DEATH OF A BATTLESHIP

THE LOSS OF HMS *PRINCE OF WALES*

December 10, 1941

A Marine Forensics Analysis of the Sinking

Garzke - Dulin - Denlay

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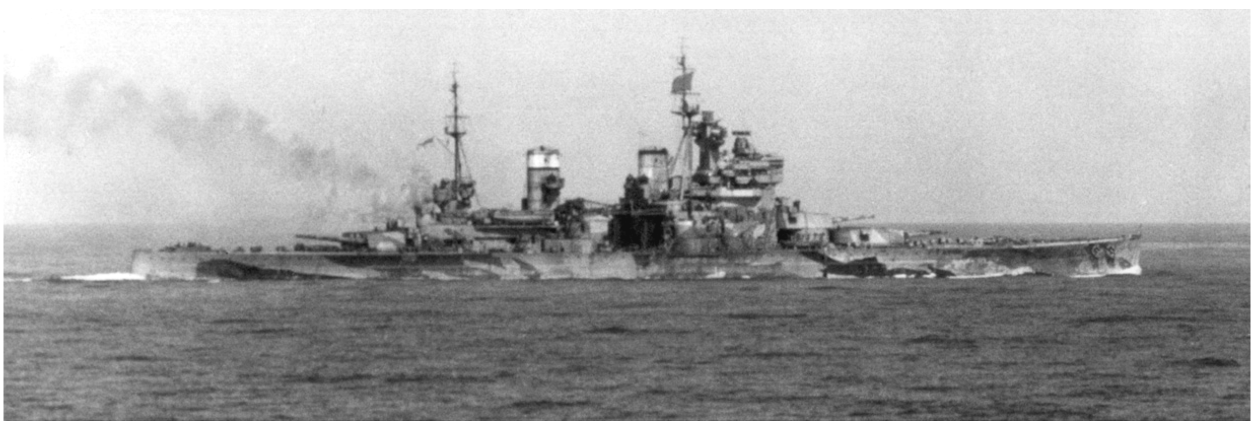
Cover. 2oz silver coin minted by the Republic of Palau, 2009. (*Authors collection.*)

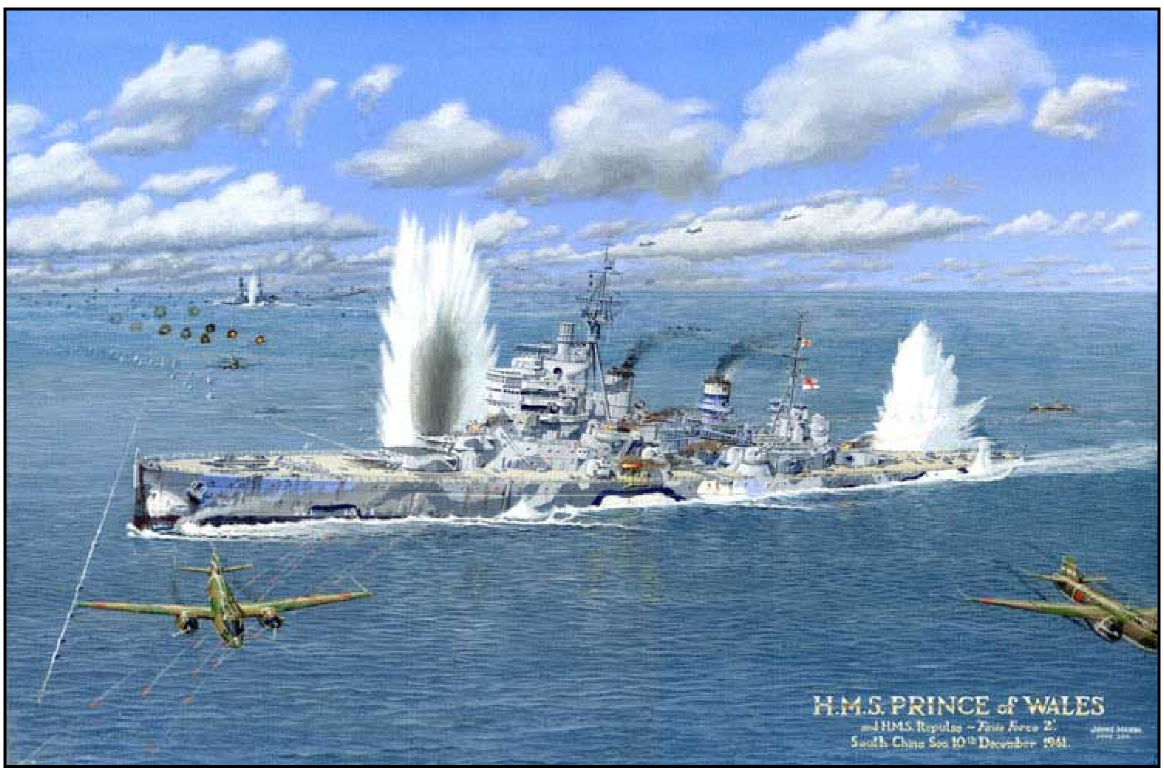
Introduction to the 2012 Revision

This paper was initially written and formatted during late 2008 and throughout 2009 in response to the significant discoveries made on the wreck of HMS *Prince of Wales* during Expedition ‘Job 74’ in May 2007, and another discovery relating specifically to the port outer propeller shaft made during a return visit by a diver who penetrated and surveyed the shafting in the port outer shaft alley in 2008.

Initially intended for dissemination via the World Wide Web once completed, the paper was selected for presentation at the September 2009 meeting of RINA (Royal Institution of Naval Architects) and IMarEST (Institute of Marine Engineering, Science and Technology) in London, UK and then put up on the web within days of that presentation. This was thought to be, except for a few typographical errors, the definitive report of the forensics analyses reflecting the 2007-2008 on-site findings.



However, just one week *after* that London presentation at RINA by author William Garzke, and the paper’s subsequent posting on the web, a major development occurred. Craig Challen, the diver who had surveyed the shafting in 2008 − up to the bulkhead of the Diesel Dynamo (or Generator) Room - Frame 206 - where it appeared any further penetration was unattainable − returned with a housed digital camera for underwater use, and not only photographed the entire length of the shafting up to his previous penetration point, but maneuvered through the restriction at Frame 206 − that had seemingly blocked his way in 2008 − and continued photographing to the forward end of the Diesel Dynamo Room where it abuts B Engine Room (Frame 184)! Here his path was well and truly blocked, as the photos clearly show, so he turned and exited back the way he came. The photos he took are truly astounding and definitively show for the first time since *Prince of Wales* sank the true nature of the internal shafting damage, including all the destroyed bulkheads and separated flanges, etc., all the way to the B Engine Room bulkhead. This photographic evidence necessitated a revision to some of the details previously published from his 2008 survey – which had been prepared from memory. At the same time as these revisions were undertaken and the few previous typos corrected, relevant data regarding a similar damage incident on USS *Pennsylvania* was added (refer to Appendix D), as were the latest photos, which can now be found in Appendix C. On 12 April 2011 author William Garzke presented a brief overview of the findings on *Prince of Wales* to the Institute of Marine Engineering, Science, and Technology, Eastern Branch, in New York City. This was done to help in the analysis of the outer port shaft failure. Shortly after that, he located the Control Room narrative that was compiled by CDR Goudy, the Chief Engineer for the Bucknill Committee that met in February 1942 to understand why one of the Royal Navy's newest battleship was lost. Hence this revised 2012 update.



FINIS FORCE Z. An artist's impression of the final torpedo strike on HMS *Prince of Wales* which occurred circa 1223. In the background HMS *Repulse* can be seen taking her first torpedo hit, after evading as many as nineteen previously aimed at her.
(*Authors collection; artist Johne Makin* **http://makingalleryplymouth.co.uk/index.php**)

A Marine Forensics Analysis of the Sinking of HMS *Prince of Wales*

December 10, 1941

by
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HMS *Prince of Wales* - a modern *King George V* class battleship - on arrival at Singapore, 2 December 1941. One of the most famous battleships in the Second World War, she was sent to the Far East to be a deterrent against Japanese aggression.

Abstract

This marine forensics analysis of the loss of HMS *Prince of Wales* is based on a series of survey dives conducted on the wreck during Expedition 'Job 74' in May 2007, two follow-up survey-dives in June 2008 and September 2009, and the monograph and reflections of one surviving officer from the Engineering Department of that battleship. Vice Admiral D.B.H. Wildish (a lieutenant at the time) was the engineering officer in charge of "B" Engine Room during the Japanese assault on his ship. He had previously served as the Damage Control Officer during the *Bismarck* Engagement in May of 1941.

Expedition 'Job 74', which carried Explorers Club Flag #118 and was led by Kevin Denlay and Dr. Andrew Fock, made a comprehensive survey of the exterior hull, which included video imagery and measurements of the torpedo holes and damaged hull sections, expanding considerably on a survey done by a Royal Navy Diving Team in 1966. Mr. Denlay also had two

of his colleagues return in 2008 to take measurements of the outer port propeller shaft. Subsequently, in 2009, one of those divers returned again to the wreck on his own initiative and took detailed photographs of the outer port propeller shaft.

Historical Background

The loss at sea of one of Great Britain's newest battleships on 10 December 1941 was a profound shock to the navies of the world, whether friend or foe. This was the first time a modern capital ship maneuvering at high speed in the open sea was sunk solely due to air attack. Designed to withstand the latest ordnance, *Prince of Wales* was sunk by a Japanese force of 85 twin-engine bombers[1] operating from air bases in Indo-China (now Vietnam).

The factors contributing to the battleship's loss dated to well before the ship's inception. The 1921 Five-Power Treaty (also referred to as the Washington Naval Treaty of 1921) set limits on future battleship standard displacement at 35,000 tons and gun size to a maximum of 16-inches (406-mm)[2]. The Treaty also terminated an earlier Anglo-Japanese Naval Treaty, thereby weakening the strategic position of the United Kingdom in the Far East. Admiral of the Fleet Lord Chatfield wrote concerning this treaty abrogation: "We had turned a proven friend into a potential and powerful foe."

Japan annexed Manchuria in 1931 and invaded China in 1937. These two events were condemned by the League of Nations as well as the United States, which was not a member of the League. The invasion of China was particularly noteworthy, because it led to the bombing of the US gunboat *Panay* on the Yangtze River and increased tensions between these two countries. Eventually, Japan's aggressive policies in China led to an oil and scrap steel embargo by the United States. This action in turn hindered the operations of the world's third largest navy.

The Japanese government was determined to follow a policy of expansion termed the Greater East Asia Co-Prosperity Sphere. Central to that plan was the extension of Japanese power and an acquisition of an empire based on European models. Oil-rich Netherlands East Indies (now Indonesia) was of particular interest in Japan's sphere of influence since the lack of adequate oil resources was a critical Japanese vulnerability. After the fall of France in June 1940, the Japanese established their bases in Indo-China, essentially asserting hegemony in the region.

[1] These consisted of 59 Mitsubishi G3M2 bombers ('Nells') and 26 Mitsubishi G4M1 bombers ('Bettys').

[2] As *Prince of Wales* was designed and built in the Imperial system of measurement, that system will still be used in this paper. However, survey data of the damaged areas are in metric units as that was the system the divers used.

The aggressive policies of Japan in the Far East alarmed the British government, particularly the move of military forces to Indo-China. Admiral Sir Dudley Pound proposed to send a fleet consisting of *Nelson* and *Rodney*, the obsolescent "R" Class battleships, and one or two battle cruisers to the Indian Ocean in May 1941. He nominated Admiral Sir Thomas Phillips to be the commander-in-chief of the new Far Eastern Fleet, but Prime Minister Winston Churchill was not satisfied with the composition of this proposed fleet. On 25 August 1941, he decided to counter the Japanese threat to British interests in Asia by having a small but powerful and fast naval squadron in the Indian Ocean that he hoped would act as a deterrent. He proposed sending the newly-completed battleship *Duke of York* (also of the *King George V* class) with an older battle cruiser and a fast aircraft carrier to the Far East. *Duke of York* was to use the opportunity to train her crew during this deployment. This proposal did not find the favor of the First Sea Lord, Admiral Sir Dudley Pound. He wanted to keep the three new battleships of the *King George V* class in the Atlantic to counter the raiding potential of Germany's *Tirpitz*, *Scharnhorst,* and *Gneisenau,* as there was always the chance that one battleship would be inactive for repairs or upkeep. Following an acerbic exchange between Churchill and the First Sea Lord, it was finally decided to send *Prince of Wales* with the battle cruiser *Repulse* and the new aircraft carrier *Indomitable*. This placated the security concerns of Australia and New Zealand, who wanted such ships in the Aden-Singapore-Simonstown area before the end of 1941.

Admiral of the Home Fleet Sir John Tovey was opposed to sending any of the new *King George V* class battleships to tropical regions because he believed that these ships' ventilation systems were not designed to operate effectively in such hot climates, the evaporators were not designed for extended periods at sea, and the variable speed gear (pumps) for the 14-inch (356-mm) turrets also would not operate effectively under tropical conditions[3]. However, on 23 October, *Prince of Wales* left Scapa Flow and at Greenock took on board Admiral Sir Thomas Phillips, who was the new commander-in-chief of the British Far Eastern Fleet. Although he was nominated for this position in May 1941, his promotion was not formally announced until 1 August 1941, during a press interview. *Prince of Wales* left the British Isles in October and made a brief stay at Capetown, South Africa during November 1941. After the battleship left Capetown, Lt D.B. H. Wildish, the officer in charge of damage control, was notified by Chief

[3] Public Record Office, ADM 199/2232 and X-in-C Home Fleet to Admiralty, 2251A;20/10/41.

Engineer L. J. Goudy that he was being relieved by Lt Peter Slade (RN) because Wildish was about to be transferred to the destroyer HMS *Isis* undergoing repairs in Singapore. In the meantime, he was given command of “B” Engine Room.

Prince of Wales arrived in Singapore on 2 December 1941, without the promised aircraft carrier. Unfortunately, the carrier of choice, *Indomitable,* had run aground entering Kingston harbor, Jamaica, in the West Indies on 3 November 1941. After inspection of the damage, she was sent to the United States for repairs at the Norfolk Navy Yard that were completed in 12 days. However, with this delay she could not reach Singapore in time to join *Prince of Wale*s. The carrier was still undergoing training in the West Indies when the battleship arrived in the Far East. There was no replacement for this carrier, as no other carrier in service could be spared.

HMS *Prince of Wales* sorties from Singapore, 8 December 1941. Two days later she and her consort HMS *Repulse* were both on the bottom of the South China Sea

The decision to deploy these two capital ships with no aircraft carrier in company had some risks[4]. During May 1941, the sinking of the German battleship *Bismarck* had demonstrated what could happen to a modern capital ship without adequate air or ship cover. Furthermore, the deployment of *Prince of Wales* and *Repulse* deprived the Home Fleet of two valuable capital ships. The Japanese had great local superiority in terms of surface ships, submarines, and aircraft. To all intents and purposes, *Prince of Wales* and *Repulse* had no chance of repelling a concerted air attack and little chance of evading the Japanese, who would aggressively search for them. However, the threat of sinking a capital ship by air attack was not yet fully appreciated in the naval communities of the allies.

[4] See Appendix B for a discussion of these risks.

Prince of Wales was not in good operating condition upon her arrival in Singapore. Captain John Leach had twice previously overruled the request of Senior Engineer LCDR Robert O. Lockley to have a routine cleaning of the boilers. Boiler efficiency is important to operating effectiveness, as boilers that are not properly maintained are susceptible to tube failures. The battleship entered the dry dock in Singapore to have her underwater hull cleaned while her boilers were given their overdue cleaning. Despite the fact that events began to happen rather quickly, the boiler cleaning was completed. Singapore was attacked by Japanese aircraft at 0400 on 8 December, shortly after aircraft from six Japanese carriers attacked Pearl Harbor on the morning of 7 December across the International Date Line.

Admiral Phillips decided to take his fleet, code-named Force Z and consisting of *Prince of Wales* and *Repulse*, accompanied by the destroyers *Electra, Express, Vampire* and *Tenedos*, to sea and attack a Japanese landing force reported to the north at Kota Bharu on 10 December. Complete surprise was the key to his plan for attacking the transports, but having been shadowed by Japanese observation spotter planes during the late afternoon of 9 December, surprise seemed impossible. Thus, he took the inevitable but only sensible decision available to him and turned back for Singapore at around 2000. (Admiral Phillips was unaware that he had also been sighted by a Japanese submarine that day − as a result of its report, the Japanese transports had been moved further north to safety.)

