TITLE:Did a “lucky shot” sink the submarine *H.L. Hunley*?

SHORT TITLE: Did a “lucky shot” sink the *Hunley*?

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KEYWORDS: lucky, shot, rifle, damage, conning tower, Hunley, submarine, sink

Acknowledgements:

We would like to gratefully acknowledge the funding provided by the Josiah Charles Trent Memorial Foundation of Duke University, which supported this study. We gratefully acknowledge the funding provided by the DoD SMART Scholarship for the research and education of Rachel Lance. We also gratefully acknowledge funding provided by the US Army MURI program (U Penn prime - W911NF-10-1-0526) partially supporting Cameron Bass. We would also like to acknowledge the professional support of Naval Surface Warfare Center Panama City Division, Underwater Systems Development and Acquisition Code E15.

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ABSTRACT

The *H.L. Hunley* was the first submarine to be successful in combat, sinking the Union vessel *Housatonic* outside Charleston Harbor in 1864 during the Civil War. However, despite marking a milestone in military history, little is known about this vessel or why it sank. One popular theory is the “lucky shot” theory: the hypothesis that small arms fire from the crew of the *Housatonic* may have sufficiently damaged the submarine to sink it. However, ballistic experiments with cast iron samples, analysis of historical experiments firing Civil War-era projectiles at cast iron samples, and calculation of the tidal currents and sinking trajectory of the submarine indicate that this theory is not likely. Based on our results, the “lucky shot” theory does not explain the sinking of the world’s first successful combat submarine.

INTRODUCTION

On February 17, 1864 the *H.L. Hunley* sank the *USS Housatonic* and became the world’s first submarine to be successful in combat. However, the *Hunley* did not return victorious to harbor after its successful mission, but instead disappeared for over 130 years. The *Hunley* was re-discovered buried in the ocean floor outside Charleston Harbor in 1995, and raised in 2000. Since its recovery it has been undergoing extensive conservation efforts at Clemson University, and these efforts have gradually removed years of marine concretion to reveal the hull beneath. Among the many discoveries made during excavation and conservation, archaeologists have discovered a large area of damage to the fore conning tower that, according to sediment analysis, likely occurred during or soon after the attack itself (1). The excavation also revealed a small piece of cast iron, shaped consistently with the edge of the undamaged porthole, buried near the bottom of the sediment below the fore conning tower (1). This location indicates that the porthole was damaged before or soon after the vessel sank, before settling to its final position on its starboard side. They also discovered that the eight men inside, responsible for navigating the vehicle and propelling it by hand crank, died while seated at their respective battle stations without switching

the bilge pumps to pump out water, and without any signs of skeletal damage or apparent attempts to escape (2, 3).

BACKGROUND

During the *Hunley's* attack, crewmembers on the deck of the *Housatonic* fired their small arms weaponry in an attempt to sink or at least deter the *Hunley*. However, the *Housatonic* crew did not identify the attack of the approaching submarine until it was too close and moving too quickly to train the heavy artillery of their battery at the correct angle, so only personal weapons were fired. Among the weaponry reportedly fired, a rifle was the most powerful and therefore had the most potential to cause ballistic damage (4). The long-standing "lucky shot" theory of the *Hunley's* sinking is that this gunfire damaged the hull of the vessel, either causing it to flood or killing Lieutenant Dixon, the man responsible for the primary controls and steering of the submarine (5). When the *Hunley* was raised, a large hole approximately 214cm² in area was discovered in the conning tower (Figure 1). Analysis of the sediment inside the vessel indicated that a hull breach in the conning tower was created during or soon after sinking (1). This breach could have been from damage to the conning tower but alternatively the same pattern of sediment could have occurred if the conning tower was not latched at the time of sinking. The "lucky shot" theory holds that either this large breach in the conning tower or a smaller hole made by a broken window in the tower is responsible for the sinking of the *Hunley*. The conning tower windows are above the waterline, so if the vessel did not sink immediately from this damage the crew would have had time to set the pumps to bilge out water or attempt to escape. Therefore if the "lucky shot" theory is true, the *Hunley* would have by definition started sinking almost immediately after its attack on the *Housatonic*.

