had occurred in the elastic hull. But the tell-tale sensor data of cyclic fatigue of the hull were apparently not recognized as critical, and diving continued until the final journey ended in a catastrophe.

5.1. Real-time sensor data

Titan was mounted with what is called a real-time hull health monitoring (RTM) system; data of acoustic and strain sensors were recorded during at least a number of dives (Dives 76 and 80–83) [14, 24]. The hull had 7 acoustic sensors, and the rear flange had 1 acoustic sensor. Separately, there were 5 strain gauges on the hull, 2 on the forward dome, and 1 on the rear flange. A loud acoustic 'bang' was

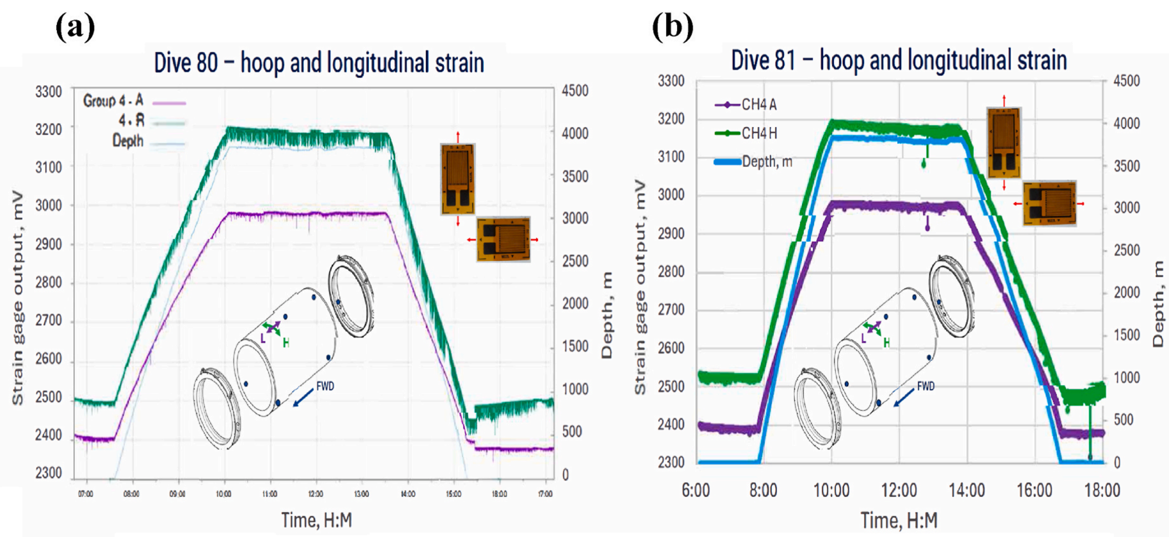


Fig. 7. Hull strain recordings of (a) Dive 80, and (b) Dive 81. The diving to Titanic depths subjected the carbon hull to larger differential stresses as can be inferred from the wider separation between the hoop (green line) and longitudinal strain (purple line) profiles at the seafloor depth. Each dive subjected the hull to cyclically increasing stress loads, which naturally contributed to material aging and fatigue.

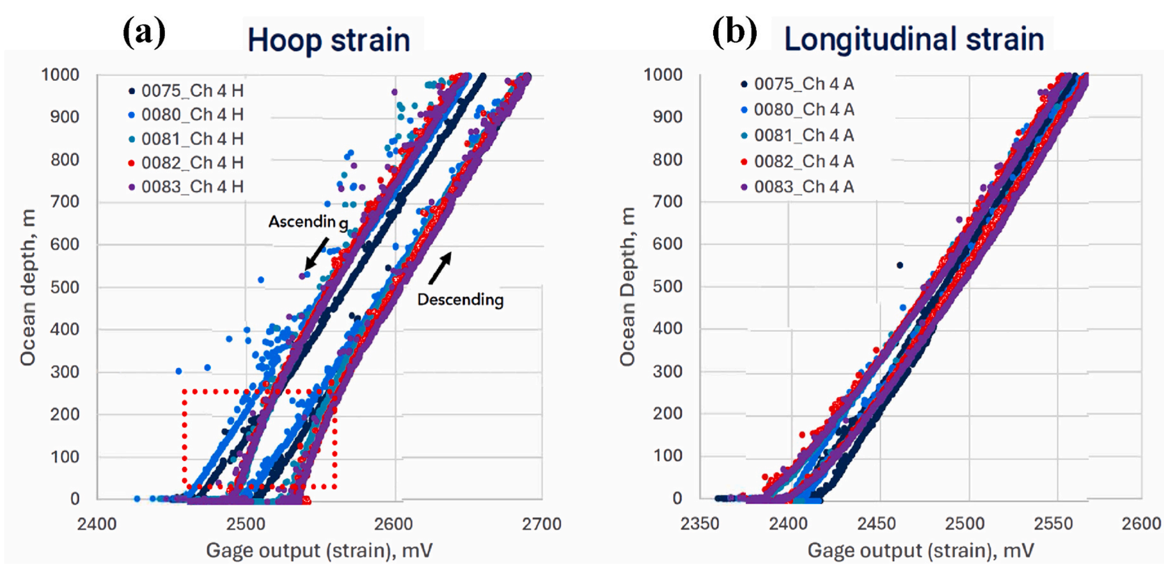


Fig. 8. Comparison of magnified portions of the strain curves for five dives (Dives 75 and 80–83). (a) Hoop strains with dotted rectangular box outlining where the hoop strains in Dives 81–83 were larger than for the previous Dives 75 and 80. The difference is attributed to structural damage after the 'bang' sound at the end of Dive 80. (b) The shift in the strain curves is opposite for the longitudinal strains, consistent with what was observed in Fig. 6b.

heard by the passengers at the end of Dive 80 (on July 15, 2022), after surfacing and it was clearly manifested on the sensor data as well (Fig. 6a).