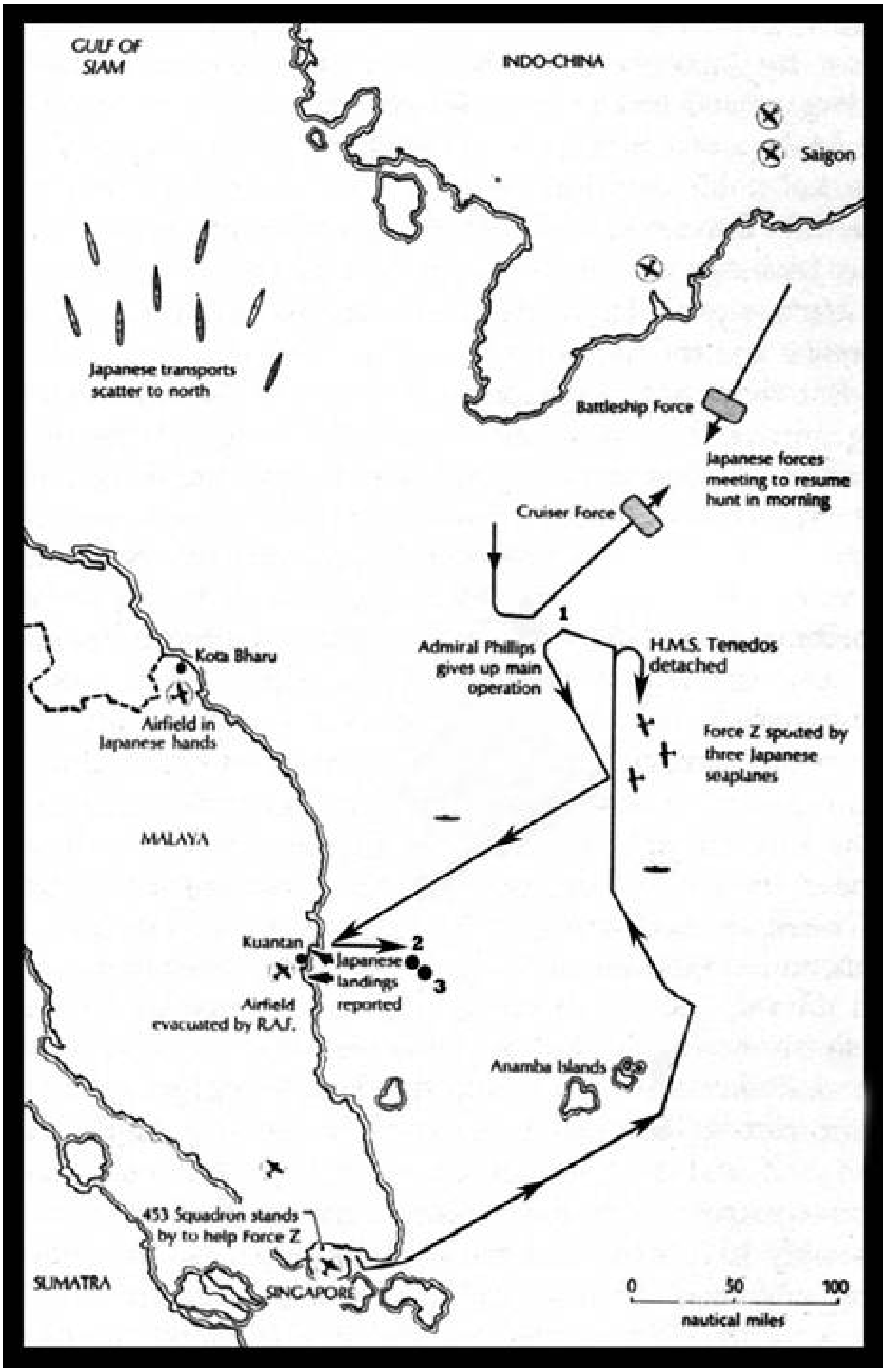
HMS *Repulse* sorties from Singapore, 8 December 1941. Although built in 1916, and still poorly equipped with anti-aircraft armament, on 10 December the old battlecruiser turned in a commendable performance until simply being overwhelmed by simultaneous torpedo attacks from several directions.

Shortly before midnight, Phillips received another report of a Japanese landing at Kuantan, which is on the Malayan coast nearer Singapore, and set course for there. Upon arriving off Kuantan on the morning of 10 December, the British fleet found no Japanese invasion force. Therefore, after investigating a tug towing several barges nearby, Admiral Phillips decided to continue on to Singapore.

Left. HMS *Repulse* is hit by one bomb (and closely straddled) in the first attack. The attacks would end one and a half hours later with an almost identical straddle and hit on HMS *Prince of Wales.* **Top Right.** Mitsubishi G3M 'Nell' bombers. **Bottom Right.** Mitsubishi G4M 'Betty' bombers.

Shortly thereafter, Force Z was sighted and attacked by a force of Japanese twin engine bombers armed with bombs and torpedoes. *Repulse* was the first of the two ships to be attacked. Around 1113, eight 250-kilogram bombs fell within ten meters of the old battle cruiser, with one striking and exploding amidships. Around 1141, another Japanese attack commenced on the port side of *Prince of Wales,* with nine twin-engine bombers carrying torpedoes fitted with 150-kilogram warheads[5]. These aircraft made their initial approach at a speed of 150-180 knots at a height of about 55 meters with torpedoes that had been set to run at a depth of 4 to 6 meters**.**

[5] The Genzan and Mihoro Squadrons used this charge in their torpedoes, while the Kanoya Squadron used torpedoes with a heavier charge of 205-kilograms.



Force Z Track Chart

Force Z's route, from leaving Singapore on the evening of 8 December until late morning on 10 December. At the time when Force Z 'turned away' south, when at its northern-most point (1), neither fleet was aware just how close they had come to one another. Black Dot 2, about sixty nautical miles off Kuantan, marks the location of the wreck of HMS *Repulse*; while Black Dot 3 marks the wreck location of HMS *Prince of Wales*, which is approximately eight nautical miles south-east from that of *Repulse*.

Eight of these planes would attack *Prince of Wales* (one plane had sheared off and headed toward *Repulse),* and she began a slow turn to port so as to 'comb the torpedo tracks. Before this maneuver could be completed, eight torpedoes were dropped at a height of 30-35 meters between 600-1500 meters from the port side of the British battleship. This type of attack was unlike any that the antiaircraft crews had drilled for or experienced in combat with Italian torpedo planes during Operation Halberd in the Mediterranean. Seven of these torpedoes were avoided but, unfortunately, one struck *Prince of Wales* on her port side aft around 1144 with great force[6]. This was the critical blow that eventually led to her loss. The ship began a heavy list to port, rapidly reaching a maximum of 11.5 degrees. By 1210 the "out-of-control" signal had been hoisted, at which time the steering gear was still not functioning. This is a classic example of a "mobility kill" as defined in modern warship design practice – the effectiveness of this battleship had been destroyed, and her survival was now seriously in doubt.

Another torpedo attack would come later against the starboard side, followed some 30 minutes later by a final attack by bombers equipped with 500-kilogram bombs.

[6] It was previously believed that two torpedoes struck the port side. This report will show that there was only *one* that struck, based on a marine forensics investigation by Kevin Denlay and associates (Expedition 'Job 74'). Although many eyewitness reports mention an immense column of water erupting outboard of P3 and P4 5.25" turrets that was thought at the time to be a hit, it was in all likelihood caused by another torpedo being set off close to the hull just milliseconds after the first - having possibly been detonated 'sympathetically' by the shock wave from the first hit less than 50 meters further aft.

The Fatal Torpedo Hit

The *King George V* class battleships were equipped with four Engine Rooms with 27,500 shaft horsepower (20,500 KW) turbines powering each of the four shafts. Each Engine Room had a Boiler Room with two oil-fired boilers feeding steam to it (see Figure 4a), combined with an associated Action Machinery Room that had a steam-driven turbo-generator that supplied electric power to the ship. The propulsive power was transmitted through a single reduction gear and a Thrust Block to a segmented line shaft that went out through a stern tube to the propeller. The line shafts were supported by bearings; at every transverse watertight bulkhead a watertight gland was fitted. A shaft strut[7] supported the exposed shafting and propeller on all four shafts.

Although the exact sequence of events in this area of the ship will always be unknown, using the techniques of marine forensics we have developed a likely sequence of events based on survivor testimony and several inspections of the wreck. (Late in World War II, the U.S. battleship *Pennsylvania* sustained a similarly-located torpedo hit. Analysis of this damage is relevant to understanding the situation of *Prince of Wales* in 1941. Refer to Appendix D for details of the 1945 damage incident.) The torpedo detonated forward of the port strut in close

[7] British terminology refers to struts as A Brackets, but the internationally accepted term “Strut” will be used in this paper.

proximity to the stern tube of the outboard shaft which received its power from the turbines in "B" Engine Room. That space was in the charge of LT D.B.H. Wildish**.** All survivors noted the heavy shaking of the ship. The torpedo explosion under the stern had the tendency to lift the stern, but the inertia of the barbette armor and the aft quadruple turret resisted the tendency of the stern to lift, causing deformation of the surrounding structure and perhaps failed riveted seams. This type of damage was experienced by the USS *Pennsylvania* when she was hit by a torpedo in the stern while at anchor in Buckner Bay, near Okinawa, on 12 August 1945[8].

The outboard port shaft strut arms were weakened by the force of the explosion and a ragged hole was torn in the hull plating approximately four meters high and six meters wide just abaft the stern tube, and the shaft itself was damaged. The stern tube was also damaged (See Figure 1), but its degree of damage is not known, nor will it be until that missing section of shafting and the associated stern tube structure is found for further examination. The outer port propeller continued to rotate at high speed and, turning out of center, started to wobble and vibrate, putting additional stress on the weakened strut. (The 2007 survey has shown that the weakened inboard strut arm of the strut eventually failed by breaking in half, while the outboard strut arm broke off cleanly at the hull. See Figure 4c). LT Wildish was unaware of this serious damage to his shafting and propeller. As communications in the ship had been disrupted, his actions were dictated by what was happening within his space. (As we will see later, this disruption of the ship's internal communication system − caused by the loss of electrical power as a result of the torpedo hit − would soon have serious repercussions for both damage control and for the ship's fighting ability.) He did experience a terrific shock response with the ship whipping around like a springboard, and that event was also noted in the testimony of other survivors. This caused some rivet failures in connections of structure around "Y" turret, as the massive weight of this structure was not as easily excited as lighter local structure around it. This would be a contributory cause to later progressive flooding in this area of the ship (Appendix D).

The shaft for "B" Engine Room immediately began to encounter serious trouble.
This situation was also monitored in the Power Control Room in "X" Engine Room, but due to the failure in the ship's communication system no voice contact could be made between these spaces. The Power Control Room was commanded by the Chief Engineering Officer, CDR (E) L. J. Goudy (RN). This was a separate space with duplicate gauges, switches, etc. to monitor and

8 See Appendix D

control the performance of all four Engine Rooms (Figure 4a).[9] Senior Engineer LCDR Lockley was also in "X" Engine Room in overall control of the four Engine Rooms.

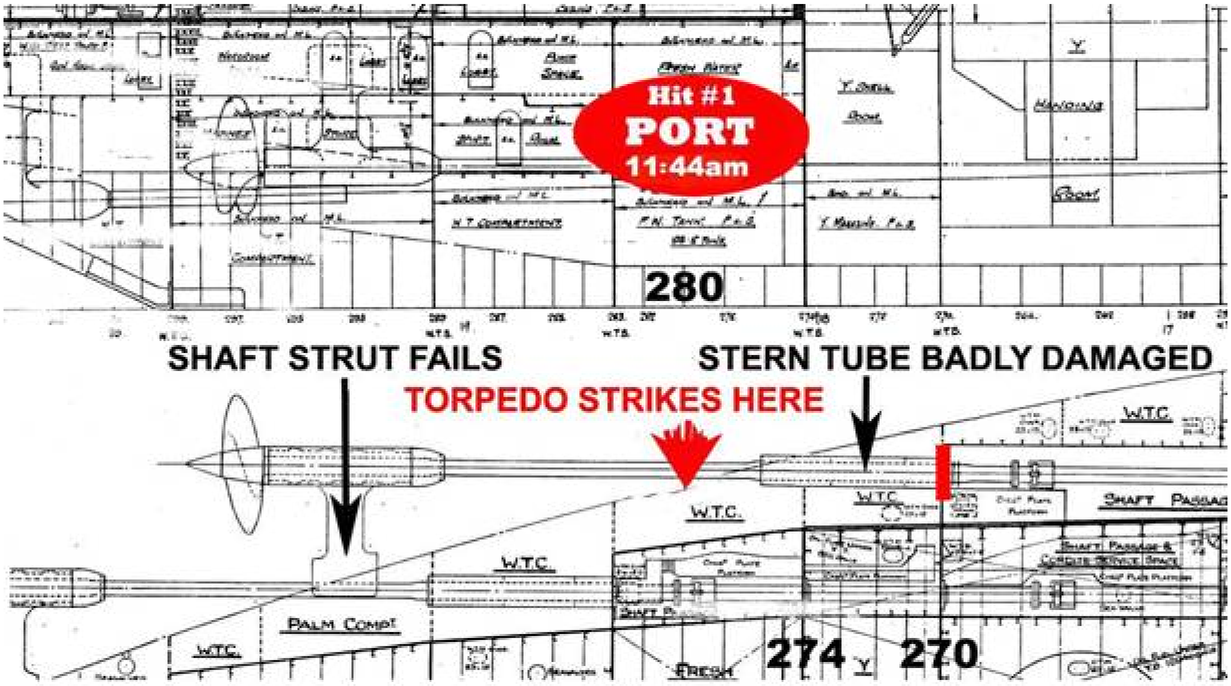


Figure 1 – Location of the First Torpedo Hit

The upper ***profile view*** shows where the first torpedo hit to port at about Frame 280, based on measurements made by the Expedition 'Job 74' diving team. The lower ***plan view*** shows the stern tube and the aft end of the outer shaft alley for the shafting from "B" Engine Room (upper shaft in plan view). The torpedo struck just abaft the stern tube, which in turn became disassembled from the shafting after the failure of the shaft strut. The explosion would have wrecked the structure of the nearest bulkhead (Frame 274) in the stern tube area and most likely caused serious damage to the bulkhead that closed off the aft end of the shaft alley (Frame 270 - red line). When the shaft began to rotate out of center it further damaged that bulkhead (Frame 270) and later demolished it when the shafting came apart.

At the moment of the torpedo's impact, *Prince of Wales* was doing 25 knots with the "B" Engine Room shaft rotating at 204 rpm. LT Wildish heard and felt the shock of an appallingly powerful explosion. The ship shook violently and great clouds of thick yellow fumes poured into the Engine Room from the ventilation trunk. The turbines started to vibrate and LT Wildish immediately thought about the failure of his propeller shaft and turbines. An order was given to Mechanician Hanley, manning the throttle, to shut off the steam immediately by tripping the emergency bulkhead stop valve. After a short pause, the valve was opened again to allow 100 lbs of steam to allow astern steam to stop the turbines.

[9] Vice Admiral Wildish has been adamant in his conviction that CDR (E) Goudy did not take proper actions to ascertain for himself the conditions occurring in "B" Engine Room, given the calamitous failures of the ship's internal communications.

With the ship moving at a speed of 25 knots, the forward motion of the ship would cause the propeller and shaft to continue to "windmill" despite the efforts of Lt. Wildish to slow the shaft. Such opposing forces put a great strain on the bolts connecting the flanges of the line shaft. LT Wildish realized the necessity of a quick decision in this emergency, as the shaft had been turning with difficulty, so he had Chief Stoker Hooper check with personnel in "B" Boiler Room to determine if there were any problems with equipment there. Hooper reported back that there was no apparent damage there. Wildish was now faced with a dilemma. His ship was under a threat of further attack and he knew his ship already had been hit by a torpedo. Not knowing the severity of damage to his shafting, line bearings, propeller and strut, astern steam was gradually reduced and finally cut off. The shaft "trailed in" and so he believed that the shaft and propeller were still functioning. He checked the turbines for the usual important details and finding no problems the steam flow was increased gradually to 158 revolutions for ahead operation; still, there was some vibration in the units. All survivors in the vicinity of "B" Engine Room spoke of continuous knocking noises for some time after the torpedo hit. They all seem to attribute the noises to damaged propeller shafting.

Just before 1151, LT Wildish then went to the aft bulkhead to make an inspection of the reduction gear and the area where the 17.5-inch (44.5-cm) diameter shaft passed through the aft bulkhead of "B" Engine Room (Frame 184) into the Thrust Block at the forward end of the Diesel Dynamo (Generator) Room immediately behind "B" Engine Room from which the shaft subsequently went on through to the "Y" Action Machinery Room aft of the port Dynamo Room. Arriving at the aft bulkhead, he found that the bulkhead stuffing gland was wrecked and there was nothing that he could do to stop the water that began to pour through the gland at the bulkhead behind which the Thrust Block itself was located. The shaft had been and still was running out of center. LT Wildish now realized that something serious had probably happened to his propeller which had caused the whole line of shafting to run eccentrically under enormous power, destroying the watertight integrity along the entire length of shafting. (Figure 3) There was nothing that could be done about that, either. LT Wildish, still believing that he had propulsive power, immediately returned to the control platform where the turbine throttles were located. The time we estimate was now around 1153. The Power Control Room narrative, compiled by CDR. Goudy, reported that there were no revolutions on the port outer shaft at 1151.

Water began rising fast in the Engine Room's bilges; the emergency pump was started and the fire and bilge pumps put on bilge suction. Still, the water level kept rising so an order was given for the main circulator to be changed from sea suction to bilge suction, the high volume pump moving water to the main condenser under its main engine. With the water level still rising, Wildish realized that the situation was clearly becoming out of hand; evacuation of the space was mandatory. He decided to let the turbines continue in operation with the machinery prepared to run underwater by increasing gland steam to the turbines and speeding up the auxiliaries. Soon the water was over the platform where the controls were, so Wildish then ordered the immediate evacuation of the space. He was the last man out – after he dogged the hatch some water started oozing out around it. LT Wildish realized that further effort to secure the hatch was needed quickly, as his experience as the Damage Control Officer during the *Bismarck* encounter months earlier had taught him that the **'**dogs**'** or handles around watertight doors and hatches had to be hammered up really tight. As an added precaution, Wildish had the shipwrights shore down the hatch. As this effort was ongoing, water began to squirt out around it. Eighteen minutes had passed from the moment of the torpedo's impact when Wildish took these actions.

Although the turbine at the time of this evacuation was set to run under flooded conditions, it did not over-speed because the steam to "B" Engine Room had been cut off while LT Wildish was in the process of evacuating "B" Engine Room. By the time the crew of "B" Engine Room was evacuating this space, gradual leakage had led to the loss of the feedwater from the tank in "B" Boiler Room, necessitating the shutdown of the two boilers there.

According to LT Watson, engineering officer for "Y" Engine Room, the turbo-generator in "Y" Action Machinery Room (See Figure 2) had its steam supply cut off immediately after the torpedo hit when the lights in "Y" Engine Room failed and the steam pressure failed from "Y" Boiler Room[10]. The loss of the latter was a contributing factor in the loss of electric power (and in turn, communications) in the stern of *Prince of Wales*. Watson did not restart the turbines for fear of additional damage to these units and the shaft trailed in at 12 revolutions (according to the Power Control Room narrative, it was recorded as 30 revolutions). He maintained that the

[10] Statement of LT. Watson (E) in charge of "Y" Engine Room to Bucknill Committee. The Bucknill Committee was set up in February 1942 to determine the factors and causes in the sinking of the new *Prince of Wales*.

turbines could be restarted but only if he felt that the ship's survivability depended on it. There is an entry at 1202 in the Power Control Room log that both turbines were no longer functioning.