Figure 1. Illustrations of the H.L. Hunley after conservation. Left: the full vessel, including the damaged conning tower, seen from the port bow. Right: Frontal view of the damaged conning tower after conservation. The starboard window shows damage attributed to erosion, while the port window and side of the tower also show the damage hypothesized to have occurred from arms fire (circled). Detailed views of the *Hunley* as it would have appeared before sinking can be explored at www.vernianera.com/Hunley, and photographs during conservation can be found at www.hunley.org.

To directly assess the “lucky shot” hypothesis, it is desirable to assess the ballistic performance of small arms of the period against the hull material. However, it is difficult to conclusively ascertain the exact composition and methods used to manufacture the conning towers of the *Hunley*, which were cast iron, without taking samples from the historical artifact itself. It is therefore difficult to perform ballistic testing using identical metal targets. However, both the Union and Confederate militaries did an extensive amount of ballistic testing using cast iron plates of varying thicknesses to investigate the durability of this material for armor on the now-famous ironclad ships used during the war(6). No records could be found that described ballistic testing with the 12.7 mm (½”) thickness used to construct the conning towers, but modern ballistic testing is frequently performed using well-validated scaling principles(7, 8). Scaling can be used to assess the effect of physical dimensions of an experiment. For example, if the thickness of a target is varied by a factor L , then the same depth of penetration of the target will occur for all impacts where the mass of the ballistic projectile used is varied by L^3 , because mass is a volumetric measurement (7-9). Projectile velocity remains experimentally constant regardless of size scale.

Additionally, investigating the motion of the *Hunley* after the attack is difficult because it is not known how quickly the crew continued to propel the boat, in which direction, or if they continued propelling the boat at all. The bathymetry of Charleston Harbor has changed significantly in the intervening years, limiting the utility of experimentation(1). Most significantly, multiple efforts have taken place between 1895 and 2002 to widen and deepen the channel entrance. Jetties were also constructed to open the channel entrance. The entrance bar had a naturally controlled depth of approximately 3 m in 1864, but over the intervening years has been progressively dredged and opened with jetties to a depth of 14.3 m (10-12). In addition, in 1942 97% of the flow of the Santee River was diverted into the Cooper River; this diversion means that the flow of water into Charleston Harbor from rivers was increased from 10 m³/s total in 1895 to over 425 m³/s from the Cooper River alone (10, 11, 13). Analysis of the shorelines near the harbor has additionally shown that where changes have occurred, they have had the effect of enlarging the basin(14). While a comprehensive analysis of the tidal prism of the harbor is beyond the scope of this publication, the increased flow from rivers by a factor of 43, the increased depth of the Harbor channel by a factor of 5, and the landscape of the tidal basin combined strongly indicate that the overall tidal prism has grown since the attack in 1864. A larger modern tidal prism means that the speed of modern tidal currents outside Charleston Harbor represent an extreme upper bound for the speeds of the currents potentially seen by the *Hunley*.

A large object that is nearly fully immersed, such as the *Hunley*, has motion that is almost exclusively dictated by currents. An object of this size would reach the same speed and direction as the surrounding currents within roughly one minute of when it began to drift freely (15, 16). Therefore, calculations using modern tidal current levels can provide a very conservative upper limit for the potential distance drifted by the *Hunley* after its attack on the *Housatonic*. A map of the attack and wreck sites is provided as Figure 2, and the values used to create the map are listed in Table 1. It has been assumed that the distance the crew of the *Housatonic* succeeding in moving the ship during the attack is negligible compared to its final wreck site(4). There are conflicting accounts regarding the exact angle of the *Hunley* to the keel of the *Housatonic* during the attack, but the accounts most commonly report that the submarine approached the *Housatonic* at a right angle to the keel and across the tidal current(4).

Figure 2. Map of the entrance to Charleston Harbor. 1865 bathymetric map of the Harbor entrance(17). Map is overlaid with relevant positions of both the *Hunley* and *Housatonic*. Stars indicate the bow of each vessel. Note that the historical hand-drawn map location for the *Housatonic* shows some discrepancy compared to modern GPS measurements.

Table 1. Values used to create Figure 2. All magnetic orientations have been adjusted to orientations relative to true north based on the magnetic declination at the location and time of the measurement (18).