The 2022 'bang' event occurred after Titan's 14th deep dive (to nearly sea floor depths) with hull V2; it was the 6th such dive in 2022, 7 had taken place in 2021. The strain monitoring system consisted of pairs of perpendicularly placed foil strain gauges (measuring strain transformed into mV signals) (Fig. 6b), which showed the hull had suffered larger strains than usual when the 'bang' occurred. The biggest strain shift was seen in the strain gauge pair (Fig. 7, Ch 4, Gr.4) adhered to the hull near the frontal flange. After Dive 80, these larger strains persisted and also occurred during Dives 81 to 83, and were manifested already early in the dives, at relatively shallow water depths (Fig. 8).

5.2. Material analyses

Hull Version 1 (V1). The first carbon fiber epoxy matrix cylindrical hull (Titan's Hull V1) was manufactured in 2017. The hull was wet wound in cylindrical direction, with pre-preg in longitudinal direction, and Titanium flanges bonded to each end, and these flanges were capped by the Titanium domes. Karl Stanley, an explorer who was on a Titan (Hull V1) dive in 2019, reported hearing cracking sounds and could locate these as coming from the region of carbon fiber hull glued to the frontal Titanium ring. Microfractures at the flange region and delamination of the carbon fiber layers of the hull itself could have been the source.

Cracks were indeed discovered in the composite hull during pre-dive inspection in spring 2019, upon which Hull V1 was retired from service in 2019. Material analysis of the retired hull showed existence of considerable mid-thickness delamination. Two pressure tests conducted

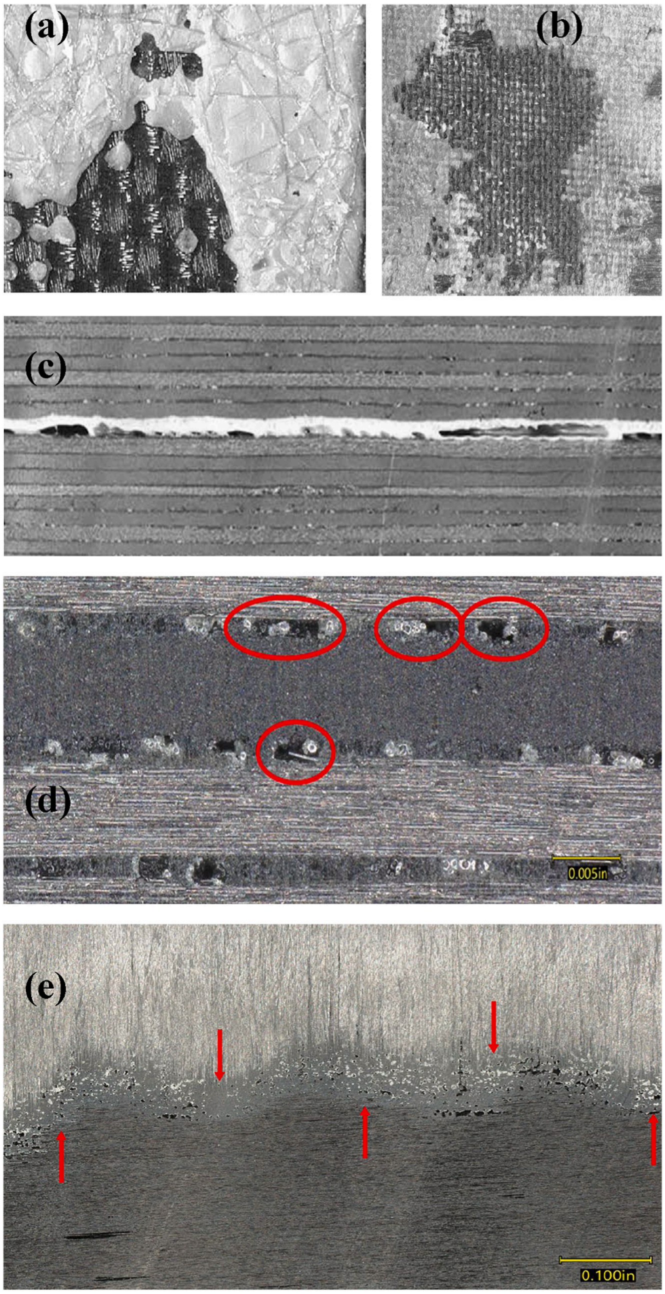


Fig. 9. Principal material analysis findings [14,24]. (a) Random cracks in solidified adhesive layer (top view), (b) Missing glue (map view), (c) Delamination along glue contact (cross-section view), (d) Micro-pores in cross-sectional views, and (e) Micropores as seen from top of hull segment.

on scaled down versions of segments of the retired V1 hull showed these were on the verge of implosion when subjected to pressures corresponding to 2800 m dept, and 'imploded' below 2800 m.

Hull Version 2 (V2). In 2020 and 2021, Titan's hull was remanufactured, into a multi-layered hull (Titan's Hull V2) made from five co-bonded, 1-inch thick, multi-cured carbon fiber layers. Don Kramer, an engineer with the US National Transportation Safety Board, told the US Coast Guard Investigation Panel during hearings on Sep. 26, 2024, that there were wrinkles, porosity and voids in the carbon fiber used for the second pressure hull of OceanGate's Titan submersible.

Two different types of sensors on Titan recorded a "loud acoustic event" that earlier witnesses testified about hearing on Dive 80 on July 15, 2022 (see Section 5.1). Hull pieces recovered after the tragedy of June 18, 2023 (Dive 84) revealed substantial delamination in the glue-bonded layers of the carbon fiber hull, due to deteriorated glue adhesive. The degraded bonding of carbon fiber lamina showed up as cracks in the adhesive layer itself (Fig. 9a), inter-lamina patches where adhesive was no longer bonded to at least one side of the fiber (Fig. 9b), leading to voids (Fig. 9c). The carbon also showed local pores (Fig. 9d). Critically, porosity zones also existed in top view of the carbon hull (Fig. 9e).