There were terrific crashing noises in the vicinity of the turbine in "Y" Engine Room, which drove the inboard port shaft. Those noises forced its shut down. Based on the inspection of the wreck, it is now believed that this action was prompted by damage to the blades of the inner propeller − evidently from debris entering the inboard propeller race − after the outer shaft and shell plating sustained damage from the torpedo hit. In addition, the steam pressure from "Y" Boiler Room failed due to damage to the oil fuel suction and failure of lubrication to the circulator.[11] Some flooding was also occurring in this space through what appears to be failed rivets or riveted seams and some oil fuel was discovered in the bilges. Efforts by LT Watson to start the pumps in this space were doomed by the power failure.

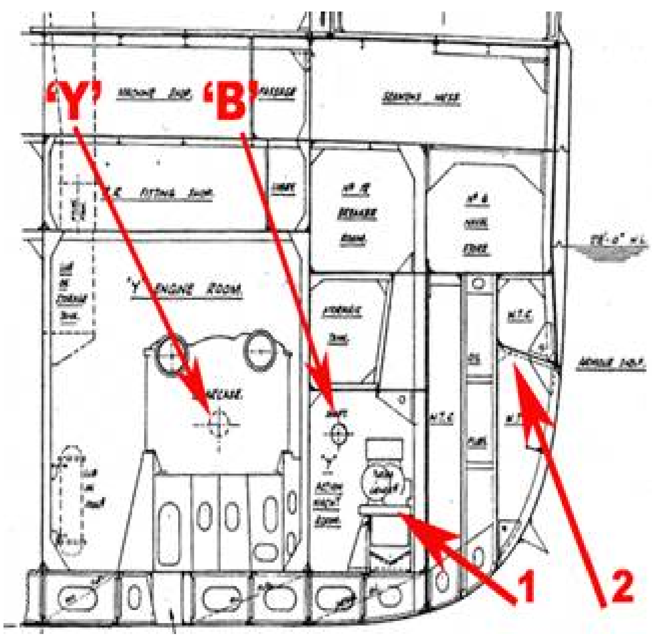


Figure 2 – Transverse Section

This is a transverse section of the ship through "Y" Action Machinery Room looking aft. "Y" Action Machinery Room was part of a long outer shaft alley from "B" Engine Room to the stern tube. Note the positions of "Y" and "B" Engine Room shafts and that the "B" shaft is centered only about 1.25-meters beneath the deckhead of 'Y' Action Machinery Room; as this will be referred to later in the paper. A section of line shaft was also reported to have fallen on the steam dynamo (1) seen against the torpedo bulkhead. Note also the shelf connection (2) that supports the lower portion of the side armor belt and its attachment to the inner bulkhead without proper backing structure.

Engine Rating Artificer J. P. Williams in the Port Diesel Dynamo Room testified at the Bucknill Inquiry in February 1942 that after the first torpedo hit, the shaft in this space began to make a violent knocking noise but within the space the shaft was rotating normally. However, aft of this space there was a very loud noise which sounded similar to the reciprocating motion that a large diesel might make. Soon after these noises, the Diesel Dynamo Room began to flood

[11] Statement of LT. Watson (E) in charge of "Y" Engine Room to Bucknill Committee.

rapidly with a mixture of water and steam. At the time Williams did not have the chance to inspect the aft integrity of the bulkhead or its shaft gland, as he was forced to abandon this space immediately.

On further examination of survivor testimony, we now believe that the port outer shaft started to fail shortly after the torpedo explosion. The failure progressed forward and that is verified by the evidence of ERA Williams. Evidence at the wreck site indicates that the stern tube had been damaged, probably severely, along with its supporting web frames within the hull and the restraining clips that held the line shafting to the plummer blocks (pedestal bearings) had been snapped off. As both port shafts were now out of action (the inner port shaft having been shut down), the ship slowed to 15 knots, with propulsive power being provided by only the starboard shafts. With the steering not functioning, the ship began to veer in a slow port turn.

Following this torpedo hit and the shock response, numerous failures were sustained by the electrical system. The after 5.25-inch (133-mm) gun turrets were put out of action, along with the ship's radars and steering gear. When the main lighting failed, dim emergency lights came on, providing limited visibility. The ventilation system already had difficulty coping with the tropical heat, and some of the fans in the stern were out of service due to the power failure, making it even more unbearable for the crew in that part of the ship. Communications were also seriously affected, making it difficult for damage control teams to be directed to portions of the ship affected by the torpedo hit. Nevertheless, these teams did rig emergency electrical leads to vital functions, established a flooding boundary, and attempted to restore the steering. Captain Leach reluctantly ordered flooding the voids of the starboard torpedo defense system to counter the port list. (See Figure 4) These efforts did reduce the port list by about 2.5 degrees, however, flooding the outer and inner voids made the ship more vulnerable to a torpedo hit on the starboard side. LT Brooke recalled that he could hear the noise of the flooding going on below coming up through the 'voice pipes'. LCDR Harland recalled that he could hear what he termed as "expensive noises" after the torpedo hit. We now attribute this to the damaged port outer shaft rotating out of center and damaging internal structure.

With the stern tube for the outboard port propeller shaft seriously damaged by the explosion, the shaft itself rotating out of center, and vibrations being transmitted throughout the shaft, the watertight glands in several transverse bulkheads along the shaft alley - Frames 270, 253, 242, 228, and 206, the latter two being the aft and forward bulkheads of "Y" Action

Machinery Room - were wrecked. The watertight integrity along the port outboard shaft had been completely compromised. However, although *all* glands were wrecked, the further forward the bulkhead, the less damage the bulkhead itself sustained. (Figure 3) This damage created a direct conduit for progressive flooding up the shaft alley, eventually flooding "Y" Action Machinery Room and, in time, the Diesel Dynamo Room. From there, flooding water would finally enter "B" Engine Room through the failed gland at Frame 184 that LT Wildish had observed.

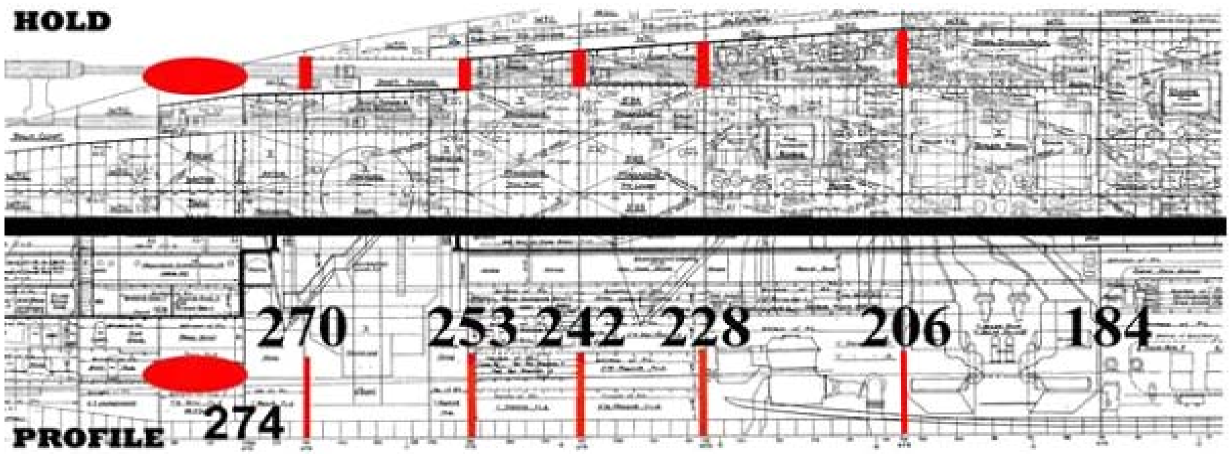


Figure 3 – Arrangement of Port Outboard Shaft Tunnel

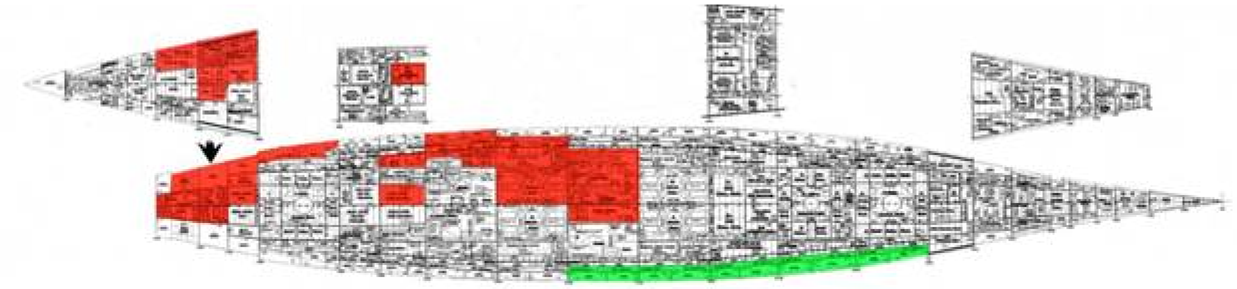
Using Expedition 'Job 74' survey measurements, we can now accurately show where the torpedo in the first attack struck *Prince of Wales* (red ellipse). The red lines mark the position of the transverse bulkheads along the shaft tunnel affected by the shaft initially running out of center and then eventually disintegrating (Frames 270, 253, 242, 228 and 206). The bulkhead at Frame 184 remains intact but its gland (which cannot be viewed because of the Thrust Block Enclosure) must have failed to remain watertight as Lt Wildish reported that water flooded through it into B Engine Room.

A survivor from the Diesel Dynamo Room had even reported that its aft bulkhead (Frame 206) had "caved in", but this has been found to be slightly in error. The shaft rotating out of center had destroyed the bulkhead stuffing gland. When inspected in 2008 and photographed in 2009 by a survey diver, the bulkhead itself was found to be relatively intact, but the gland the shaft passes through was wrecked, with the surrounding structure misshapen and elongated. When LT Wildish restarted the turbine in the ahead position, the shaft, rotating out of center, started to come loose from its remaining pedestals and bearing covers which subsequently led to the failure of the bolts connecting the 17.5-inch line shaft flanges. This situation then caused the line shaft to come apart (Figure 6) which resulted in varying degrees of destruction to the previously damaged shaft tunnel bulkheads at Frames 270, 253, 242, 228, and 206 (see Figures 3 and 11).

If / when it is possible to recover some of these failed bolts, it may be possible to develop a better understanding of this shafting failure. There are several factors that probably contributed to this dramatic and unexpected event:

- While fitting out in early August 1940, *Prince of Wales* was damaged by a near-miss bomb that detonated about 10 feet (3 meters) from the port side in way of the after 5.25-inch gun battery, causing dramatic buckling of shell plating to occur over some 25 feet. (See image page 57.) Numerous rivets were sprung, and a number of port outboard compartments were flooded, causing a ten-degree port list, a situation which the inspecting naval constructor deemed serious. Permanent structural repairs of the local damage were completed. Reports of the repairs to the battleship make no mention of the inspection or repair to machinery systems in the vicinity, such as the port side propeller shafting or to the connections of the port bearing housings (plummer blocks) to the shell, particularly in that section of shafting just aft of B Engine Room.
- Analyses of shock damage incidents later in the war and more recently indicate it is highly likely that a number of the bolts in various shafting flanged joints on the port side were damaged at this time.
- The torpedo detonation occurred well aft on the port side, somewhat confined by the overhang of the stern structure, lifting the stern. The massive inertia of the heavily-armored after quadruple 14-inch gun turret would have resisted such motions, inevitably leading to numerous localized structural failures and contributing to a susceptibility to progressive flooding aft. Refer to Appendix D for an analysis of a similar damage incident affecting USS *Pennsylvania* (BB 38).
- The shock impulse resulting from this torpedo detonation certainly could have further weakened the bolts holding the flanged joints together.
- The vibration caused by the wrecked propeller shafting contributed to the ultimate devastation recently discovered by Australian divers.
- Finally, the continued forward motion of the battleship caused the wrecked shaft to "windmill" – leading to further damage as the pull on the damaged structure led to further structural damage and the parting of the port propeller shaft.

LOWER DECK



UPPER AND LOWER PLATFORM DECKS

HOLD

Figure 4 – Flooding Diagrams after First Torpedo Hit

The black arrow head denotes where the first torpedo struck. The red areas in the above lower-level diagrams (Hold, Platforms, and Lower Deck) of *Prince of Wales* denote the areas in the ship that were flooded after the first torpedo strike. The green area is the section of the starboard Side Protection System that was intentionally flooded to try to correct the list and trim after the massive influx of water to port.

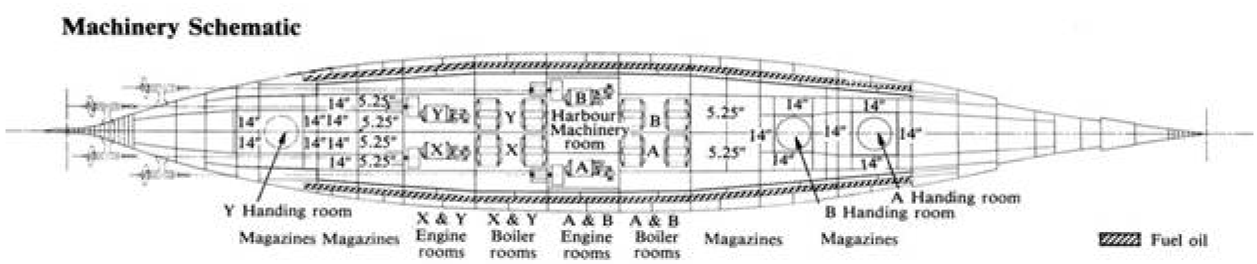


Figure 4a – Machinery and Magazine Arrangements Schematic

The above schematic shows the layout of Boiler Room and Engine Room machinery spaces and the various Magazines for the 5.25-inch and 14-inch guns in relation to one another. Also note how the center section of the “triple layered” Side Protection System was filled with Fuel Oil.

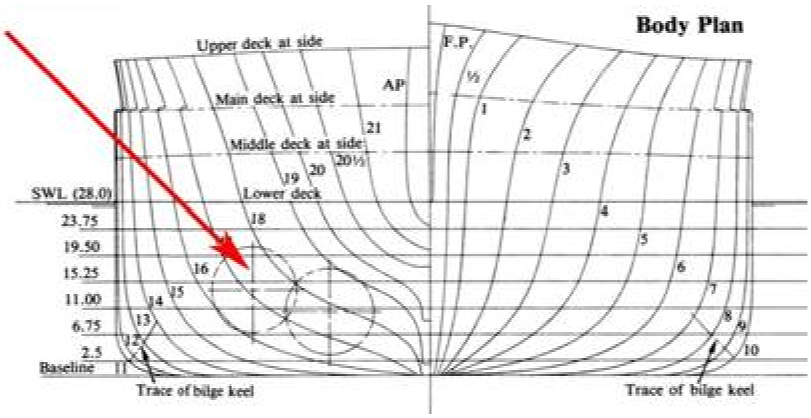


Figure 4b – Location of the Port Torpedo Hit

The red arrow above points to the approximate location of the port torpedo hit, just where the outer propeller shaft exited the hull. Note how the hull curves under where the torpedo struck the hull. This may account for why no column of water was seen to be 'thrown upwards' by this hit, as did occur with all the other hits.

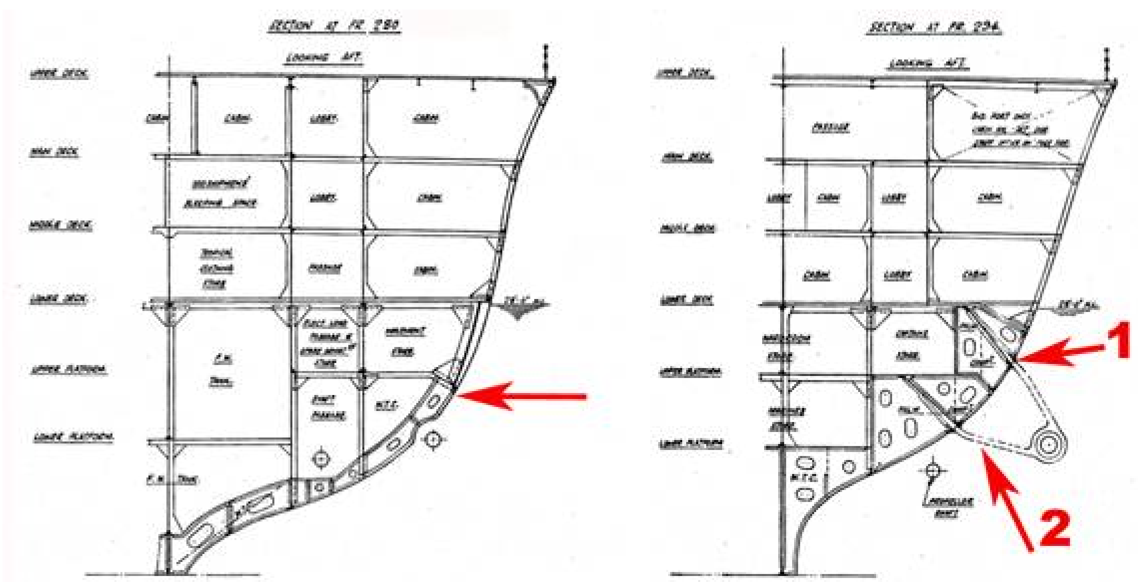


Figure 4c – Cross Sections of Port Hull in Way of Torpedo Hit

Cross sections of port hull at Frames 280 and 294, *looking aft*. **Left**. The torpedo struck at about Frame 280 just above the outer port propeller shaft (red arrow). **Right.** Frame 294. The outer strut arm (1) of the outer strut eventually broke off flush with the hull while the inner strut arm (2) broke in half. (Note: The later hit above the starboard outer strut broke its arms in the opposite manner, i.e. the outer strut arm broke in half, while the inner strut arm broke off flush with the hull.)