Item	Value	Source
Final location of the wreck of the <i>Hunley</i>	32.720836, -79.77467	(19)
Orientation of the wreck of the <i>Hunley</i>	223.5°	Map pg. 88 (20), also (21)
Final location of the wreck of the <i>Housatonic</i>	32.72115, -79.77795	Diagram pg. 54 (22)
Orientation of the wreck of the <i>Housatonic</i>	235°	(22)
Orientation of the <i>Housatonic</i> during the attack	291.6°	(4)
Orientation of the <i>Hunley</i> during the attack	111.6°	(4)
NOAA Charleston Harbor Fort Sumter	32.715, -79.79233	(23)

METHODS

Ballistic Testing

To assess the plausibility of the principal hypothesis that the *Hunley* sank rapidly owing to a “lucky shot” that led to a large hole in the conning tower, a reproduction Civil War firearm was used to shoot Minié rounds at cast iron samples of different thicknesses. While vintage Civil War firearms can still be found, it is difficult to confirm their structural integrity and that they are safe to fire repeatedly. The replica was therefore used for safety reasons. Two thicknesses of cast iron samples were used as targets: 3.2 mm (1/8”) and 12.7 mm (1/2”). The firearm was a replica of an 1853 Enfield, firing 475-grain (30.8 g) Minié bullets using 60 grains (3.9 g) of FF grade black powder from a distance of 25 meters (27.3 yards). This distance was determined to be 25% closer than the minimum plausible distance between the guns and the *Hunley*, based on the structure of the *Housatonic* (4, 24). While the Enfield was traditionally the firearm of the Confederacy, it was extremely similar in construction to the Springfield rifles used by the Union and also fired the same rounds with the same muzzle velocity (274-304 m/s); the difference from a terminal ballistics perspective is therefore not experimentally important (7, 8). The site of impact was filmed using high-speed photography, and videos have been posted as supplementary information.

Calculating the Sinking Rate

To calculate the possible rates of sinking of the *Hunley* after hull breaches of various sizes, a system of equations was established to describe the various forces acting on the vessel. This system of equations is shown in Table 2.

Table 2. Equations used to calculate the sinking motion of the *Hunley*. All units in m, kg, s. Simplifying assumptions are described in the text.

Description	Equation	Eq. #
Bernoulli's equation	$v_{H2O}(t) = \sqrt{\left(\frac{2}{\rho_{H2O}} * [P_{H2O}(t) - P_{GAS}(t)]\right)}$	(1)
Total volume of water entering the hull	$V_{H2O}(t) = \int_0^t A * v_{H2O}(t) dt$	(2)
Drag force on a cylinder	$F_d(t) = \frac{1}{2} * C_d * \rho_{H2O} * v_{HUNLEY}^2(t) * W$	(3)
Newton's First Law	$a(t) = \frac{1}{m_{HUNLEY} + \rho_{H2O} * V_{H2O}(t)} (-m_{HUNLEY} * g + \rho_{H2O} * g * [V_{HUNLEY} - V_{H2O}(t)] + F_d(t))$	(4)
Vertical distance traveled	$d(t) = \int_0^t v_{HUNLEY}(t) dt$	(5)
Water pressure at the hull breach	$P_{H2O}(t) = P_{ATM} - 10069 * d(t)$	(6)
Ideal gas law	$P_{GAS} = \frac{P_{ATM} * V_{INT}}{V_{INT} - V_{H2O}}$	(7)

A	Surface area of the hull breach (1.96×10^{-3} or $2.14 \times 10^{-2} \text{ m}^2$)
$a(t)$	Vertical acceleration of the vessel as it sinks
C_d	Drag coefficient on the cylinder (discussed below)
$d(t)$	Depth of the vertical center point on the conning tower
$F_d(t)$	Drag force on the sinking vessel
m_{HUNLEY}	Mass of the vessel (8,505 kg)
P_{ATM}	Atmospheric pressure (101,325 Pa)
$P_{GAS}(t)$	Pressure of the gas remaining inside the vessel
$P_{H2O}(t)$	Water pressure at the level of the hull breach
ρ_{H2O}	Density of sea water (1026.98 kg/m^3)
$V_{H2O}(t)$	Volume of water inside the vessel ($V_{H2O}(0)=0.39 \text{ m}^3$ of ballast water)
V_{HUNLEY}	Total volume of the vessel (9.46 m^3)
V_{INT}	Starting internal gas volume of the vessel (7.61 m^3)
$v_{H2O}(t)$	Velocity of water entering the hull breach of the vessel
$v_{HUNLEY}(t)$	Vertical velocity of the vessel as it sinks
W	Width of the <i>Hunley</i> (1.22 m)

These equations were programmed into the computing software Matlab (Version R2015b, ©The Mathworks, Inc.) and integrated iteratively using Euler's method with a time step of 0.01 seconds. To compute drag force, the vessel shape was approximated as a cylinder. Drag coefficient was also assumed to be constant at either the maximum or minimum possible value (1.0 and 0.5 respectively) for the relevant range of Reynold's numbers.