Many large slabs of intact hull fragments were found at the crash site on the ocean floor. These hull fragments appeared more or less rectangular (Fig. 10a) and came off via large longitudinal tear fractures between Layer 1 and composite Layers 2/3, as seen in Fig. 10b. The longitudinal fracture line is consistent with inward buckling of relatively thin, delaminated hull slabs, assisting the failure process during an implosion.

Separately, the bonding between carbon fiber and Titanium is not a simple process, and many have criticized OceanGate for not applying state-of-the-art technology, such as Carbotanium [25]. The Titanium flanges, to which were bolted the end caps, were themselves glued with adhesive to the carbon fiber hull. One may argue, with the hull tube showing such ample signs of delamination, that the outer Layer 5 (which was glued to the flanges) may have developed extremely large stresses near the bonds with the titanium rings. In fact, this is exactly what the strain gauge readings after Dive 80 increasingly showed (see Section 5.1 for details).

6. Discussion

This independent assessment provided a brief overview of the technical data and analysis of the implosion of the Titan sub that occurred June 2023 during a mission to visit the wreck of the Titanic. One of the possible theories about what made the Titanic (the target of the Titan's mission) sink, is that the bolts used to fix the steel plates to the hull's ribs of the Titanic were too weak. The bolts sheared off and hull plating came off easily when the iceberg indented the ship's hull, causing the steel to tear apart. Ironically, a nearly similar conclusion can be drawn from analyzing the wreckage of the Titan tourist sub, sheared off bolts of the front cone accompanied by the pressure chamber collapse. However, a more nuanced view is possible, based on the many observations that nearly all components used in the sub were stressed near or beyond their critical limits. For example, the transparent view port that was mounted on the front was an experimental design. The view port was rated to only 650 m (2130 ft), and analysis by an independent expert concluded the design would fail after only a few 4000 m dives.

6.1. *Key failure mechanism*

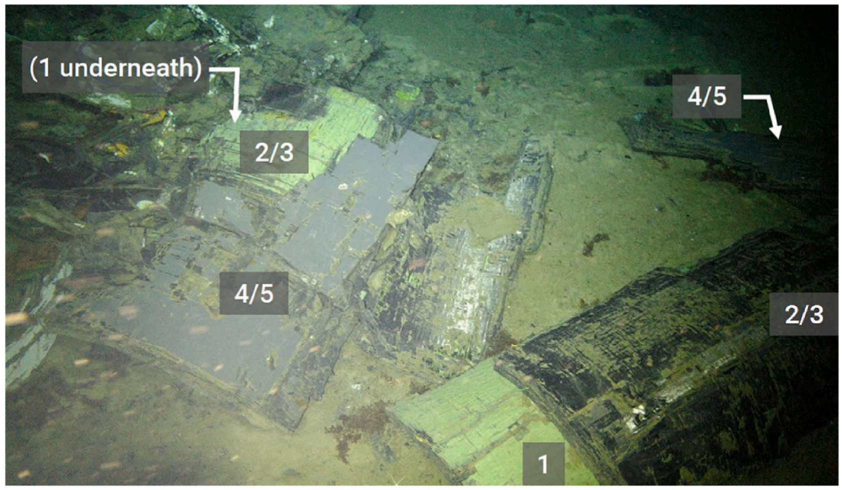
The Titan's front cone was found intact on the sea floor, but was no longer attached to the Titanium ring that it was originally bolted to. Separately, there is compelling evidence from material analysis for carbon hull weaknesses, as was observed for each of the two hulls used for the Titan over only brief periods, as follows:

- Hull V1 (built in 2017) developed cracks and delamination after only 50 dives, leading to its early retirement in 2019. Pressure tests indicated it could not withstand depths near the Titanic wreck.
- Hull V2 (built in 2020–2021) had significant manufacturing defects, including voids and porosity in the carbon fiber, along with deteriorated bonding between the carbon fiber multi-layer, as well as between the carbon fiber and the Titanium end-flanges, all may have contributed to the implosion. The vessel had made tens of dive trips prior to its demise. The dive numbers used in Figs. 6 to 8, may in fact have been started already during Hull V1 dives.

Here is a breakdown of the key elements of the failure mechanism:

1. *Analysis of the incident*: Still images and video footage of the Titan sub's wreckage, as well as pre-incident and post-incident tests and

(a)



(b)

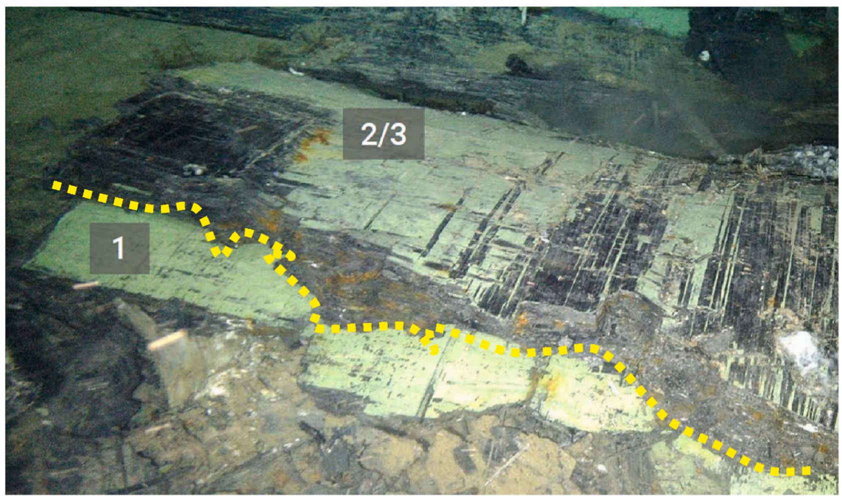


Fig. 10. (a) & (b) Crash site of Titan's debris field with rectangular fragments of delaminated slabs of 5 layer thick multi-layered carbon fiber hull [24]. All layers are 1-inch thick and Layer 1 was originally innermost, and Layer 5 outermost. Dashed curve (yellow) in lowermost image outlines trace of tear fracture at contact between Layers 1 and 2.

images of the sub's intact parts, were used to assess the cause of failure. Analysis of these public data sources was conducted to infer the origin of the hull breach and the principal mechanism of collapse. The abundance of large rectangular slabs of delaminated carbon fiber layers is striking.