Outboard on the port side, when "Y" Action Machinery Room and No. 6 Diesel Dynamo Room (immediately aft of "B" Engine Room) initially began to flood, they did so at a rate that enabled personnel there to escape, although "Y" Action Machinery Room, aft of No. 6 Diesel Dynamo Room and closer to the affected propeller, flooded more rapidly. No. 8 Diesel Dynamo stopped immediately after the torpedo explosion, while No. 6 Diesel Dynamo stopped after "Y" Action Machinery Room had flooded completely. The flooding in these two spaces expanded upwards and inboard, as some of their personnel left watertight hatches open or insufficiently dogged. There was substantial flooding on the middle deck in the compartments forward of the aft main battery turret. The shock effect of later torpedo explosions possibly loosened the clips on the watertight doors or escaping crew did not completely hammer them tight. Water came up the trunk from the port shaft alley and poured onto the Middle Deck. The doors to the trunk on that deck were later secured by a damage-control party with much difficulty, because that deck had a large amount of water on it.

Gunners Mate Alan McIvor was in one of the port 5.25-inch Gun Turrets (P3). He describes the terrifying noise caused by the port torpedo explosion: *"A matter of seconds before being hit, we'd been training our gun on one of the planes that had taken part in this first attack. Suddenly there was a tremendous explosion. I can best describe the noise as tons of plate glass shattering on a pavement. Immediately, we lost all power to our gun which was stopped whilst training aft".*

At the Bucknill Committee hearings, LCDR Terry, who was stationed on the quarterdeck at the time of the first torpedo hit, testified that he saw the torpedo hit the ship at some point abaft of the aft quadruple ("Y") turret. (Many survivors who witnessed this torpedo hit also maintained that this was the only port torpedo hit. As it turned out, they were correct.) The furnishings in the staterooms in the area where this torpedo hit were tossed around and the scuttles to those affected cabins were loosened, opening yet another source of flooding resulting from the list to port, the stern trim, and sinkage from all the flooding water that entered the ship.

By 1202, the situation had drastically worsened; both port shafts were no longer operating, communications were limited, and there were terrible temperature conditions below deck as many of the electrically-driven ventilation fans were not functioning, resulting in officers and ratings having to work in relays just to keep vital machinery running under extreme temperature conditions. Even though there was a significant amount of flooding on the port side -

resulting in a 11.5 degree list and a trim by the stern of 5 feet (1.5 meters) - within six minutes of the torpedo hit counter-flooding in the outboard voids of the starboard torpedo defense system (Side Protection System) did reduce the port list to 9 degrees by 1210, but that list still affected the antiaircraft fire for those few guns still operational. In addition to the list and trim, there was a considerable reduction in electric power that had plunged much of the stern portion of the ship into darkness. Dim emergency lighting had come on, but even that in the stern area failed as emergency power was curtailed by the loss of dynamos.

Another witness at the Bucknill Committee inquiry, Stoker James, testified that he saw the shaft break in "Y" Action Machinery Room. His testimony was challenged because senior naval architects and marine engineers examining his testimony found it difficult to believe that a 17.5-inch line shaft would actually 'break'. As it transpired, Stoker James was the *only* survivor whose testimony correctly described a complete shaft failure. It was not until video footage shot during Expedition 'Job 74' in 2007 was studied by British author / historian John Roberts[12] − who quickly noted that a flange on the protruding port shaft should not have been located outboard of the stern tube − that it became obvious that there was something amiss internally with the shafting. Following this surprise observation, author Denlay had two of his colleagues explore the area in more detail in 2008. The results, shown in Figure 6, proved Stoker James was correct! As we now know, the damage to the stern tube, the shaft's internal supports and bulkhead glands had caused the shaft to rotate with difficulty, eventually causing failure of the bolting in flanges along its length, including an unsupported section of line shaft between bearings in "Y" Action Machinery Room. Eventually the shaft strut and propeller broke away from the ship, along with the 17-meters of shafting aft of the last flange joint, causing in the process the stern tube to be ripped out of the hull. Debris from this failure then entered the propeller race of the inner port propeller and damaged its blades, which in turn affected its operation; the resultant blade damage being filmed on the wreck in 2007.

However, the failure of the shafting (i.e., shearing at the flanges) would have been extremely violent and we would have expected that everything in "Y" Action Machinery Room to have been damaged and any personnel there would have been killed or seriously injured by flying debris. How, then, did Stoker James witness this event and survive? It appears he must

[12] John Roberts is an expert on British battleships and is an author of the books, *British Battleships* and *The Battlecruiser HMS Hood*.

have been at the hatch from "Y" Action Machinery Room to No. 12 Breaker Room (above). Once he saw what was happening, he left the area. The hatch was obviously never closed or secured correctly; the survey diver recalled seeing the hatch in that space open during his shaft inspection in 2008. This was probably due to the considerable amount of steam that was reported to have collected in the forward end of this space, making hatch 'security' untenable.[13]

Further consequences of this shaft failure accounts for the actions of occupants of the magazines for the two port after 5.25-inch turrets (P3 and P4)[14]. Believing that the noise generated by the shaft's failure was another torpedo hit in their area of the ship, they proceeded to flood all their powder and shell magazines, which contributed to the initial list becoming 11.5 degrees to port, although later reduced to 9 degrees by 1210. That list had serious repercussions. The forward starboard 5.25-inch dual-purpose turrets (i.e. anti-aircraft or surface targets) were unable to depress their guns low enough to engage further attacking torpedo aircraft, while there was no electric power at all to the aft group of 5.25-inch turrets. This power loss also affected vital internal communications, ventilation, steering gear and pumps, and for training and elevation of the 5.25-inch guns and the Pom-Pom machine guns and meant that the ship's pumps could not pump flood water fast enough to counter the rapidly progressive flooding. Only the S1 and S2 5.25-inch turrets were manageable, but compromised by the 11.5-degree initial port list. The gun crews were unable even to train other turrets manually using chains and the Pom-Pom gun crews also had difficulty bringing these heavy machine guns into manual operation. (*Prince of Wales* was, however, still able to fire at a high level bombing attack with S1 and S2 turrets during the bomb attack starting at 1241). The extensive internal flooding and port shaft damage had left the ship under power from only the starboard engines and able to make only 15 knots at best and, with her electric steering unresponsive, the ship was virtually unmanageable.

With the steering gear out of action after the power failure, an attempt was made to have emergency power leads connected to vital functions. In the meantime, a standby steam connection from X Engine Room was in operation. Out of eight generators (six 330-kw DC turbo-dynamos and two 330-kw diesel dynamos), only three turbo-dynamos were operational when the second torpedo attack commenced at 1219. As stated previously, this power loss

[13] The exhaust steam pipe from the turbodynamo was not insulated and there was a steam connection to the hydraulic pump. It appears likely that there was a pipe rupture when seawater made contact with these pipes and there was a report that two badly scalded men exited the escape trunk in this space.

[14] The British numbering system for the eight secondary 5.25-inch guns were Turrets S1 through S4 for the starboard side and P1 through P4 for the port side, starting with the forward most mounts.

affected the operation of the 5.25-inch dual-purpose secondary armament as well as the Pom-Pom machine guns and the radars, so *Prince of Wales* was left with little anti-aircraft protection. (The three 14-inch main battery turrets were never used during any of these attacks.) Officers and men alike were no doubt stunned; it had taken just one torpedo and less than half an hour to turn the pride of the British navy into an unresponsive, indefensible wreck of a ship – a turn of events few would have ever thought remotely possible.

During late May and early June of 1966, the Far East Clearance Diving Team of the Royal Navy, joined by Clearance Divers from HMS *Sheraton* and the Royal Australian Navy's *C.D.T. 1*, carried out a "practice" survey over a period of 11 days in three specific locations on the wreck. One of their investigations took place in the vicinity of the outer port propeller. However, because of strict operational depth limitations for the navy divers of 180 feet (55 meters) [*who at the time were only breathing air, as opposed to mixed gas*[15]*, and being surface supplied, as opposed to using open or closed circuit SCUBA*], their survey was somewhat limited in coverage. That survey nevertheless revealed that the propeller for the outer port shaft was missing and the bare shaft had pulled away from the ship, snapping the strut arms in the process. It should be noted, however, that this navy diving team and, it seems, all other divers in the interim including the Expedition 'Job 74' diving team at first, believed the propeller had snapped off at the strut and the shafting that was left visible was actually part of the outboard shafting aft of the stern tube. It was John Roberts' observation - which confirmed that the flange on the end of this length of shaft was from *inside* the ship, i.e. inside the shaft tunnel - that had prompted co-author Denlay to initiate a closer inspection of the shaft by his colleagues in 2008. The 2008 shaft tunnel exploration found that the port shafting was separated at numerous shaft flanges and the transverse bulkheads along the shaft alley had large elongations where the shaft passed through. Subsequent dives in September 2009 then provided dramatic photographic evidence of the entire shafting and (the remains of) all bulkhead glands up to the Thrust Block/Engine Room bulkhead.

[15] 'Mixed gas' is a term used for Helium based breathing mixtures generally used for commercial (and often military) diving, but its use is much more operationally complex than 'air' diving. However, its use greatly reduces (or eliminates) the effects of nitrogen narcosis and helps alleviate the likelihood of oxygen toxicity, both dangerous and often fatal occurrences inherent with deep air diving. Today, more and more experienced 'recreational' deep divers now use mixed gas when diving below 40 meters as, *if correctly trained in its use*, the benefits are highly significant and outweigh the complexity. *Expedition 'Job 74' divers all used mixed gas for their dives.*

The Second Torpedo Attack

After *Prince of Wales* had hoisted the "Out of Control" Signal at 1210, Captain William Tennant aboard *Repulse* decided to close *Prince of Wales*. At 1219, with *Repulse* only some 825 meters from *Prince of Wales* in an attempt to render assistance to the flagship, twenty-six planes massed for a torpedo attack on the two ships. Seven of these aircraft approached the crippled battleship from the starboard bow; however, three of these veered off to attack *Repulse* instead. This attack on the two British capital ships left *Repulse* dead in the water listing to port. She sank very soon after at 1232.

Prince of Wales, unable to maneuver, was a helpless target that was hit in quick succession by three torpedoes along her starboard side[16]. These torpedoes were armed with a larger warhead − 205-kilograms − than the first one that hit to port. One torpedo struck the hull right at the bow, almost directly beneath the forward of the two starboard anchors, tearing a jagged hole approximately seven meters in diameter right through the ship as it 'blew out' to port, leaving about two meters or less of split plating between the hole and the bow, with a fracture through the stem post itself. This caused the immediate flooding of the two peak tanks and possibly the gasoline (petrol) tanks behind them. The forward end of the aviation gasoline tank just aft of the peak tanks may have sustained damage, but there was no explosion or fire.

The torpedo that struck in the vicinity of Frame 109 to starboard caused relatively heavy damage, as a huge plume of oil and water shot up alongside "B" Main Battery Turret[17]. The Side Protection System inner voids had been earlier flooded in this area to correct the port list resulting from the first torpedo attack, and Captain John Leach had reluctantly decided to flood the outer voids there as well when the first phase of counterflooding had proven to be ineffective. He knew that the flooding of the outer *and* inner voids would reduce the effectiveness of the torpedo defense system in that area of the ship, but it was essential to reduce the trim and list to try to permit the antiaircraft battery to function. Washrooms on the Lower Deck and living spaces on the Middle Deck were flooded by a mixture of salt water and oil. Breaker Room 1 was

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[16] A review of survivor testimony reveals that some sailors did report a fourth torpedo hit, while Japanese aviators claimed five. This paper will confirm beyond doubt (referencing Expedition 'Job'74' survey data) that there were *only* three actual hits during this devastating attack. However, there is some circumstantial evidence that there may have been one 'non contact' torpedo explosion close to the hull in the area of the mainmast that was, presumably, set off as a 'sympathetic detonation' by the shock wave from one of the actual hits.

[17] Lt. Geoffrey Brooke (RN) was in the Air Defense Station and watched this and the other torpedoes approach *Prince of Wales* from the starboard side. He has maintained in his book "*Alarm Starboard*' that the hit near "B" turret was the last to hit. However, other survivors and some authors have claimed a different sequence for the hits.

flooded with oil through a hatch that was opened so its crew could escape. Water in the voids of the torpedo defense system had prevented it from functioning as designed; hence, much of the energy from the torpedo's explosion was vented into the ship. This may have been the cause of the collapse and breakage of gear in the cordite and shell-handling rooms of "B" Turret and the 14-inch Transmitting Station. The middle deck had an irregular hole some 1.25 meters in diameter at Frame 109 under a washroom. This is believed to have been caused by a degaussing generator being hurled through that deck by the effects of the detonation.

The most devastating hit from the torpedo attack on the starboard side occurred abaft of "Y" Turret, leaving a hole approximately eleven meters long and four meters high in the hull (Figure 5) and immediately jamming the starboard outer shaft. The result was that the turbines in "A" Engine Room driving this outer shaft came to a complete and abrupt halt. Only the inner starboard shaft was now in operation. In 1966 and again in 2007, divers examining the wreckage found the outer shaft (44.5cm dia.) was bent inboard to the extent that its propeller was wedged over the inner shaft. The fact that the outer shaft was bent inboard and the propeller is wedged over the inner shaft and between the keel plate meant that the outboard shaft strut failed, and on inspection in May 2007 the outer strut arm of the outer strut was seen to have snapped in half.

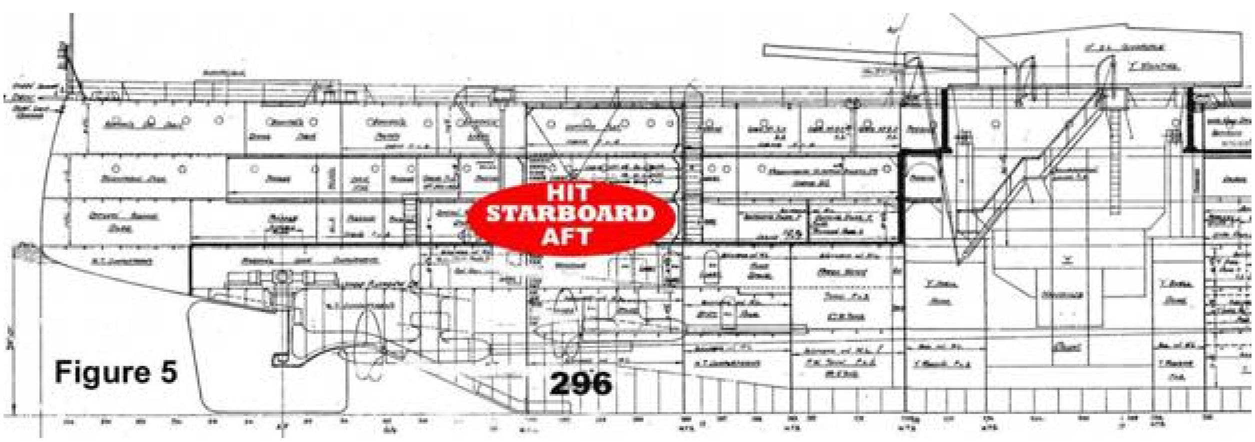

Figure 5 – Location of Torpedo Hit on Starboard Side Aft

Prior to these three hits to starboard it was thought by some that there was at least a chance the ship could be saved; however we now know from examining the photos of the extensive damage seen right throughout the port outer shaft tunnel (Challen 2009), that this was almost certainly not the case. As can be deduced by how high 'up' the starboard hull-side (Figures 5, 5a and 10) the after-most torpedo impacted *Prince of Wales,* her stern had to have already settled perilously low for this torpedo to have struck as high (on the hull) as it did. This was the result (of the flooding) from the single torpedo hit well aft on the port side that had resulted in a “mobility kill”; it not only wrecked the effectiveness of *Prince of Wales* as a combatant, it had also effectively sealed her doom through progressive flooding.

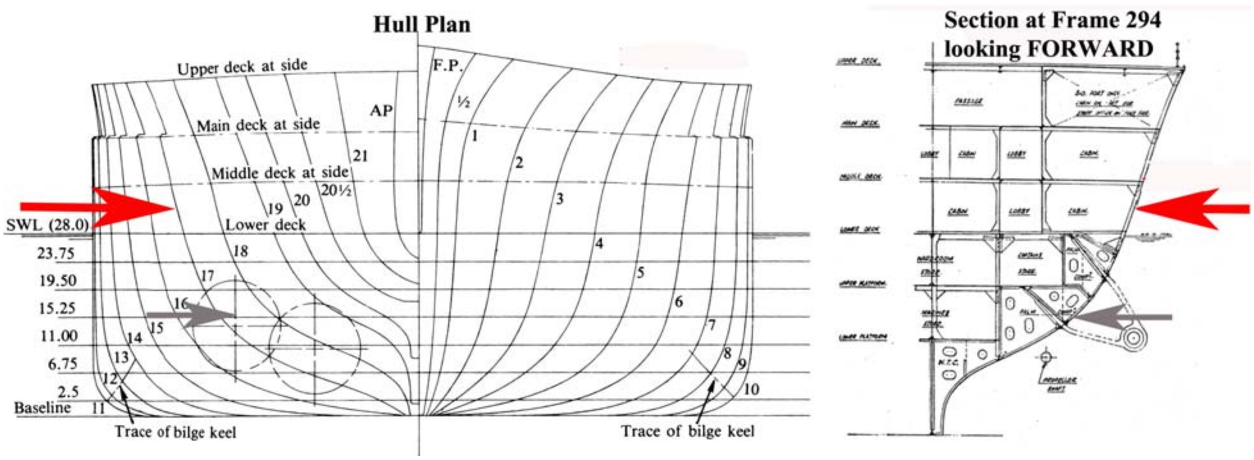

Figure 5a – Height of the Torpedo Hit on Starboard Side Aft

The RED arrows above points to the approximate location of the STARBOARD aft torpedo hit. For comparison the smaller GREY arrows points to where the first torpedo hit on the PORT side aft. Note how much higher on the hull the starboard torpedo impacted, which gives an indication of just how far the stern had settled in the thirty five minute interim between the port and starboard aft hits.