Sinking times for two scenarios were assessed: the fastest plausible case and the slowest plausible case. The fastest case used the minimum drag coefficient (0.5) and assumed that the hull breach was instantly flooded over its full surface area. The surface area of the damage to the conning tower was measured to be $1.94 \times 10^{-2} \text{ m}^2$ plus the area of the 2" diameter window (Figure 1). The slowest possible case used the maximum drag coefficient (1.0) and a surface area of $1.96 \times 10^{-3} \text{ m}^2$ (surface area of just a broken 2" diameter conning tower window, with no additional damage). The code specified that should the internal gas pressure exceed the external water pressure, inward water flow would stop. The slowest case was additionally varied so that the window gradually filled with water starting at its lower edge rather than being instantly swamped instantaneously over its full surface area.

To begin sinking via water intrusion, the *Hunley* would first have to sink sufficiently that the theorized hull breach was at the water line. Using the 3D model described in full detail in Ref. (25), the amount of water required to sink the vessel to this level was calculated to be 0.78 m^3 , equivalent to about double the volume of ballast water in the vessel during the time of the attack. The conservation efforts revealed that the rest of the hull was likely intact at the time of sinking and the vessel first settled on the ocean floor in an upright position (1).

Tidal Analysis

To estimate the tidal currents in 1864, first modern tidal levels were found that matched the tides at the time of the attack. Next, measured data of current speeds for the modern tides were used to estimate the currents seen by the *Hunley* in 1864.

Charleston Harbor is a harmonic tidal station; therefore it is possible to accurately calculate the tidal levels surrounding the time of the attack on the *Housatonic* even though no measured data exist (26, 27). The tidal levels for Charleston Harbor on February 17, 1864 were calculated using the National Oceanic and Atmospheric Administration's Center for Operational Oceanographic Products and Services (NOAA CO-OPS) website (station ID 8665530; location 32.7817, -79.925) (23). Next, a modern date (February 21, 2013) was found with almost identical ($R^2=0.999$, see Figure 4 below) tidal levels and at a similar point in the lunar cycle; the tidal patterns were offset within the day by 33 minutes compared to the tides of February 17, 1864. The tidal current velocities had been measured and recorded on the 2013 date using tidal current stations downstream from the mouth of Charleston Harbor; these current velocities were obtained from the NOAA CO-OPS website for the station closest to the wreck site of the *Housatonic*: Charleston Harbor Fort Sumter Range, Buoy 8 (23). This station is 1.57 km from the wreck site of the *Housatonic* along a compass heading 253.09° (Figure 2).

Since Buoy 8 is located more centrally relative to the mouth of Charleston Harbor, it receives more direct current flow from between the jetties at the harbor entrance. Based on the changes that have been made to Charleston Harbor and its entrance that would likely serve to alter the direction and substantially increase the speed of the ebb tidal current, we assert that the currents measured in 2013 provide an extreme upper bound on the current speeds that could have moved the *Hunley* in 1864 following the attack. The recorded current patterns from the tides in 2013 were offset by 33 minutes to align them with the timing of the tides in 1864 during the *Hunley* attack.

The reconstructed current velocities were integrated starting at the time of the attack to provide estimates for the total distances the *Hunley* could have traveled. The travel distance was calculated for each of the calculated rates of sinking, and also until the time of the next slack tidal current. This calculation was also used to estimate the minimum length of time it would have taken for the vessel to travel the 310 m distance between the *Hunley* and *Housatonic* wreck sites without additional motive power (22). It was assumed that the distance moved by the *Housatonic* following the attack was negligible compared to its final wreck site since it sank in less than three minutes (4).