2. *Mechanism of hull failure:* A sub relies on hermetic (airtight) seals and an elastic hull to withstand the difference in pressure. Even a small breach, or "tiny flow path," can lead to a rapid collapse of the air volume inside Titan's hull, leading to its implosion. This is unlike what happens in damaged ships and submarines, when settling on the seafloor at shallow depths; the hull will not implode, the destructive inflow of water slowly fills the compartments and sailors will eventually suffer dry asphyxia, when the last air pockets run out of oxygen.
3. *Collapse of air volume during implosion:* The air volume trapped inside the sub at the surface remains at near-surface pressure. However, if a sub, like the Titan did, descends to extreme depths, the pressure outside its hull increases dramatically. The sub's elastic hull is responsible for withstanding this immense pressure difference with the ambient ocean water and its interior air space. Evidently, Titan's hull's sealing function was compromised, and the external water pressure could transmit to the air space within, causing the air volume to collapse instantaneously. This violent collapse is known as an "implosion," a catastrophic event that led to the destruction of the sub.

The realization that air-collapse is the leading implosion mechanism, which subsequently crumples what is left of the leaking sub's elastic hull, and was then followed by a thermodynamically driven mini-explosion, has been little emphasized before. The commonly held idea always seems that pressure-induced failure of the hull is the primary cause and occurs when the elastic strength limit of a hull is exceeded by the external pressure. The hull is envisioned to break as a first requirement, which then leads to flooding of the vessel. This is indeed what happens when vessels sink in shallow waters.

But shallow water wreckage is not involving the violent collapse of air volumes as seen in true implosion events. Deep sea implosion of submersibles is a mechanism very different from simple compartment flooding in shallow waters. The key is that fluid connection via a small leak pathway is the primary cause of the implosion, with elastic buckling and subsequent fracturing of the hull being a mere consequence of the leak. Incidentally, while such tiny leaks are enough to implode a submersible at great depths, such tiny leaks would not sink a vessel in shallow water.

6.2. Most likely failure scenario

After careful analysis of all available information and examining the prior test data, the present author feels confident to conclude what is the most likely series of events that led to the loss of the Titan sub.

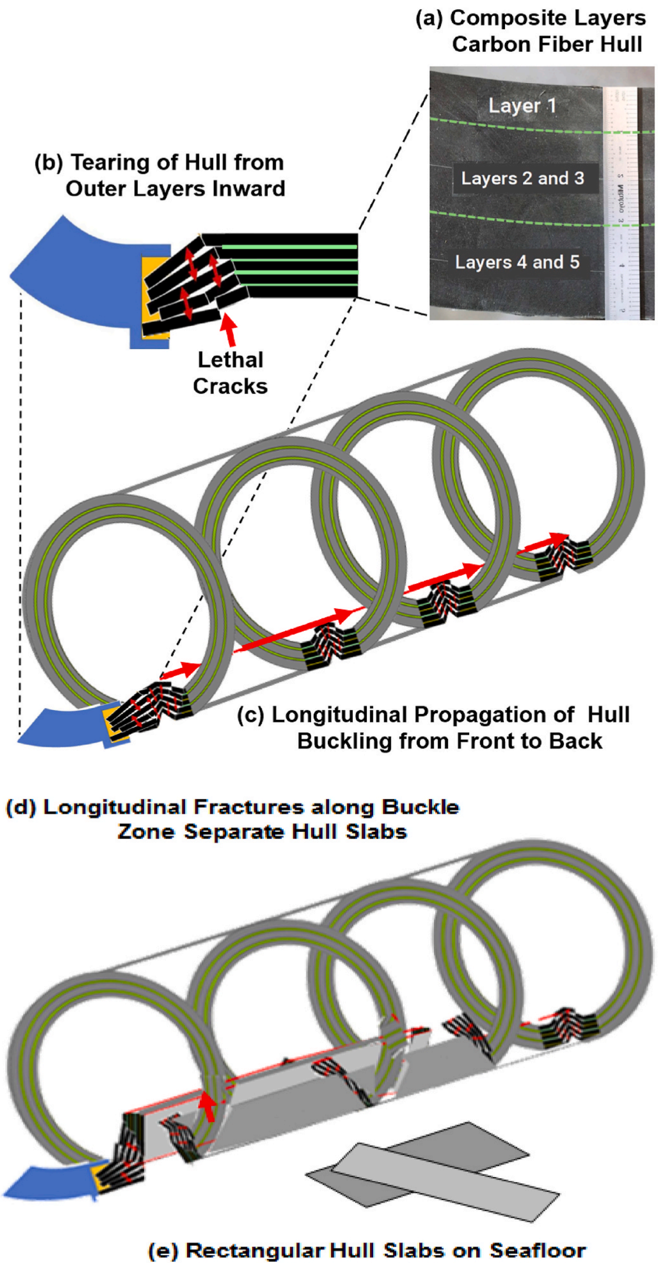


Fig. 11. (a)–(e) Principle sketch of the most likely failure scenario via longitudinal buckling and fracturing. The failure process started with delaminated slabs in the 5-layer thick multi-layered carbon fiber hull. All layers were 1-inch thick and Layer 1 was originally innermost.