The three torpedo hits on the starboard side nevertheless seriously added to *Prince of Wales* woes, especially the after-most hit, as it negated all the damage-control efforts to complete a flooding boundary in the stern. The flooding they caused did, however, help reduce the list to port from nine degrees (as it was before the three starboard hits) to three degrees. The draft of the ship now increased significantly though, leading to further uncontrollable progressive flooding. With the both outer shafts damaged and the port inner shaft not operational, the ship’s speed was cut to 8 knots. (See Figure 6 for the status of shafting as surveyed in 2007, 2008 and 2009.)

Some reports claimed another torpedo exploded just forward of “Y” turret in the area abreast of the mainmast, but the 2007 survey found it did not hit or penetrate the hull, although voids between Frames 228-234 were flooded as well as a stoker’s washroom on the lower deck. Definite evidence of flooding in the shaft alley or spaces bounding this area that were immediately inboard of the torpedo (or holding) bulkhead of the torpedo defense system could not be firmly established by survivor testimony, since many of these areas had been evacuated shortly after the first torpedo attack. It is known, however, that “X” Action Machinery Room and the Diesel Dynamo Room aft of “A” Engine Room as well as the Breaker Room 13 above remained watertight. Some flooding did occur in Breaker Room 15. However, although Expedition 'Job 74' diving team's video survey footage from May 2007 conclusively shows there is no evidence whatsoever of a fourth torpedo hit producing a hole in the hull in that area, there is ample evidence of longitudinally split hull plate seams throughout that area and beyond.

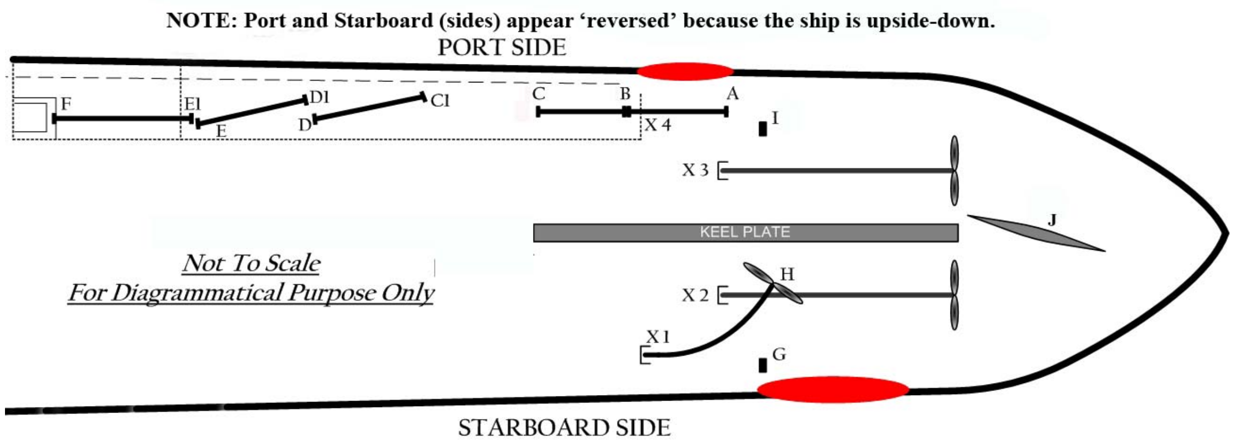

Figure 6 – Illustration of Propeller Shafts inc. Interior of Port Outer Shaft Tunnel

The illustration shows the after part of the upside down HMS *Prince of Wales* as surveyed by divers in 2007, 2008 and 2009. Label F is the dislocated flange at the Thrust Block. E1 is the flange at the opposite end of that length of shafting which protrudes about half a meter through the elongated gland of the partially intact aft bulkhead of the Diesel Dynamo Room. (F, E1/E, D1/D, C1/C and A are all flanges that have separated, while B is the only flange still intact.) The line shafting E-D1 (and the forward third of the shafting D-C1) are the sections of shafting found in "Y" Action Machinery Room. The position where the intact flange marked B is now is where the stern tube would have been. (Although the hull in this area is now heavily damaged, X4 is the approximate point where the shafting would have originally exited the hull). X1, X2 and X3 are where the three remaining shafts exit the hull. Labels I and G are the short stubs that remain of, respectively, the inner and outer Strut (A-Bracket) arms for the outer propeller shafts. Label H is the current position of the starboard outer propeller and shaft. Label J is the current position of the rudder, the leading edge pointing off-center at an angle of approximately 20 degrees towards the port hull; which indicates a turn to starboard. The ship however was turning to port when hit, so how or when the rudder angle was altered is currently unknown. The red ellipses show the actual positional relationship of the torpedo holes to the shaft and propeller locations and the size of the holes relative to one another.

The 2007 survey also discovered that there was significant longitudinal indentation of the hull plating for 65 meters along the hull on the starboard side of the ship and for 70 meters along the port side hull as well. (Figure 7) This leads to the conclusion that non-contact explosions, either from 'near-miss' bombs or torpedoes, caused considerable indentation on both sides of the ship and flooding of the outer voids through failed riveted seams; as these indentations could not result from the 'implosion phenomenon' as most of these areas were already flooded prior to sinking. Some of the indentations closely resemble the damage that *Prince of Wales* sustained from a near miss 250-kilogram bomb that exploded ten feet (three meters) from the ship's port side aft during a German air raid in August 1940 when the battleship was afloat at the fitting out dock at the Cammell Laird Shipyard. Examinations of the wrecks of USS *Yorktown* and RMS *Titanic* have also shown the propensity of rivet failure in an impact or explosion environment.

The Final Bomb Attack

A final aerial attack was made on *Prince of Wales* by eight 'Nell' bombers at 1244. The tight formation made its approach from the port bow, and the planes dropped seven 500-kilogram bombs − one bomber was unable to release its projectile − from a height of 2,560 meters. Five of these planes were damaged by shells from three of the four forward 5.25-inch gun turrets still able to operate (S1, S2 and P2). One of these seven bombs hit the Upper Deck on the port side of *Prince of Wales* and penetrated near or through the catapult mechanism amidships, exploding below on the armor of the Main Deck in a space called the Cinema Flat. Fragments riddled the ship's sides and air intakes, causing additional flooding in the amidships portion of the ship. Side scuttles[18] were distorted and when water flowed into the Main Deck, it created a large free surface effect which further reduced the stability of the ship[19]. The deck above where the bomb exploded (i.e. the Upper Deck) was blown upwards and the port aircraft crane's foundation was wrecked. The explosion also caused some piping, cabling, and ventilation trunks to fall down; a fire broke out in an office on the Main Deck; and there were heavy casualties among some 200 to 300 men being treated in an emergency first aid station that had been set up in the Cinema Flat. LT Wildish[20], suffering from acute heat exhaustion, was in this area and was among those who were injured. He suffered a temporary loss of hearing, multiple burns, and bleeding caused by a bomb fragment wound in his right thigh.

According to a number of survivors, bomb fragments also riddled the uptakes and intakes of "X" Boiler Room, forcing its shut down. Some of the fumes from the bomb's explosion and its flash caused casualties amongst the Boiler Room's personnel and everyone in "X" Boiler Room was evacuated. This explosion also caused the steam flow to "X" Engine Room to be lost temporarily until an alternate feed of steam from "A" Boiler Room was cross connected. *Prince of Wales* eventually drifted to a stop with no motive power and no steering capability. The end was now very near.

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[18] The word 'scuttles' in British terminology refers to portholes.

[19] The presence of entrained water throughout the ship and the side protection system before she finally sank negated the possibility of implosion in this vessel.

[20] LT Wildish was among a team of officers who tried to keep "X" Engine Room operational.

Gunners Mate Alan McIvor of *Prince of Wales* (P3 5.25" turret) has never forgotten this bomb attack. He recalled: "*I was standing at the open entrance to our turret; suddenly there were three tremendous explosions, the force of which threw me back inside. I soon realised I'd been very lucky, for the shock of these detonations lifted our gun turret off its trunion*[21]*, and I'm certain if I hadn't been sheltered from the main blast, I wouldn't be here today."* The other six bombs exploded close to *Prince of Wales* and caused both splinter and water-hammer damage, resulting in indentations in the hull plating that can be seen on both sides of the wreck today, which in turn led to additional flooding due to popped rivets and failed seams in riveted joints. (Figures 7, 9, 10.)

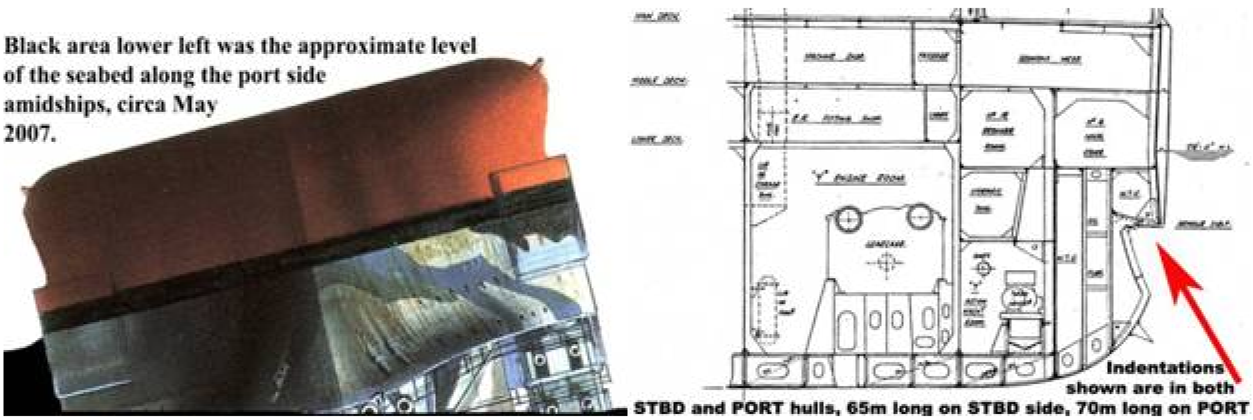


Figure 7 – Prince of Wales at Rest on the Seabed

Prince of Wales rests upside-down at a depth of 68-meters and is tilted over on an angle of between 15 and 20 degrees to her port side, with the starboard deck edge about 5.5-meters up off the seabed at its highest point amidships. The Expedition 'Job 74' diving team found a 65-meter long concave indentation on the starboard hull and a 70-meter long concave indentation on the port hull just below the side armour belt during their survey of the hull in May 2007 (see also Figures 9 and 10). As shown in the above diagrams the indentations are very concave just below the armour belt, the concavity gradually decreasing down from the armor belt to a point just above the bilge keel. There is also a distinct 'knuckling' of the hull in several places along both port and starboard indentation areas, and very noticeable longitudinal splitting of seams along almost their entire length. (The original survey reports of said hull damage can be accessed in their entirety via the web links listed on page 79 of this paper.)

By 1250, the situation aboard *Prince of Wales* was grim, as she had taken aboard some 18,000 tons of water and the near-miss bombs permitted additional, catastrophic flooding through failed rivets and parted seams that significantly reduced her stability and hastened the by-now inevitable sinking of the battleship.

[21] This fact will be seen as significant later in the paper in relation to the identification of a 'working chamber' from beneath a 5.25" mount that is upside down out on the seabed (near what is believed to be the port aircraft crane). However, McIvor's terminology here may however be somewhat incorrect. The gun cradle has trunions and the turret rests on a roller path - either he meant the gun came off its trunion or the turret off its rollers.

A radio message had been sent to Singapore earlier requesting tug assistance; however, it was now too late. Her quarterdeck began to sink below the water surface as the battleship slowly started to settle by the stern. The destroyer *Express* came alongside shortly after the bombing attack and began to evacuate non-essential and injured personnel. At 1300, the bridge ordered "X" Engine Room personnel to secure the turbines. Then at 1324, the battleship suddenly lurched to port and capsized so rapidly that its bilge keel almost overturned the destroyer *Express*. The upside down hull then remained afloat for a few short minutes before her bow slowly rose into the air and she disappeared underwater by the stern. It had taken just 100 minutes for Japanese aviators - the disciples of the 'Master of Sempill'- to capsize and sink one of Great Britain's newest battleships. As LCDR Cain of the escorting destroyer HMS *Electra* said in reflection to the mission of Force Z, *"It was a bold scheme………if it had come off as planned it might have changed the course of history; that it did not come off is one of the saddest tragedies of our time".* As it transpired, this dramatic event was a turning point in the history of the battleship. Modern aircraft had definitively demonstrated that the battleship, like any other warship, was liable to destruction by air attack unless properly defended.

This image is a composite by the author of two photos taken from the destroyer *Express* that came alongside the starboard side to evacuate personnel off *Prince of Wales.* When the battleship capsized, her starboard bilge keel came up underneath the destroyer, causing *Express* to take a very large roll to starboard. Note the high elevation of S1 and S2's 5.25-inch guns (far right) that had fired at the Japanese bombers during the attack at 1244. (Interestingly, the barrels of S2 were found to have snapped off on impact with the sea bed after the ship capsized (see photo page 27), while the barrels of S3 (far left) were not visible during Expedition 'Job 74, having either snapped off and/or were buried under the seabed.)

Survey Dives on HMS Prince of Wales

Over the intervening years there have been several ‘survey’ dives made on the wreck of *Prince of Wales* by British and Australian teams**.** Initially, the Japanese had wanted to retrieve some of the radar equipment from the wreck of *Prince of Wales* and although they located the wreck in early 1942, it appears that owing to operational constraints they made no dives on the wreck. The Royal Navy sent a diving team in May 1966 to survey the wreck and the torpedo damage, as *Prince of Wales* had embodied the latest British technology in underwater defense systems against torpedoes when the *King George V* class was designed in the mid 1930’s. This paper, however, will concentrate on the dives made by Kevin Denlay and his colleagues on the wreck in May 2007, June 2008, and September 2009 where much new forensic evidence on the damage to the ship was discovered.

During Expedition ‘Job 74’ in May 2007 a total of 47 dives were made on the wreck using Closed Circuit Rebreather (CCR) SCUBA systems and a mixed gas diluent termed TRIMIX, which is a combination of Oxygen, Helium, and Nitrogen. Bottom times on the wreck were up to 50 minutes, with total dive times in excess of three hours. In general, two dives per day per diver were conducted. Shallow decompression was performed on ‘trapeze-like’ bars[22] slung under the dive vessel using surface-supplied Oxygen or utilizing the diver’s own CCR.

During the expedition, Denlay used an underwater propulsion device, commonly referred to as a ‘scooter’, to explore and video the full length of the port and starboard hull sides. When points of interest were located, free swimming divers then investigated and photographed these areas in detail, using standard definition video and, on one occasion, digital stills. (Disappointingly, the high definition video system that was intended for the survey was dropped and *lost* by a diver while swimming on the surface *at the beginning of the first dive on the first day!*)

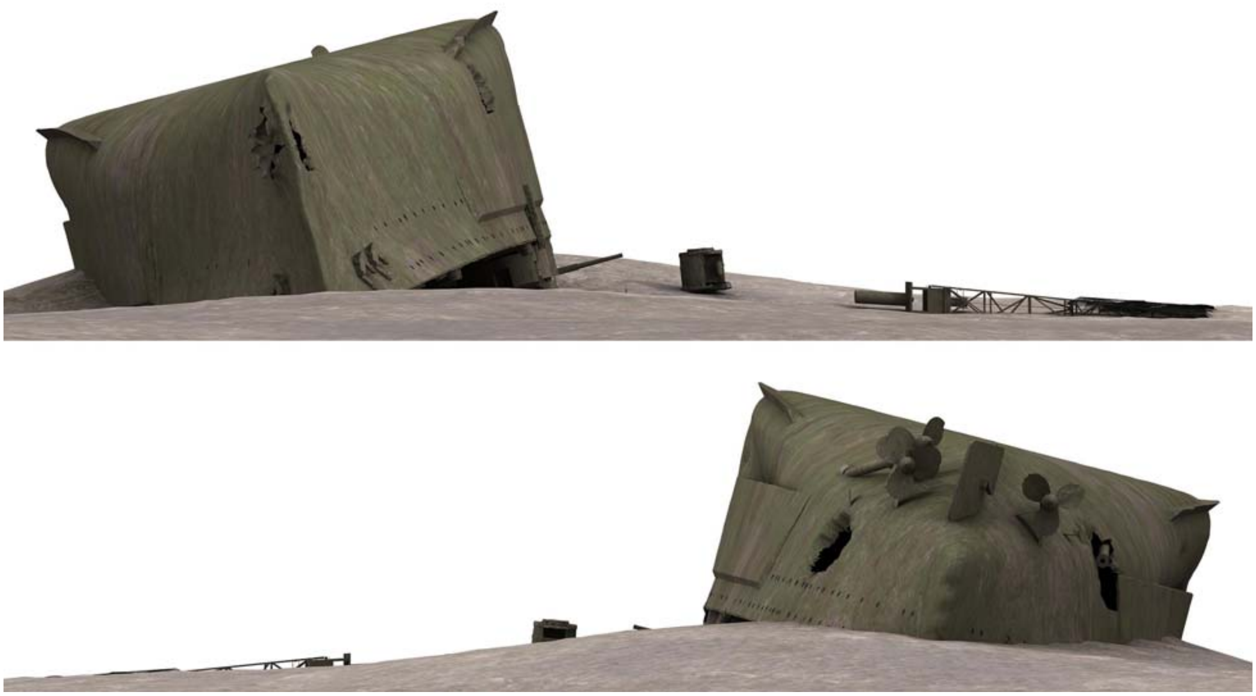
Then in June 2008 a second brief visit was made to the wreck and a single dive was made by two experienced wreck divers who, at the request of Kevin Denlay, were to survey the protruding length of shafting that could be seen outside the port hull aft. Upon measuring this outer length, one of the divers found he could continue the survey by making his way through the

[22] Commonly referred to as a ‘decompression station’ this device is a set of three 4-meter long tubular ‘bars’ slung trapeze-like under the support vessel, at 9-meters, 6-meters and 3 meters respectfully. Divers returning from the depths can then ‘spread out and relax’ during the longest part of their decompression schedule, as opposed to being all bunched up on the down line or, worse, the anchor chain. 100% Oxygen is supplied via a low pressure hose from a large cylinder on the dive vessel to a series of individual breathing regulators at the 6-meter bar.

damaged − and restricted − stern tube receptacle; and soon found himself inside the shaft alley itself. A third visit was made to the wreck in September 2009 and this time photographs with strobe (flash) lighting were taken inside the shaft tunnel showing in detail the significant bulkhead damage and separated flanges. These photographs reveal the true nature of the damage sustained in the first torpedo attack and will be discussed in detail later in Appendix C.[23]

The Wreck

Prince of Wales rests at an average depth to the seabed of 68 meters on soft sand in the South China Sea. She is almost completely inverted with her port side imbedded in the seabed at an angle of about 15 to 20 degrees from the horizontal[24].