RESULTS

Ballistic Testing

The thinner 3.2 mm (1/8") cast iron samples shattered into multiple pieces on impact. However, the rounds fully penetrated the 12.7 mm (1/2") thick sample representative of the *Hunley* conning towers. The sites of penetration were only slightly larger than the Minié rounds themselves, with indications of minor plastic deformation around the edges (Figure 3).

Figure 3. Cast iron samples after ballistic testing. The hemispherical thinner samples (a) fractured cleanly in a radial pattern, while the plate the same thickness of the Hunley's conning towers (b) showed clean penetration by the Minié rounds and only minimal signs of fracture after repeated shots. The black dot illustrates the cross-sectional area of the rounds.

Sinking Rate of the Vessel

As discussed in the Methods, two cases were modeled: a fast case and a slow case, with some variations implemented in the slow case to assess the sensitivity of the model. The fast case, which modeled the full extent of the damage seen to the conning tower, indicated that the keel of the boat sank to a depth of 9 m (depth of the ocean floor at the wreck site) in 1 minute 42 seconds, while the slowest case computed a sinking time of 5 minutes 27 seconds. However, when the parameters of the slowest case were varied so that the broken window area filled gradually rather than being instantaneously swamped with water, the total sinking time increased to nearly 58 minutes.

Tidal Analysis

The tidal patterns for February 21, 2013 and February 17, 1864 are shown graphically as Figure 4 and the resultant tidal current speeds are shown as Figure 5.

Figure 4. Tidal patterns. The heights of the tides surrounding the Hunley's attack on the *Housatonic* in 1864, as well as the tides on February 21, 2013. The tidal levels are almost identical in both magnitude and timing, with $R^2=0.999$.

Figure 5. Maximum possible speeds of the tidal currents occurring outside Charleston Harbor, overlaid with maximum possible distance traveled. Maximum distances are the current levels integrated with respect to time starting at the time of the attack. The extreme furthest distance that could have been traveled after the attack as a result of

the tidal current was calculated to be 1.57 km. Current speeds are negative to indicate outgoing tide.

Integrating starting at the 8:45 pm time of the attack allowed for an estimate of how far the vessel would travel as a result of the tidal currents. The vessel could have traveled 1.57 km before the time of the next slack tide, and it would have taken at least 14 minutes 30 seconds to travel the 310 m between the *Hunley* and *Housatonic* wreck sites. The “lucky shot” theory requires that the *Hunley* started sinking immediately after it was hit by rifle fire during the attack. If the vessel began sinking immediately and sank over a period of 14 minutes 30 seconds, it would have been filling through a hole no more than 1.8 cm (0.7”) in diameter. However, for the fastest case, in the 1 minutes 42 seconds estimated time to sink, the vessel could have traveled at most 38 m based on modern current levels. For the slowest case, in the 5 minutes 27 seconds estimated time to sink the vessel could have traveled at most 119 m. A distance value was not computed for the slow case with gradual filling of the window area because, at nearly 58 minutes to sink, this case required more time than the relevant tidal cycle. The estimated maximum possible distance traveled is shown overlaid with current speeds as a function of time in Figure 5. Figure 6 shows the horizontal distances traveled for each case, with the actual distance between the wreck sites.

Figure 6. The calculated trajectories of the sinking submarine for the various cases. Calculated distances are maximums because of elevated current speeds in 2013 relative to 1864.

DISCUSSION

The historical documentation of ballistic testing of cast iron shows similar results to the tests presented herein, with rounds either plastically denting or passing cleanly through the sample. Figure 6 shows an example of the results from two such ballistic tests. The test in part (a) used a cast iron plate of thickness 11.4 cm (4.5”), which is thicker than the *Hunley*’s 12.7 mm (½”) conning towers by a factor of $L=9$. The projectile mass of 32.2 kg (71 lbs), when divided accordingly by 9^3 , results in a scaled mass of 44.3 grams. Standard Minié rounds weigh at most 34.0 grams (525 grain). Therefore, this plate was hit with projectiles 30% larger than the scaled projectiles used to target the *Hunley*, and fired by Whitworth cannons that use much higher muzzle velocities than rifles. However, this historical data suggest that

even this increase in firepower was insufficient to cause widespread damage of the type seen in the conserved conning tower. This historical test, which also produced small, clean penetrations through the target, therefore indicates that the 12.7 mm ($\frac{1}{2}$ ") sample used to model the conning tower would likely need to be hit with a much larger projectile before it experienced extensive damage similar to the conning tower of the *Hunley*. It is therefore unlikely that the damage to the conning tower observed upon its raising was caused by arms fire from the crew of the *Housatonic*.