1) The sensor data (Section 5.1) unequivocally revealed that the cyclic loading of the sub's hull was accompanied by both audible and recorded cracking sounds. This sound was produced by the cracking of brittle glue layers, the unbonding of entire patches of adhesive between adjacent multi-layers, and progressive delamination of voids filled by air and/or vapor) between the multi-layers, and these voids were flattened when pressurized at great depth, causing further delamination. All of these observations point toward a rapidly aging carbon fiber hull that was 'groaning' under the weight of the repeated deep dives.
2) The abundance of rectangular hull slabs, relatively intact, unequivocally reveals that these slabs detached from the hull mainly via longitudinal fractures in the length direction of the sub. The known and plausible mechanism for creating such longitudinal tear fractures is inward buckling, consistent with the implosion of a cylindrical hull.
3) Differential strains, recorded by the strain gauges, were largest near the frontal Titanium flange glued onto the carbon tube. The assumption made here is that advancing delamination had during the fatal Dive 84 finally made its way to the contact region between the titanium ring and the carbon hull. This created an incredibly weak point, waiting to snap under the 'right' circumstances.

The inferred ultimate sequence of failure via a series of cascading events during the catastrophic collapse is conjured here to involve ten critical steps (I-X), as follows:

I. Delamination and microfracturing during cyclic loading of successive dives had already separated hull slabs, preferentially along the degraded adhesive between Layers 1 and 2, and between Layers 3 and 4 (Fig. 11a). The preferential separation of these segments can be inferred from the many slabs found on the crash site that had separated along primarily these two joints.
II. At the final dive, the process of progressive delamination and micro-fracturing was further progressing, starting near the frontal titanium flange (Fig. 11b). In fact, inner Layers 1 and 2/3 did not need to be breached to implode the sub, as inner hull layers would already buckle (Fig. 11c), due to them acting as a thinner tube not built to resist the enormous external pressure loads still increasing as the sub descended deeper and deeper.
III. The pressurized seawater first tore through Layer 5, and then seesawed its way inward, across Layer 4. Then the failure first advanced by tearing along the delamination contact between Layers 3 and 4, facilitated by the prior aging and fatigue process which had already fractured and loosened adhesive, and created voids filled with ambient fluids via micro-pores.
IV. The longitudinal buckling of the delaminated hull started near the frontal flange (Fig. 11c), where the hull initially buckled inward as the differential strains were highest there. The three innermost layers (Layers 1, 2 and 3) of the hull could now be directly loaded by the outside pressure, and reached stress values high enough to buckle fold inward, along much of the length in longitudinal direction.
V. Catastrophic longitudinal fracturing of nearly the entire hull occurred (Fig. 11d). The hull was breached, and the air volume inside the sub collapsed. With the hull now massively failing via the longitudinal fractures, the thermodynamic process climaxed as well.
VI. The collapsing air clump inside the sub reached 1600 K and heated up the seawater rushing in to create a steam flash. The latter pushed the fractured hull panels outward in a secondary steam-driven explosion event that superseded the initial air-driven implosion event.
VII. The secondary steam-flash driven explosion blew out the Perspex eye mounted on the sub's frontal end-cap, and broke the tiny bolts connecting the front cone to the Titanium flange at its base. The frontal flange was found cleanly detached from both the carbon fiber tube and the front cone.
VIII. The crew may have heard the initial cracking which occurred for may be over a period of less than a minute (see Section A2), as seawater tore its way inward through the five layers of Titan's carbon fiber hull. Then the actual implosion instantly crushed their bodies and crumpled their tissues in a painless millisecond. Their remains were next strewn around by the final steam-flash driven, secondary explosion.
IX. The above implosion-explosion process occurred at about 3500 m depth, which means about 277 m above the seafloor below. All debris sank to its final resting place from the point source of the disaster. This explains why we have a 450 m long debris field, about 200 m wide, where parts of the lost sub were found.