Above. Two views of what the wreck site looks like if viewed from ahead (**top**) and astern (**bottom**).

The port hull deck edge remains buried from the very stern to almost outboard of "A" Turret forward, which appears to be 'holding' the bow forward of there up off the seabed by a couple of meters. The starboard hull rises off the sand, in varying degrees, from just abaft the face of "Y"

[23] It is important to note that the 2008 dive was *not* a preplanned excursion / penetration inside the ship. The sanctity of the wreck - a designated War Grave - had been respected during Expedition 'Job 74' (2007) and this diver (in 2008) had only been tasked with surveying the shafting protruding from the damaged stern tube receptacle. His decision to continue surveying the shafting on up the shaft alley was a spur of the moment decision that, as it transpired, yielded extraordinary results. His photographic excursion dive in 2009 was also at his own initiative.

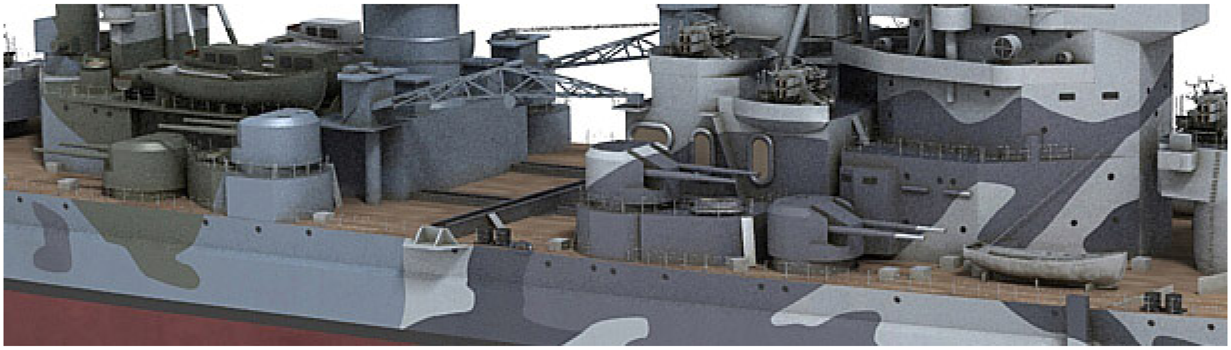
[24] The fact that *Prince of Wales* is inverted on the seabed is attributed to the shallow depth of her descent to the seabed. In much deeper water she may have righted herself once filled completely with water.

Turret aft all the way forward past the bow stem. The roof of secondary turret S4 (5.25-inch guns) is level with the sea floor with its guns pointed to starboard at a minimum elevation. Turret S3 is partially buried in the sand with its casemate and part of the mounting exposed but with no guns visible; presumably they are buried under the seabed. This turret essentially points astern.

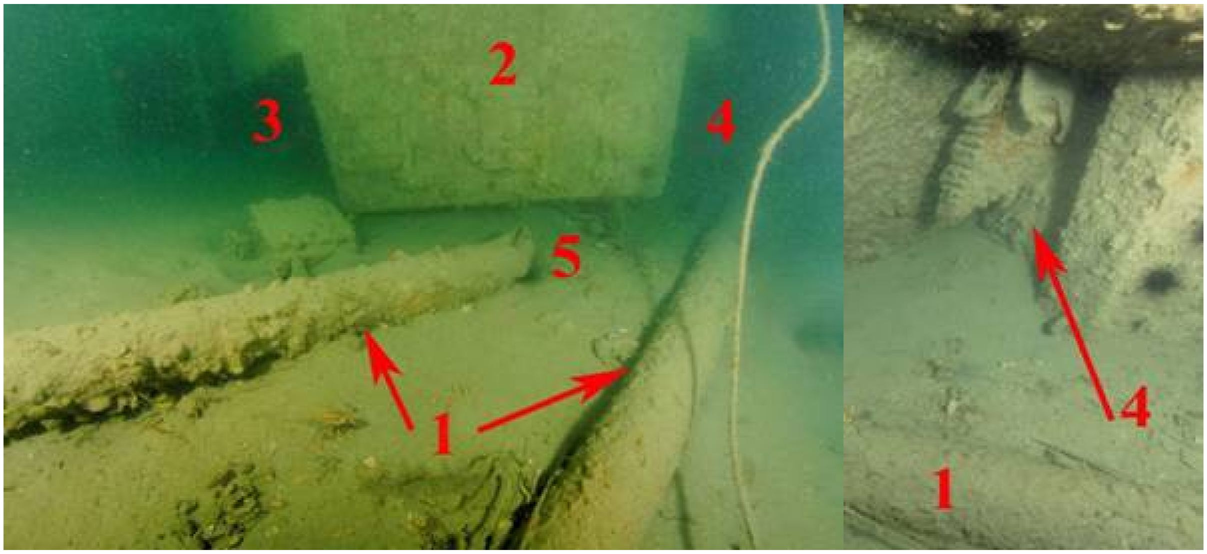
Left. The remains of a Carley float on the seabed near S2 turret. **Right**. A section of the *starboard* aircraft / boat crane lays on the seabed next to the wreck abreast the catapult deck.

The catapult area is 'open' approximately halfway across towards the port side (about a meter or more past the starboard turntable) to where sand has built up over time preventing further exploration in that direction. Several Carley floats (life rafts) can be seen on the seabed beneath the starboard deck near S2 turret, and a small section of a crane lies just outboard from the edge of the wreck in this area also.

Turret S2 is partially buried in the sand with its casemate and most of the mounting exposed. However, when the ship struck the seabed, the guns broke away from the mounting and now lay beside it on the seabed**.** This turret is trained forward, pointing off the starboard bow. Turret S1 is well clear of the sand with its guns intact and is also pointed off the starboard bow.



The four starboard 5.25" guns that can be seen on the wreck, right to left, S1, S2, S3, S4.



Left. The guns of S2 turret (2) have been torn out of their mounting apertures (3 & 4), caused no doubt as the guns, near maximum elevation (see image page 24), struck the seabed with the weight of the ship settling on top of them. Both gun tubes (1) lay on the seabed with torn jagged ends (5) where they ripped from the mounting. **Right**. A close up of the turret aperture (4) where one of the barrels (1) tore out from.

The forward superstructure is, surprisingly, completely buried under the seabed to the level of the Shelter Deck (USN 01 Level) and there is some evidence of buckling in the superstructure plating at this point. “B” Turret itself is almost completely buried, although its underside (nearest the superstructure) and barbette are fully exposed. The (starboard) side armor has separated from the base plate of the turret, possibly from the weight of the ship bearing down on it, allowing the gun chambers to be seen through the split. “A” Turret and its starboard rangefinder are visible as are three of the four 14-inch guns. The starboard gun is fully exposed with the other two guns progressively covered with sand. The fourth or port gun, at the time Expedition **‘**Job 74’ was conducted, was completely covered by sand. Forward of ”A” Turret the deck is less than two meters clear of the sea floor, with the last 20 meters or so having sagged slightly more (from, it seems, the now unsupported weight of the large anchors at - and chain within - the bow itself).

There is a substantial debris field off the starboard side of the ship aft that is believed not to have been previously noted or explored in any detail. This debris field was explored out from the level of “Y” Turret to approximately 60 meters from the starboard side of the wreck. A major segment of what we believe is the port aircraft / boat crane lies in this field, pointing directly out to starboard and heavily encased in fish trawler netting. The tubular ‘strut’ on which the crane base rotated (Figure 8) is visible sitting up off the seabed and is only about 10 meters or so from the starboard hull. It is known that one 500-kilogram bomb hit near the port crane and exploded below the deck in way of the catapult – in an area called the Cinema Flat – causing a bulging in the deck structure above and weakening the crane foundation**.**

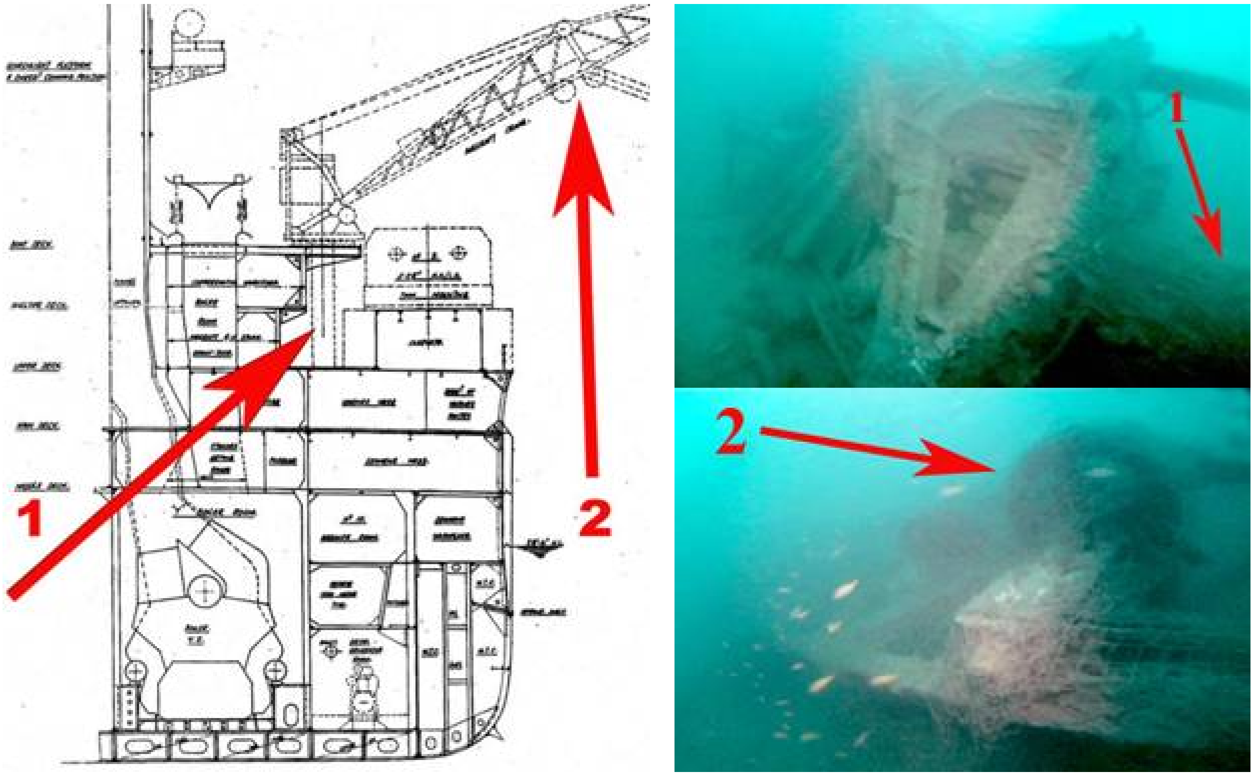
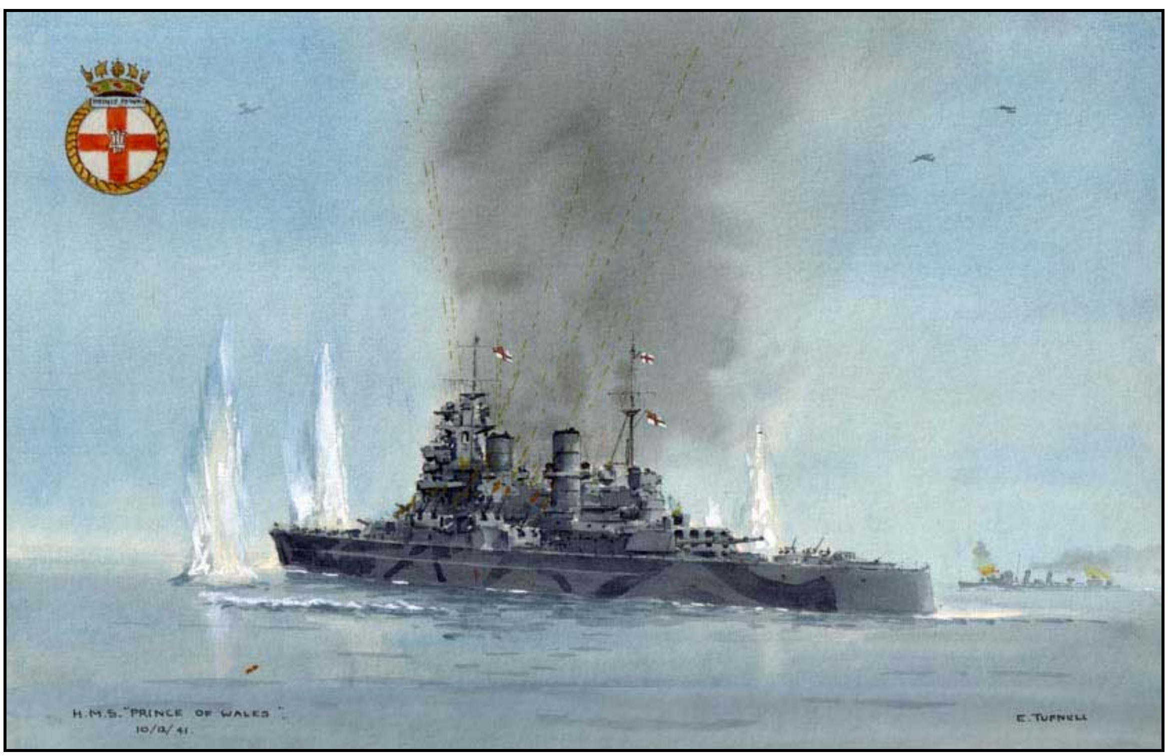


Figure 8 – Bomb Damage to the Port Aircraft/Boat Crane

One of the seven 500-kilogram bombs released by the Japanese bombers struck on the catapult deck in the vicinity of the port aircraft / boat crane. What is believed to be the remains of this crane lays off the starboard side of the wreck with the tubular base support (1) and pulley wheels (2) clearly visible. Arrows 1 and 2 in the images at the right (which are from video taken at the wreck site) correspond to the same 'items' that Arrows 1 and 2 point to in the schematic.

Between the starboard hull and the displaced cranes' location on the seabed is what appears to be one of the port 5.25-inch turrets inverted in the sand (most likely P3) with its rotating ring and working chamber clearly exposed; although the gun chamber itself is completely buried under the sea floor. The only explanation for this structure being there on the seabed is that it must have 'fallen out' from its deck location when the ship capsized. We now know that the foundation for this turret was damaged by the 500-kilogram bomb hit, which in turn allowed it - and the adjacent crane - to fall off during the capsizing process. (Note the statement of P3 Gunners Mate McIvor - page 33 - that the force of the nearby bomb explosion **"***lifted our gun turret off its trunion"* (or more precisely "off its roller ring**"**.)

Left. Twin barreled 5.25-inch dual-purpose turrets under construction at the Vickers Armstrong facility. Note the incomplete turret's rotating roller ring in the background left (1) and the working chamber beneath the turret on right (2). For scale comparison note the man standing to the left of arrow 2. **Top right**. The inverted 'working chamber' on the seabed as seen if approached from astern. **Bottom right.** A close-up of the chamber, but as seen when approached from forward; note the 'roller ring' at bottom left.



HMS *Prince of Wales* under attack, painted by naval artist Eric Tufnell. (*Authors collection.*)

Torpedo and Bomb Damage Details

PORT SIDE TORPEDO HIT

On the port side aft there is a single torpedo hole approximately 4 meters high and 6 meters long extending aft from just forward of where the outer shaft exited the stern tube gland (this hole is centered at approximately Frame 280, Figure 1):

The initial damage was mainly confined to the outer hull structure, strut, and propeller. However, damage from the torpedo explosion also extended into the ship and forward into the outer stern tube receptacle, and the damage there was particularly devastating. No ascending water column was seen from this hit (apparently because of its location well under the hull).