Figure 7. Results from 1863 ballistic testing using cast iron targets (6).(a) The image states that this 4 $\frac{1}{2}$ " thick cast iron plate was shot multiple times with cast steel shot weight 71 lbs. Each circular site represents a separate test shot, with all sites showing plastic deformation or clean penetration by the projectile. (b) Historical photos from Confederate testing of cast iron plates, showing clean penetration or plastic deformation at the site of impact rather than large-scale shattering. The historical tests indicate that cast iron with the thickness of the conning tower would either be dented or penetrated cleanly by rifle fire, but likely would not have been shattered.

The 1864 tidal patterns are consistent with historical testimonies that the crew of the *Hunley* would have timed their departure with the outgoing tide to maximize their speed and minimize the required effort (5, 28). They are also consistent with the testimony of the crew of the *Housatonic*, whose reports stated that the tide was either "half ebb" (pgs. 587, 591) or "low water" (pg. 540), with the tidal currents setting to the northeast (4).

The computed sinking rates of the vessel also show stark contrast with the main assertion of the “lucky shot” theory that the *Hunley* began sinking during or immediately after its attack. Assuming the *Hunley* began sinking immediately, none of the calculated sinking times provide sufficient travel time for the *Hunley* to reach its final resting location, even though the 2013 tidal current speeds are almost certainly higher than those that occurred in 1864. If the conning tower was indeed broken by rifle fire, or even if only a window was broken, and the vessel began to swamp immediately, it would not have spent enough time subject to the tidal currents to reach the location at which it was discovered in 1995. The hole size required for the vessel to start sinking immediately and sink at a rate that would allow it to travel 310 m is a maximum 1.8 cm (0.7”) diameter. However, this maximum hole size is still smaller than the holes in the thick cast iron sample during the ballistic testing, which were 2.2 cm (0.9”) diameter and larger.

Based on the results of this study, it seems unlikely that the crew survived the attack on the *Housatonic*. The tidal currents and the rate of sinking indicate that the submarine stayed afloat for some period of time following the attack, or alternatively sank very gradually. When this study is combined with the archaeological evidence showing that the bilge pumps were not set to pump water and the crew did not attempt to escape the vessel, it seems unlikely that they merely continued to crank as the interior of the vessel slowly filled with water (3).

The primary limitation to this study is the number of changes that have taken place at the Charleston Harbor entrance since 1864. These changes have most likely served to alter the flow of water out of the harbor during an outgoing tide. However, by using modern current levels, we can set the upper bound on the plausible distance the *Hunley* could have traveled as a result of tidal current.

It is impossible to verify identical composition of modern cast iron against the *Hunley*’s conning tower without taking a material sample, which would violate the legal regulations protecting this historic artifact. It is therefore possible that our modern tests vary in their response to the ballistic projectiles. However, the consistency of our results with the Confederate tests of armor plate indicate that the observed conning tower damage was most likely not the result of ballistic trauma, and even if ballistic trauma did occur the resultant rate of sinking is not consistent with the final location of the vessel.

This study contains an analysis of one of the popular theories to explain the cold case of the *HL Hunley*. The unique nature of the theory forced the development of new methods to analyze tidally driven motion in a body of water. This case also serves as an analysis of ballistic behavior and risks of trauma behind a heavy metal intermediate target.

CONCLUSION

The first known reference to the “lucky shot” theory was the testimony of the crew of the *Housatonic* in the Naval Court of Inquiry following its sinking. The theory was revived in modern times by James Kloeppel in his seminal book on the *Hunley*, written in 1987 (5). When these two documents were written, there was sufficient mystery shrouding the condition and location of the still-lost *Hunley* that the theory was plausible and needed to be considered. However, given the modern discoveries unearthed during its excavation and conservation efforts, it seemed that the plausibility of the “lucky shot” theory should be re-evaluated. The calculations and experiments presented herein indicate that

the vessel instead drifted with gradual intrusion of water until settling where it was discovered, and indicate that the “lucky shot” theory is improbable.

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