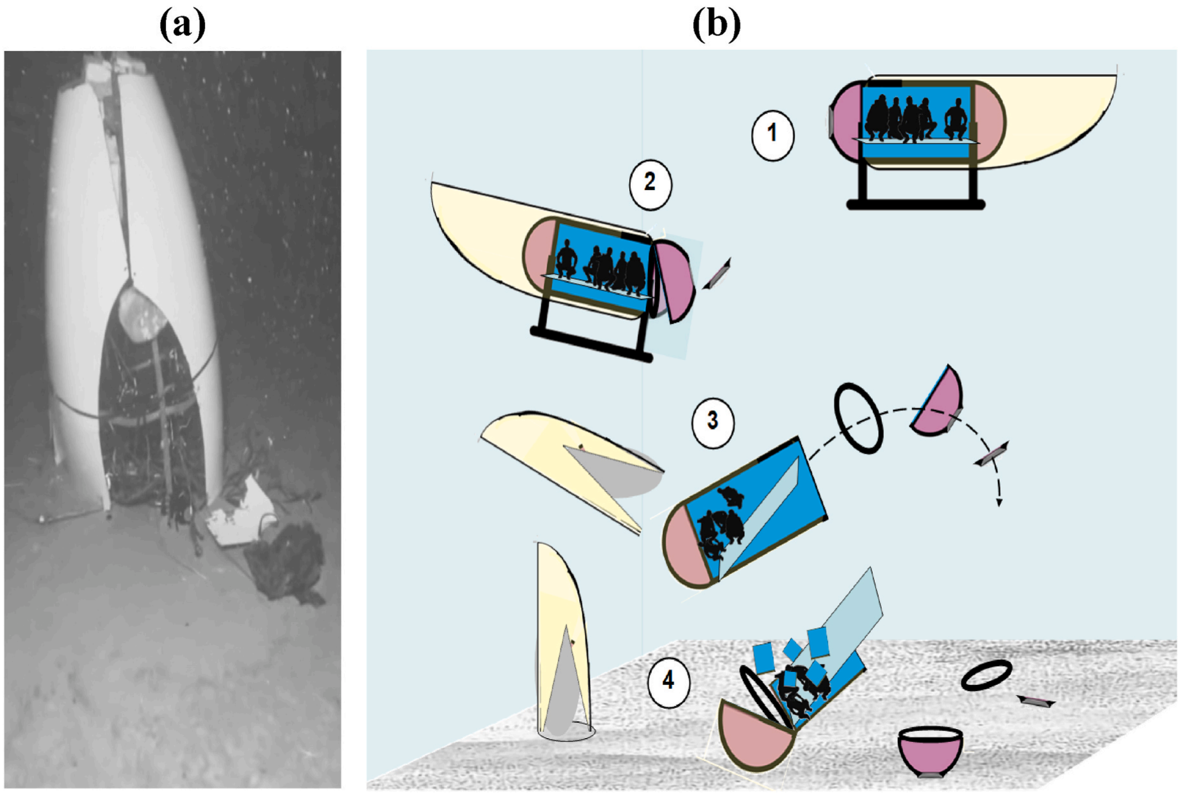


Fig. 12. (a) Crashed exterior jacket of the Titan sub as found on the sea floor. (b) Sketch of events during demise of the Titan sub. Stage 1: Shortly before implosion at about 3500 m depth; Stage 2: Leak near front cone leads to instantaneous implosion (stretched over time in illustration); Stage 3: Hurling away of hull elements during secondary steam-flash driven explosion; Stage 4: Final resting place of wreckage on sea floor at 3777 m. Relative position not to scale.

X. From the elliptical shape of the debris field, it can be inferred that the local ocean flow direction was northwestward at the time of the accident. Then everything went silent. May the submersible crew, Stockton Rush, Paul-Henri Nargeolet, Hamish Harding, Shahzada Dawood and his son Suleiman, rest in peace.

6.3. Global series of events

Fig. 12a shows the exterior jacket of the Titan sub as it was found crashed into the sea floor. The sketch of Fig. 12b attempts to reconstruct the global sequence of events leading up to the sub's implosion. After dropping ballast as conveyed during last contact with the support vessel, the crew said: "all good here" at 10:47am local time on June 18, 2024 (Stage 1). However, the sub most likely had developed cracks through outer Layers 4 and 5 of the carbon fiber hull. Having different loading on the inner Layers 1–3 meant buckling started, and implosion of the vessel's hull was imminent. For illustration purpose the hull's implosion and subsequent explosion processes are unrealistically stretched over time. The Perspex lens blew out almost immediately during the explosion (Stage 2). The sub disintegrated, causing jumbling of the floorboard, the hurling away of the cover wings (yellow), and the primary air implosion and subsequent steam-flash explosion quickly superseded each other (Stage 3). Ultimately, all structural elements landed on the sea floor (Stage 4), where they have been photographed and recovered by remote controlled robots.

One other aspect to consider is buoyancy control. Titan lost communications to its surface ship, the Polar Prince, just 6 seconds (!) after it had acknowledged it dropped about 70 pounds (32 kg) of drop-weight [while typically carrying about 200 pounds (91 kg) to 300 pounds (140 kg) of drop-weight on board].

One awkward thought is the risk of an erroneous drop-weight action, which would occur when an operator — either unknowingly or inadvertently — drops weight too late and too slow for the depth and speed already reached. Buoyancy control issues can also go undetected when the pilot thinks he dropped weight, but it did not happen in actuality due to malfunctioning of the weight drop mechanism. In fact, such malfunctioning has occurred on previous Titan trips, but did not lead to a hard landing. The average descend rate of the Titan during its final trip was 38 m/min; when communication contact was lost the sub was at 3500 m depth, still 277 m above the sea floor, which at the average descend rate it would have reached in about 7 and a half minutes.

Finally, it is to be expected that the Perspex lens, which was not salvaged, lies intact on the ocean floor, because of its minimal bolting (as it was well supported at its base against inward forces, but not for outward forces, as these were not expected to occur). The eye can be found very close to the end caps (Fig. 13), which were recovered June 2024. The location of the frontal 'End Capsule' (also retrieved) has the following coordinates: 41 44.04568 N; 49 56.53634 W. The eye may be a target for future expeditions. It was announced in May 2024 that Larry Connor and Patrick Lahey, founders of Triton Submarines, are developing a 2-person submersible that allegedly can reach the Titanic safely and repeatedly.

7. Conclusions

The implosion of the Titan submersible during its June 2023 dive to the Titanic wreck provides critical insights into the engineering and material shortcomings that contributed to its catastrophic failure. Analysis presented during the MBI hearing indicated a primary failure mechanism initiated at bond interfaces between the multi-layers of the carbon fiber hull (Hull V2). The bonds were compromised by several factors, including manufacturing defects such as interlaminar voids, porosity, and inadequate adhesive integrity, which collectively led to