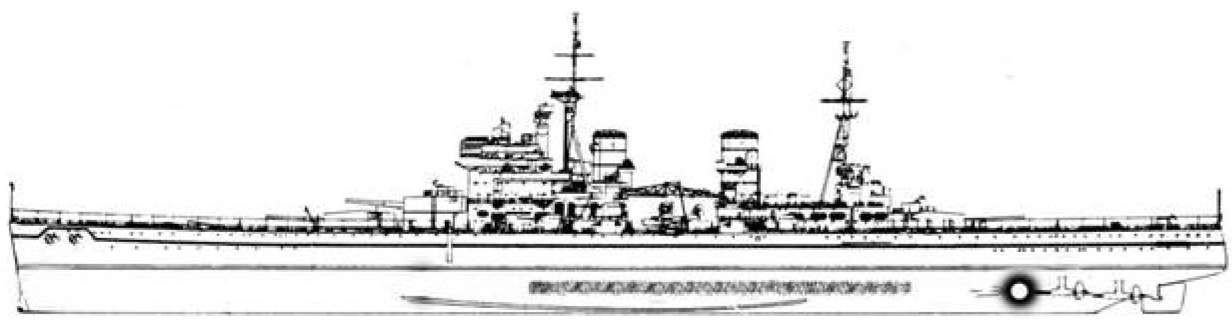
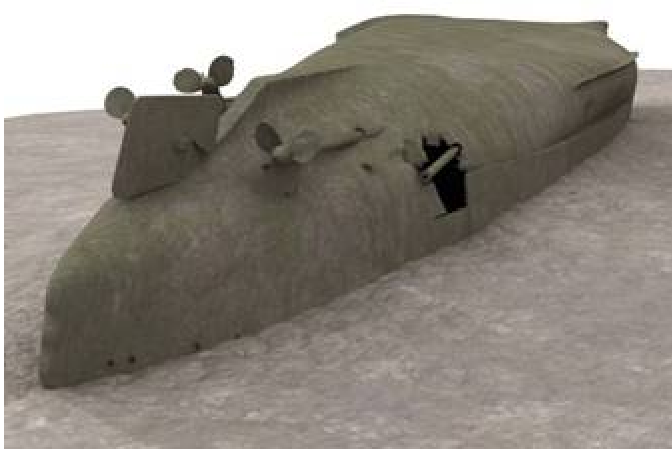


Figure 9 – Location of the Port Side Torpedo Hit

Prince of Wales was doomed by a single torpedo hit well aft, which subsequently wrecked the port outer shaft and caused massive flooding along much of the shaft alley within the ship. Near-miss bomb damage amidships in a latter attack compounded the problem by adding substantial progressive flooding due to failed rivet joints and split longitudinal seams along the base of the armor belt. Significant hull indentation is seen throughout the shaded area abaft the forward superstructure. (See also Figure 7)

a) The blades of the propeller for the port inner shaft are missing large pieces of their edges, indicating that they were struck by debris from the initial torpedo explosion or by either the outer propeller or other debris when it broke away.

b) The port outer shaft has come apart at the flange about 8 meters forward from the opening in the stern tube where the shaft emerges (Flange 'A', Figure 11). The receptacle for the stern tube has been ripped open large enough for a diver to enter forward along the shaft**,** and has a rip – or tear - on the outboard side which extends forward about two meters. The damaged web frames in the stern tube receptacle are now clearly visible, as is the one remaining intact flange (Flange 'B', Figure 11).



c) There is a plate of armor collapsed inwards at the forward edge of the hole. Another plate just aft stands somewhat vertical, and appears precariously balanced. The hull forward and aft of this hole is significantly damaged and distorted for approximately 2 meters in either direction.

d) The September 2009 excursion up the port shaft alley revealed the damage caused by the shaft rotating out of center, which was caused by torpedo damage to the stern tube, propeller shaft, and strut. The holes in transverse bulkheads at Frames 206, 228, 242, and 253 are huge, some 4-6 feet in diameter. Several hatches were discovered opened either from the intense water pressure or left opened by escaping crew. In the latter case, if the hatch had been quickly dogged and not firmly closed, the water pressure would have sprung them open.

STARBOARD SIDE TORPEDO HITS

Due to their locations on the actual side of the ship – as opposed to 'under the ship' as the port aft hit was - these three hits exhibited the typical venting plumes, or water columns, extending high into the air after their detonations.

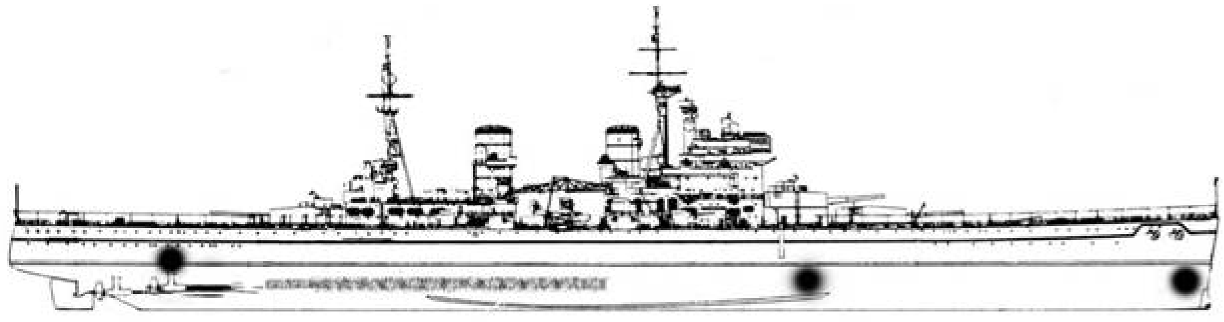


Figure 10 – Location of Three Torpedo Hits on the Starboard Side

There are three well-spaced torpedo hits along the starboard side. Just which one was the last to hit is still a point of contention between authors and historians. The shaded area abaft the fore-funnel is the concave section of the hull as shown in Figure 7**.** Note again how much higher the aft hit is because of the stern having settled following the flooding from the first hit to port aft.

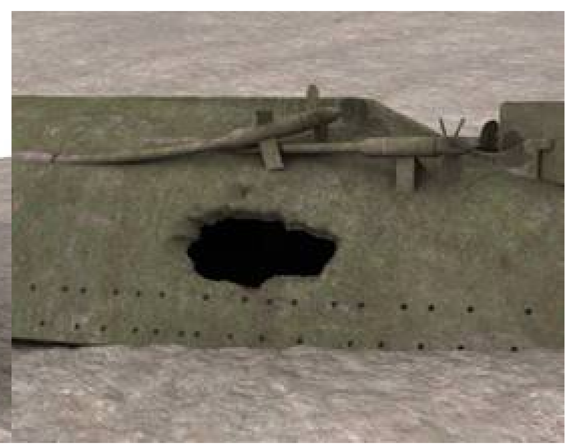
Of the three starboard hits the after-most one was the most serious (*the after-most hole is centered at approximately Frame 296, Figure 5*), the forward two being somewhat superfluous in the cause of her demise.

a) The outer shaft strut is broken and the propeller (still attached to its shaft) and the remains of the strut are wedged over the inner shaft. (When the ship was upright this would actually have been, in reality, wedged 'below' the inner shaft.) The outboard propeller shows considerable damage to its edges as it was still rotating when it was jammed into its present position. The outer shaft struts' *inner* strut arm now points *laterally* down across the inner shaft, while the *outer* (half strut) points upwards. The remaining half of the outer strut arm is still attached to the hull just above the torpedo hole, while the inner strut has snapped off cleanly where it joins the hull.

b) There is a hole approximately 4 meters high and 11 meters long in the area of the hull above the remains of the outer shaft struts outer arm. This indicates that the torpedo struck the ship on the hull above and only just abaft the *outer* strut arm and in comparison to all the other torpedo hits, this damage is located much higher on the hull side. This also indicates just how far the stern had already settled[25] in the forty minutes since the first torpedo hit to port.

c) The torpedo damage extends into the ship, with decks visible inside the hole.

d) There are rips and tears in the surrounding plates and supporting structure that have been pushed in fore and aft of the hole for about two meters in either direction.

[25]According to the testimony of CDR Goudy the stern trim had increased from 5 feet to 8 feet (1.5 to 2.4 meters) at this point in the action, but it seems from the position of the torpedo hole that it was considerably more.

e) The flooding boundary that had been established before this hit occurred was now destroyed. Prior to this hit, the aft end of the quarterdeck had already been precariously close to the waterline and this hit now added even further to the 'down by the stern' trim. As the stricken battleship trimmed down more by the stern, the quarterdeck level settled into the water. The ship's remaining stability and buoyancy were now seriously compromised.

There is another hole outboard of "B" Turret on the starboard side just aft of the forward end of the bilge keel, with one 'edge' of the hole being at the base of the armor belt (*this hole is centered at approximately Frame 109*).

a) The torpedo hole is approximately 4 meters high by 6 meters wide.

b) The hit was made in way of the torpedo defense system and there appears to be no significant breach in the inboard bulkhead of the air/fuel/air sandwich layer.

c) It also appears that the torpedo exploded just below the lower edge of the main side belt which helped to contain it and aided in venting the blast effects.

d) There is a hole in the Middle Deck over the defense system into the Seamen's Mess area, reported to have been caused by a degaussing generator being blown up through the deckhead.

There is a ragged hole approximately 7 meters in diameter through the bow of the ship (*the hole is centered at approximately Frame 8*). The plating is bent outward to port implying a starboard torpedo explosion and the stem post is fractured, indicating just how far forward this torpedo hit. There is often a considerable amount of fouled/discarded trawler netting to be seen around this hole.

Final Bomb Attack Damage Details

The near-miss bombs during the attack at 1244 caused considerable dishing in of the hull plating and opening of riveted seams over a length of about 70 meters along the port hull, from a point halfway between where the outer shaft exits the hull at the stern tube and the aft end of the bilge keel (*approximately Frame 255*), all the way forward to below P1 5.25-inch turret (*approximately Frame 140*). The starboard hull is also dished in a similar manner for about 65 meters, starting where the outer shaft exits the hull at the stern tube (*approximately Frame 282*) to abeam the aft edge of the forward funnel *(approximately Frame 170).*

Left. Starboard side hull indentation (also see Figures 7 and 10). **Right.** Port side hull indentation (also see Figures 7 and 9).

The hull is concave where it should be convex just below the lower edge of the side armor. The indentation is about one and a half to two meters deep at its deepest (i.e. most indented) point. These indentations were probably caused by the explosions of near miss 500-kilogram bombs, adding to the damage caused by the previously-mentioned sympathetic detonations of one or more torpedoes close to the hull and possibly also due to hydrostatic pressure as the ship descended to the sea bed. The difference in mass of the upper hull protected by thick armor and the lower hull of thinner plate made this damage more pronounced, as the shelf-like structural joints between the armor belt[26] and the relatively light lower hull structure was pushed inboard, puncturing the inboard bulkhead for the fuel and ballast tanks. Differential water pressure between the outer voids and the sea outside the hull existed prior to damage, but rivet failures would allow slow flooding of the outer voids in the torpedo defense system as the ship began to settle to the seabed. One would also expect such implosion damage to occur further down the hull toward the bilge. The port lower hull was immersed longer and deeper than the starboard shell. This possibly might explain the differences in the extent and depth of the port and starboard folds. These folds are more pronounced and extend further forward to port since the outer voids were not flooded to control list and trim. Many of the forward starboard voids were flooded and the torpedo hit just abaft "B" turret would provide equalization in pressure. However, there were indentations within the folds, marking points where the near-miss 500-kilogram bombs exploded. In those areas of the hull there were failed rivets or slightly parted seams that would allow flooding of the outer voids of the torpedo defense system. This is further reason for serious examination of riveted hulls to determine sources of potential flooding.


FINAL AND HOME -- STOCKS

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War Extra!

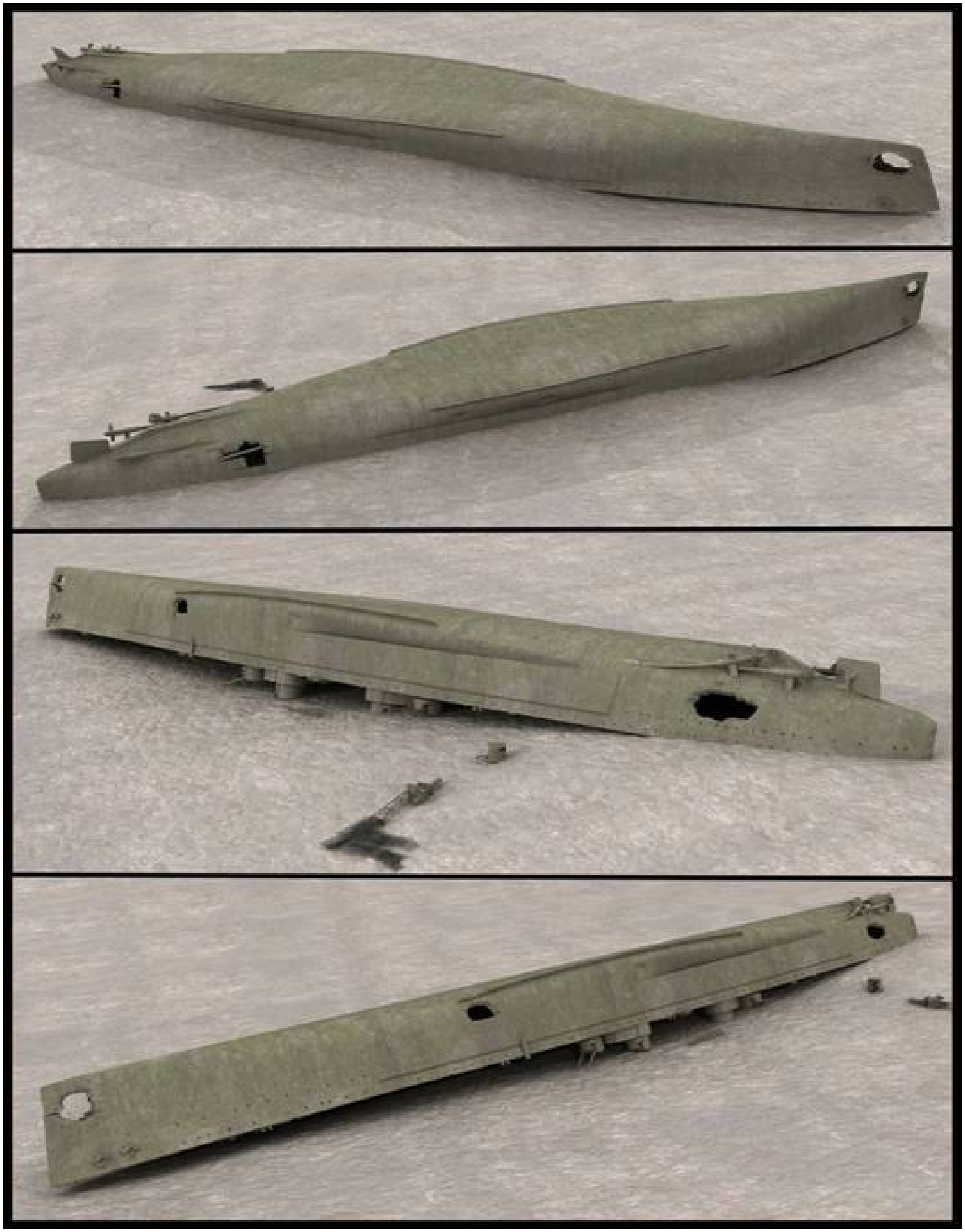
HMS PRINCE OF WALES, CRUISER REPULSE SUNK

Jap Planes Strike British off Malaya

Report U.S.-Jap Fleets Battle off Manila

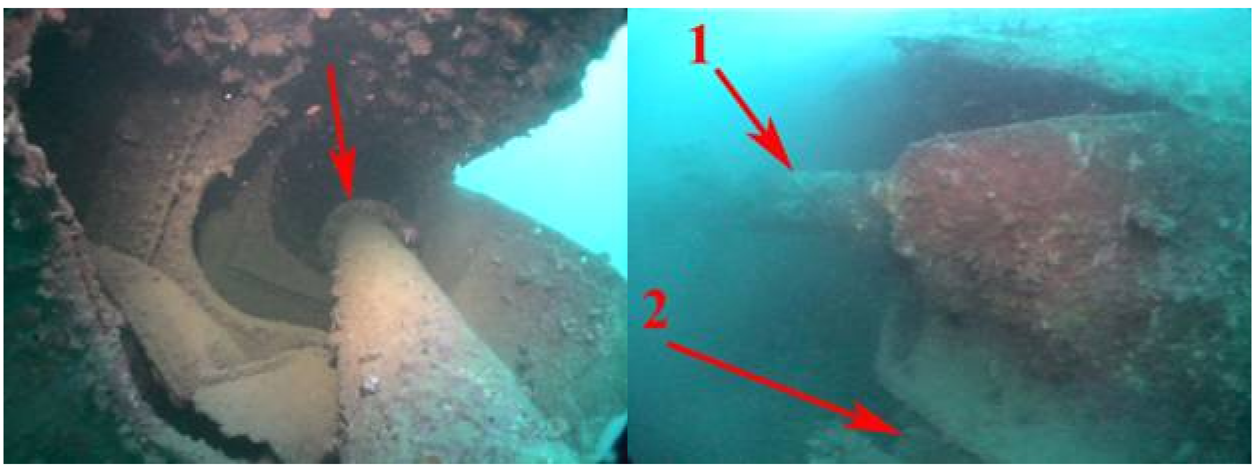
[26] See Figures 7 and 8 for the structural detail that supports the lower end of the armor belt.

The wreck of HMS *Prince of Wales* shown from various angles as seen at the time of the Expedition 'Job 74' survey; May 2007.



The 'Broken' Shaft

In June 2008 Kevin Denlay asked two of his colleagues who were returning to the wreck on a recreational diving trip - Craig Challen and Paul Garske, two very experienced deep wreck divers - to make a closer inspection of the port outer shaft as well as take some measurements there. Unfortunately they only had time for one dive in June 2008 before the dive vessels' itinerary caused them to move on. Nevertheless, Mr. Challen exceeded Denlay's expectation by entering the ripped open shaft tube receptacle; maneuvering around the (deformed) web frames and the next (intact) flange; and then swimming down the length of the shaft tunnel completely unobstructed until, unbeknownst to him at the time, he came to the aft bulkhead of the Diesel Dynamo Room (Frame 206)! Here he found his progress impeded (or, as we shall see in retrospect, he *thought* he did at the time) by what seemed to be an impossibly tight a squeeze (in diver parlance this is what is called a 'restriction') through the deformed shaft gland into the Diesel Dynamo Room, so he 'turned the dive' and exited back out along the shaft tunnel.



Left. Looking forward along the section of shaft that protrudes from the damaged stern tube receptacle. Note the deformed web frames that supported the stern tube and the intact flange (Flange B, lower plan position, Figure 11) that the diver maneuvered around to gain access to the shaft tunnel proper. **Right**. Viewed from 'outside' the shaft can be seen hanging down 'unsupported' (1) and a split along the hull at the base of the armour belt (2), caused by the effects of the torpedo explosion, can also be seen.