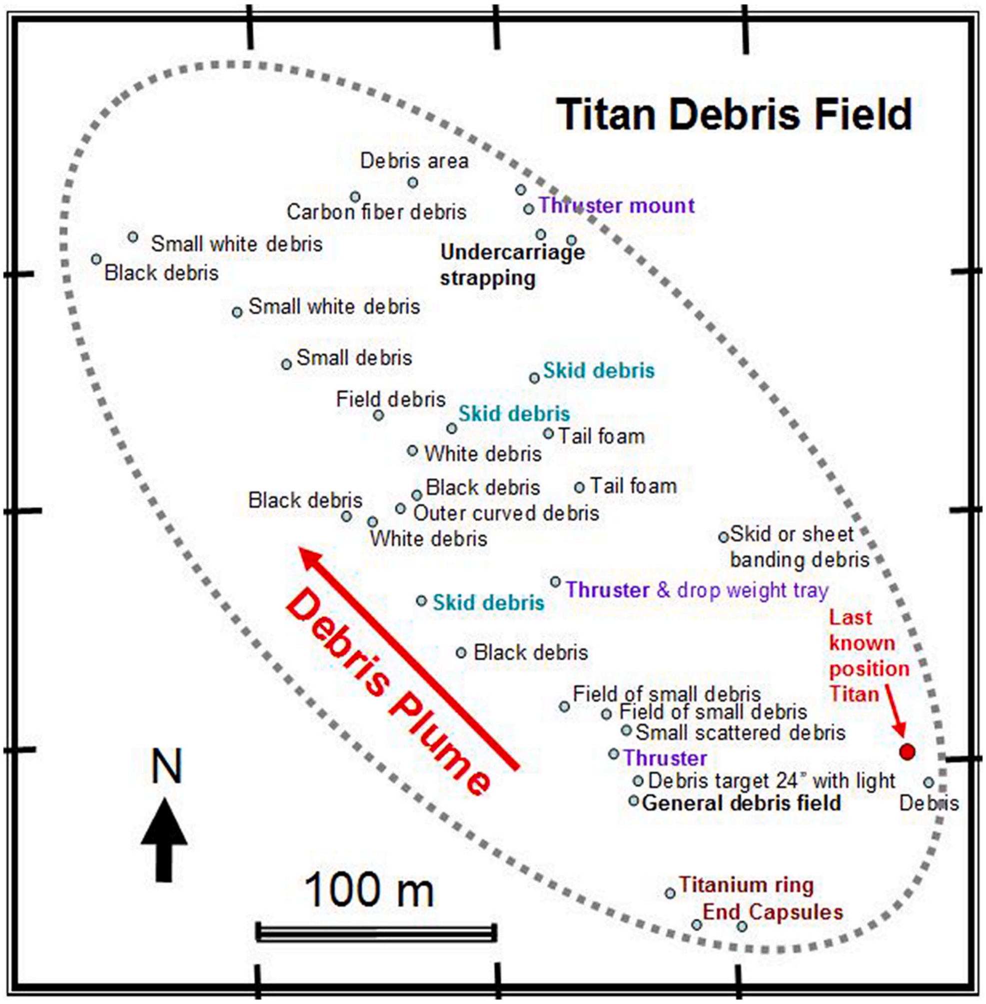


Fig. 13. US Navy map of Titan debris field [26], which covers an elliptical plume region about 450 m long and 200 m wide. The red arrow is the approximate sub-oceanic current direction inferred from the plume shape of the debris and the heavy parts (end capsules and metal ring) lying below the last known position of the Titan sub.

significant delamination and structural weakening over the hull's operational lifespan.

Sensor data from the Titan's real-time hull health monitoring (RTM) system highlighted alarming acoustic signatures and strain anomalies during previous dives, notably after Dive 80, which were indicative of escalating cyclic fatigue. These pre-incident indicators were not acted upon, allowing operations to continue, despite the growing risk of failure. Moreover, the use of undersized bolts for critical joints and a transparent viewport with a pressure rating significantly below the operational depth (650 m versus the target of 3800 m) further exacerbated the vessel's susceptibility to failure.

The implosion mechanism was characterized by a rapid collapse of the internal air volume due to overwhelming external hydrostatic pressure, which together with the additional stress at the onset of the implosion exceeded the structural integrity of the compromised hull. This process resulted in a violent implosion, distinct from the gradual flooding typically observed in shallow-water incidents, leading to immediate loss of vessel integrity. Thermodynamic interaction of the collapsing air and seawater caused a secondary, steam-powered explosion, scattering the sub's debris over the seafloor.

A thorough analysis revealed the most likely sequence of events leading to the catastrophe:

1. **Structural Weaknesses**: Hull V2 showed significant manufacturing defects, including voids and porosity that compromised adhesive bonds in its multi-layered carbon fiber structure.
2. **Cyclic Loading**: Real-time monitoring detected audible cracking and microfracturing due to repeated deep dives, particularly near the titanium flange where stress concentrated.
3. **Breach and Buckling**: A tiny breach allowed seawater to enter, leading to rapid inward buckling and catastrophic longitudinal fracturing as external pressure increased with depth.
4. **Implosion and Explosion**: At approximately 3500 m depth, the air volume inside collapsed, reaching temperatures of 1600 K, which triggered a steam flash explosion that violently disintegrated the sub.
5. **Impact on the Crew**: The crew likely heard cracking sounds just moments before being crushed during the implosion, leaving them with no chance to react.

In light of these findings, there is an imperative need to advance design protocols that incorporate robust fatigue analysis, enhanced bonding techniques, and stringent quality control measures in the manufacturing of deep-sea submersibles. Implementing state-of-the-art materials and engineering standards, along with a rigorous evaluation of real-time monitoring data, is essential to ensure the safety and reliability of future underwater exploration vehicles. The Titan incident serves as a pivotal case study for the marine engineering community, highlighting the critical need for comprehensive risk assessment and mitigation strategies in high-pressure environments. Additionally, there is an urgent need for improved design standards, rigorous quality control in manufacturing, and enhanced real-time monitoring of experimental submersibles to prevent similar failures in future deep-sea exploration endeavors.

Compliance with ethics guidelines - The author declares he has no conflict of interest or financial conflict to disclose.

Disclaimer - The assertions made in this paper are based on research and expertise of the author and KFUPM is not liable for the findings and opinions expressed.

Declaration of competing interest

The author declares that he has no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Implosion and fracture propagation rates and acoustic effects

This appendix makes estimations of certain physical phenomena during the implosion of the Titan sub, such as the implosion rate (Section A1), the fracture propagation rate in the hull (Section A2), and the acoustic effects (Section A3).

A1. Transient pressure increase of air collapsing in a cylinder

The rate of a pressure transient is controlled by the hydraulic diffusivity of the air mass and the pressure difference between the outside and the sub's interior (here assumed filled with air at initial atmospheric, surface pressure). The hydraulic diffusivity D_hD of the air mass in the cylindrical hull of finite radius, r_e, can be defined by:

$$D_h = \frac{r_e^2}{8\mu c} \tag{A1}$$

Substituting in Eq. (A1) the cylinder radius, $r_e = 0.84$ m, air dynamic viscosity, $\mu = 1.81 \times 10^{-5}$ Pa s, and air compressibility, $c = 10^{-5}$/P, gives $D_h = 4.9 \times 10^8$ m^2/s.

The normalize pressure change transient, $\frac{\Delta P(r,t)}{|\Delta P_0|}$, can now be computed using a recent solution [27,28], with $r > 0$:

$$\frac{\Delta P(r,t)}{\Delta P_0} = 1 - erf\left[\frac{r \ln r}{2\sqrt{D_h t}}\right] erf\left[\frac{(2r_e - r)\ln(2r_e - r)}{2\sqrt{D_h t}}\right] \tag{A2}$$

Substitution of $D_h = 4.9 \times 10^8$ m^2/s gives the pressure escalation curve for the confined space for $0 < r \le r_e$. The pressure throughout the cylinder will have achieved the external pressure when at $r = r_e$ the pressure change $\Delta P(r_e, t)$ becomes equal to the imposed pressure change ΔP_0 (such that $\Delta P(r_e, t) = \Delta P_0$) which occurs when:

$$erf\left[\frac{r_e \ln r_e}{2\sqrt{D_h t}}\right] erf\left[\frac{(2r_e - r_e)\ln(2r_e - r_e)}{2\sqrt{D_h t}}\right] = 0 \tag{A3}$$

Note the imposed pressure change ΔP_0 is the difference between the ambient pressure and initial pressure in the sub. Eq. (A3) can be simplified to:

$$erf\frac{r_e \ln r_e}{2\sqrt{D_h t}} = 0 \tag{A4}$$

From Eq. (A4) it follows that the inside pressure reaches the outside pressure in a fraction of milliseconds.

A2. Fracture propagation rate in a longitudinal fracture

This study inferred that longitudinal buckling resulted in longitudinal fractures which propagated from the front to the back of the carbon fiber hull in zipper-like motion. The energy source for the fracturing was the hydraulic pressure of the seawater fluid column squeezing forward primarily between the delamination contact between Layers 3 and 4 (Fig. 11a–c). The pressure at the assumed implosion depth of 3500 m below sea level was about 350 bar (~5076 psi), which is similar to the pressures reached during hydraulic fracturing operations in shale wells. Recent work found that the fracture propagation rate is rather slow ~0.92 ft/min on average for over 400 such fractures analyzed [29,30].

The rate, expressed in petroleum industry's imperial field units (0.92 ft/min), translates to a metric rate of 4.6 mm/s. This sluggishness can be attributed to the enormous confining pressure at the fracturing depth, and the slow filling of the dilating fracture by frac fluid pumped into the opening cracks. The same sluggishness may be assumed to have initially occurred in the buckling and fracturing process of the hull, up to the moment when direct fluid communication was established between the inner air and outer water bodies, which would have caused the mechanism of instantaneous implosion to occur (at the speed estimated under Section A1).

Assuming at least some of the longitudinal length of the outer layers of the hull tore before the implosion, and having a total hull length of 2.54 m, traversing that length at 4.6 mm/s would take 552 s or ~9.2 mins. However, hull breaching would likely have occurred long before a full length tear of the outer hull layers, so the estimated time is an unlikely upper limit. When one assumes, more conservatively, that the outer hull would have torn only over 1/10 of its total length (before implosion failure), it would still have taken a tantalizing 55.2 seconds, long enough for the crew to realize they were about to be imploded.

A3. Acoustics of air implosion and steam-flash explosion

The down-weighted sub can be assumed was slowly descending close to the buoyancy point when its implosion took place. Thus, the source of the implosion sounds was more or less static, which implies the Mach number was negligibly small (and close to zero, i.e., $Ma \to 0$). This is relevant, because we may immediately rule out the occurrence of any supersonic shock waves.

We may next estimate the travel rate of sound waves (1) in the imploding air pocket, (2) in the fracturing carbon fiber hull, and (3) as ultimately transmitted through the seawater from its imploding/exploding point source.

The speed of sound in all three media involved will be governed by a relatively simple analytical equation, featuring the elastic bulk modulus, K, and the material density, ρ, of the respective media:

$$v_c = \sqrt{\frac{K}{\rho}} \tag{A5}$$

Solving Eq. (A5) for all three materials, the speed of their sound waves, using approximate inputs, are for air, seawater, and carbon fiber, respectively, 345 m/s, 1500 m/s, and 5000 m/s. Unlike the sound waves in liquids, the carbon fiber hull also may transmit transverse shear waves, but these are always slower than the longitudinal pressure waves, and are therefore not considered here.

Confined to the sub's small dimensions, any sound would take about 0.1 milliseconds to be heard by the crew. It is inferred here that the crew would have heard the intensifying cracking sounds of the buckling hull for may be up to 55.2 seconds, which was the time estimated (Section A2) for the micro-fractures and pores to tear-up the required pathway for the buckling and fracturing of the hull's individual layers to occur before hull-breaching was achieved.

The fracturing of the hull occurred at rates estimated in Section A2, which again requires a check whether a supersonic Mach number may have been reached. Namely, if the zipper motion of the fracture was propagating faster than the speed of sound in the sub's air, this would have been manifested as a supersonic boom. However, the speed of sound in the sub was 345 m/s, and the estimated fracture propagation rate in its hull occurred at about 0.0046 m/s, meaning the Mach number was $Ma \to 0$, which rules out any supersonic boom, for which the critical threshold requires $Ma > 1$.

Ultimately all of the sub's sound waves were transmitted into the surrounding sea at a rate of 1500 m/s. These sound waves were allegedly picked up by the classified US Navy's SOSUS or IUSS network. The Navy acknowledged an anomalous sound was registered consistent with an implosion/explosion event, but this news was not made public until the wreckage had been located.

Data availability

The authors do not have permission to share data.

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