The June 2008 shaft survey, the first time anyone has ever entered this shaft alley since *Prince of Wales* sank, had proceeded like this: When Mr. Challen passed the intact flange (Flange B) visible in the stern tube receptacle (see above photo) he discovered that the length of shaft that protrudes from the hull - which is no longer supported, but simply counter-balanced in the stern tube receptacle - was attached to another length of shaft that continues on – also, as it turned out, unsupported save for how it rests in the stern tube receptacle - forward into the shaft tunnel. (During Challen's foray, Mr. Garske remained on the outside near the stern tube receptacle, belaying the survey line.) Challen then continued on along this length of shaft, through the wrecked bulkhead at Frame 270 and over an open hatch in the deckhead, all the while the shaft tunnel getting progressively wider. When he then reached the flange at the end of this (second) length of shaft (Flange C), he was astonished to find no shaft continuing further forward! Undeterred he swam on, passing over several longitudinal holes in the deckhead and on through the reamed out bulkhead at Frame 253 - with still no shaft in sight. Continuing on he then passed though the wrecked bulkhead at Frame 242, observing two more open hatches in the deckhead either side of this bulkhead. Then, soon after passing through that bulkhead at Frame 242, he finally came to the next length of shafting but was again surprised to find that it was not supported in its rightful way. Its end flange (Flange C1) was now above him and jammed firm into the outside edge of what was once the tunnel floor (now the 'ceiling' because the ship is inverted) and the shaft itself stretched away into the distance angling down obliquely towards what was the deckhead (but now the 'floor' of the tunnel as it were). Unfortunately at this point the survey line reached its maximum length, so this was the furthest inward measurement the diver could record in 2008.[27] However this measurement showed that a large gap or 'division' of approximately 14 meters had occurred when Flange C and Flange C1 separated. (This large gap would later prove a key in determining the actual sequence, or order, in which the shaft flanges failed.)

Leaving the survey line at this flange, he continued in along this next length of shaft, which is about 10.8 meters long, and on through the bulkhead at Frame 238 (the aft bulkhead of Y Action Machinery Room) until he came to the flange on its end (Flange D). Here he again found that it had also separated from the next length of shaft further forward, which was also laying on the deckhead unsupported, but the gap between the two at this point was only about one meter when measured diagonally across the deckhead to the next flange (Flange D1). He then continued on along the next length of shaft, which is about 8.7-meters in length, until he

[27] The original intent was only to measure the exterior length of shaft that protruded from the stern tube receptacle, hence the survey line Challen had with him was not very long. (Note: All shaft sections are of different length so this measurement would have conclusively proven which section it was that protruded, as there was still speculation in some circles that it was *not* an interior shaft length protruding; it seems despite John Roberts earlier "out-of-place" exterior flange observation, the old "the shaft couldn't have broken" mantra from 1942 still held sway with some.) It was only when Challen reached the first (intact) flange and saw he could maneuver around it did he make an 'on the spot' decision to carry on surveying up the shaft alley itself; only to then discover and definitively prove the shaft was actually 'broken', or more factually, separated at numerous flanges.

came to the flange on its end (Flange E). Again he found it too was also separated from the next length of shaft but only by the smallest of gaps, actually it almost abuts against the next flange (Flange E1), whose shafting protrudes about half a meter out through a distorted bulkhead gland in what otherwise appears to be the 'relatively' intact bulkhead at Frame 206, the aft bulkhead of the Diesel Dynamo Room. (See Figures 3, 6 and 11) The diver then concluded that although the bulkhead area surrounding this gland was severely distorted, there was not a way forward through it, nor he thought enough room beside the shaft in the elongated gland itself for him to squeeze through.[28]

This bulkhead seemed to effectively then bar any further inward progress along the shaft, so the diver turned back and exited out the same way he came in; again observing that there were several open hatches and longitudinal 'holes' in the tunnel floor (deckhead) along the way. The data that Mr. Challen had obtained from this survey was thought at the time to be the definitive survey of the shafting, as penetration further forward along the shaft seemed well and truly blocked.

Nevertheless, in September 2009, Mr. Challen returned to the wreck and made a second inspection of the port shaft alley, this time using a camera and lighting, and the photographs he obtained now reveal the true nature of the damage caused by the shaft rotating out of center and then flailing apart. (See photos Appendix C) In addition, on this excursion, Mr. Challen found that he *was* able to squeeze through, with a little effort, the elongated shaft gland opening in the bulkhead at the aft end of the Diesel Dynamo Room (Frame 206) that had blocked his way the year before! (See photo of that elongated gland on page 73, second row, right.) Once through that restriction he swam all the way to the forward end of the room (i.e. to the Thrust Block enclosure) and photographed the connection to the thrust bearing housing that is attached to the aft side of the aft transverse bulkhead of "B" Engine Room (Frame 184). To *our* surprise, the line shaft is completely decoupled from the thrust bearing with all the bolts and nuts missing.[29] Given this fact, it would appear then that the single reduction gear, located just forward of that bulkhead, had to sustain some damage also. However, access to that space may be impossible

[28] It should be noted that up to this point the diver had swam with ease through all of the destroyed bulkheads aft of this point (Frames 270, 253, 242 and 238). That is, the damage had been so great to each of these bulheads that they posed no restriction whatsoever to his forward progress.
[29] There are in fact no bolts to be seen remaining in *any* of the separated flanges anywhere along the shaft tunnel!

based on testimony provided by Vice Admiral Wildish. The dogs or handles to the Engine Room access hatch that Wildish exited from were hammered shut and the hatch held down by shoring.

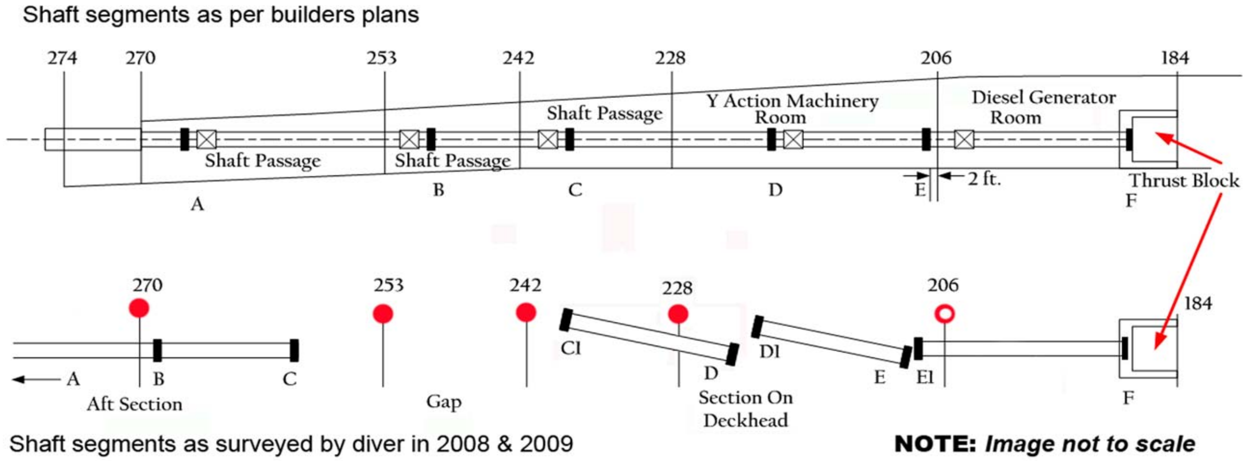


Figure 11 – Illustration Comparing the Port Outboard Propeller Shafting

A comparison of the intact port outer shaft (upper) and the separated sections as surveyed (lower), with bulkhead frames numbered and flanges marked A, B, C, D, E, F. Flange B is the *only* flange that remains intact aft of the Thrust Block itself; the length of shafting missing (approximately 17-meters) aft of Flange A having separated with the propeller when it broke away. The distance across the gap between separated Flange C is approximately 14-meters (C to C1). Solid red dots indicate the destroyed bulkheads along the shaft tunnel, while the outlined red dot (frame 206) indicates a partially destroyed bulkhead.

It is now clear that the shaft failed at the four consecutive flanges aft of the Thrust Block / Engine Room bulkhead; i.e. the forward flange in the Diesel Dynamo Room at the Thrust Block (*Flange F*), the flange in "Y" Action Machinery Room just aft of the bulkhead to the Diesel Dynamo Room (*Flange E, Figure 11, inboard Frame 207*), the flange *towards* the aft bulkhead of the "Y" Action Machinery Room (*Flange D Figure 11, inboard Frame 221*), and the *next* flange aft of "Y" Action Machinery Room (*Flange C, Figure 11, inboard Frame 239)*. [At this point it can be seen that not only has the shaft separated at this flange, but the intact section of shaft (two lengths) further aft has also been pulled aft-wards from this flange – and partly out through the stern tube receptacle - when the separation took place.] The next flange aft of this 'break' remains intact (*Flange B, Figure 11, inboard Frame 251*), but is now situated in the damaged stern tube receptacle (*inboard of Frame 272),* i.e. approximately fourteen meters further aft than it should be located. The 'final' flange on the shaft, that was situated just inside the shaft passage itself also failed (*Flange A, Figure 11, inboard Frame 266*) and when the propeller broke away it took with it the stern tube and the approximately seventeen meters of shafting that extended from this flange (*Flange A*) just forward of the stern tube all the way to the propeller boss itself.

This, then, is the flange now seen on the end of the length of shaft protruding from the damaged stern tube receptacle that was first identified by John Roberts. So, all told, the port outer shaft parted at five separate flanges: one just forward of the stern tube, one two shaft lengths up the shaft tunnel, one at the end of the next length of shaft, one at the end of the next length of shaft where it abuts the Diesel Dynamo Room bulkhead, and one at the Thrust Block housing itself.

Analyses

It certainly now appears that Stoker James was entirely correct when testifying before the Bucknill Inquiry that he saw the port outer shaft come apart in his space (the Y Action Machinery Room). However, when did that occur? When Mr. Challen first examined the shaft tunnel (in 2008) he reported seeing an open hatch which he believes was at the forward end of "Y" Action Machinery Room. Whether this was the result of human failure to close or by virtue of the water pressure forcing it to open is difficult to determine. Vice Admiral Wildish has maintained from his experience as a damage control officer that, unless extra force was applied to engage the dogs to a hatch, water pressure could force them open. This would explain why Breaker Room No. 13 and other adjacent areas flooded so quickly, and given the incredible din from that shaft tearing itself apart, coupled with the inrush of water through open hatches (via flooding up the shaft tunnel), it is no wonder that seamen in that area thought another torpedo had hit abreast or just aft of the mast. It would appear then that sometime around 1149 the shaft in "Y" Action Machinery Room parted. [30]

We also know however - from the destruction of all the bulkheads in the shaft alley, the aft bulkhead of "Y" Action Machinery Room and the severe distortion of the shaft gland in the aft bulkhead (Frame 206) of the Diesel Dynamo Room (Challen, 2008/2009) – that for water to be flooding into "B" Engine Room through the failed gland in its aft bulkhead at the Thrust Block, both "Y" Action Machinery Room *and* the Diesel Dynamo Room *had* to have already been fully flooded *before* LT Wildish could have made his observation.[31] The large openings are

[30] It is now believed that the turbine did not over-speed because the steam supply to "B" Engine Room had been cut off.
[31] Because the shaft passes through "Y" Action Machinery Room and the Diesel Dynamo Room *just under the deckhead*, water *must* be at or above the level of the shaft to flood *on through the ruptured glands* in, sequentially,

testimony to the fact that a great amount of flooding and large hydrostatic loads were experienced in the port shaft alley that could have forced open hatches that exposed spaces above to rapid flooding. We now estimate that LT Wildish made his observation on the shaft rotating out of center at approximately 1154.

The complex sequence of events that followed the torpedo detonation aft in way of the port outer propeller shaft, including numerous photographs of the shaft itself as it now lies, is discussed in Appendix C.

Besides Stoker James in “Y” Action Machinery Room, Engine Rating Artificer J. P. Williams in No. 6 Diesel Dynamo Room also observed the shafting failure process. When the bearing cover for the pedestal bearing in “Y” Action Machinery Room failed the flange bolts sheared and the small line shaft over the generator eventually fell on top of it. At or about the same time, the line shaft connected to the thrust bearing in the housing also failed from combined tensile (from the propeller, strut and shafting) and torsional loads (shaft rotating violently out of center).

With this failure, the shaft was no longer coupled to the reduction gear or turbine. Why didn't the turbine over speed? Either the inertia from the destruction of the structure around the shaft’s passage through transverse bulkheads or shutting off the steam to the turbines prevented that. On the latter, testimony of survivors from “B” Boiler Room confirm that steam was shut off before that space was abandoned. There is no indication when that abandonment would have occurred. The violence of the shafting rotating out of center is crucial in the formation of the large openings in all the bulkheads. The thrust bearing was adversely affected and the rotation out of center created a hole in Bulkhead 184 which we cannot observe due to the thrust bearing housing which is on the aft side of that bulkhead which also forms the aft boundary of "B" Engine Room.

The pictorials of that shaft alley (see Appendix C) help clarify what happened to this propeller shaft. The precise times and sequence of failure will never be known. Unfortunately, we do not know the precise times when Stoker James left “Y” Action Machinery Room or when Williams left the Diesel Dynamo Room. Those time details would improve the estimation of the actual sequence of events.

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the aft bulkhead of the Diesel Dynamo Room and then, *only after that room in turn fully flooded*, the aft bulkhead of “B” Engine Room where the Thrust Block gland was located that, circa 1154, LT Wildish observed having failed.

To reiterate then; the first torpedo hit at 1144 on the port side aft, inflicting a devastating "mobility kill". During the second torpedo attack, circa 1224, another hit near the starboard outer shaft worsened the flooding and accelerated the sinking of the already doomed *Prince of Wales*. The first torpedo hit resulted in an 'Out of Control' signal to be hoisted at 1210, as it had reduced the ability of the ship to maneuver with any degree of control, hence the message to Singapore for tug assistance at 1220. Speed had also been reduced to a maximum of 15 knots. More alarmingly, most of the power supplies to her dual-purpose 5.25 inch guns were inoperative, making her more vulnerable to further air attacks. The second hit aft then rendered the ship an almost stationary target, unable to even maneuver to defend herself.

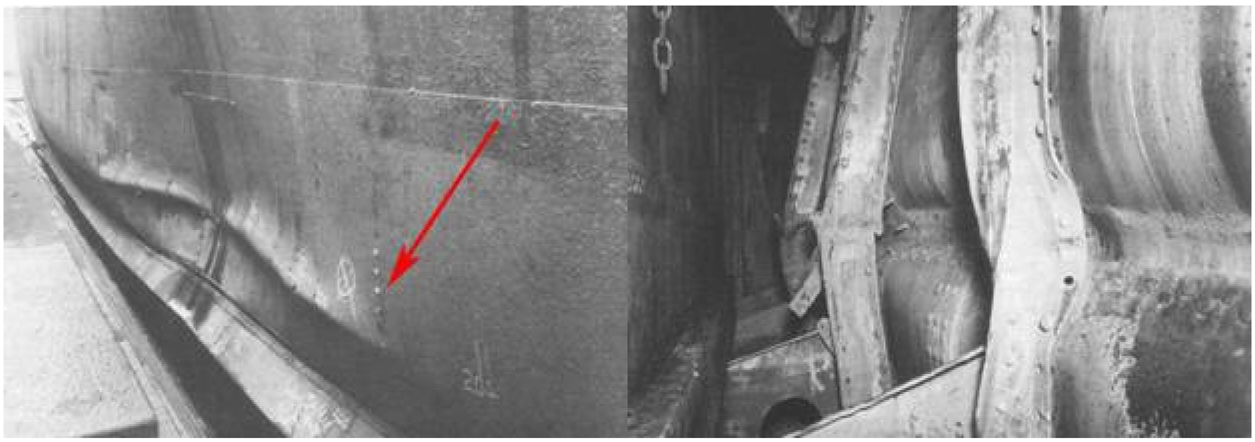
The testimony of survivors also confirm that the Engine Room ventilation systems did not perform adequately, and there were a number of heat exhaustion cases that were being treated by the time of the last bomb attack at 1244. This 'ventilation problem' was Admiral Sir John Tovey's chief objection to deploying any battleship of the *King George V* class to the Far East. Those limitations were corrected in all four surviving sisters during extensive refits from 1942-1944.

There has also been some speculation that German bomb damage to *Prince of Wales* sustained during the night of 31 August / 1 September 1940 while she was undergoing outfitting in the large fitting-out basin at Cammell Laird Shipyard could have contributed to the outer port shaft failure on 10 December 1941. There was a 2.25-foot (0.67-meters) indentation in the plating between Frames 184 to 228, with damage centered around a main transverse bulkhead at Frame 206. The near-miss bomb's explosion between the basin wall and ship must have produced a shock effect. According to a report of the damage from this incident, six affected plates and backing structure were replaced in Rosyth during February 1941. From the official report, efforts were made to repair the plating and backing structure, although no mention is made of the shafts.

There is no doubt that the shipyard was under great pressure from Whitehall to repair the damage as quickly as possible so the ship could be deployed as soon as possible, according to information from Fleet Admiral Sir Henry Leach (RN) in a letter dated 1 July 2009 to author William Garzke.[32] The list caused by the water-hammering effect of this near-miss bomb

[32] Admiral Leach is the son of Captain John Leach, who was the captain of *Prince of Wales* and was lost when she sank.

generated progressive flooding in the incomplete ship and produced a list of almost 10 degrees before pumping and an assist from a land-based fire department could remove it; the implications of same causing grave concern to dockyard officials and navy officers alike. The significance of this particular bomb hit was that although the bomb's explosion did not rupture plates, it did damage to riveted connections that allowed flooding to take place through failed rivets.



These two photos show the (German) bomb damage sustained to the port side of *Prince of Wales* while fitting out at Cammell Laird Shipyard in 1940. **Left**. Dished in hull plating stretched from Frame 184 to Frame 206 – note the plugs in the way of popped rivets (red arrow). This damage bears a direct resemblance to what has been discovered in both hull sides on the wreck. **Right**. The internal deformation in the area of the damage shown at left and is typical of a compartment of the side protection system.

What is important in the analysis of the August 1940 bomb damage and the damage from the last bomb hit and associated near misses from Japanese aircraft is the significant effect that the port near misses may have had in the capsizing of the ship. Many of the starboard outer voids of the Torpedo Defense System in way of the starboard near-miss bomb explosions had been flooded to control the port list from the port torpedo hit. With the voids already flooded no additional water could be taken aboard in those voids. The extensive damage to the riveted seams below the armor belt on the port side allowed significant flooding in the outboard voids and fuel tanks (that had oil transferred to the starboard side) and was the 'straw-that-broke-the-camels-back' in causing the ship to capsize.

Note the following calculations from the U.S. Navy's Damage Control Handbook in relation to what might at first appear to be insignificant damage from the bombing when contrasting simple 'split riveted seams' to the large torpedo holes**:** *"A small hole below the waterline will let in a great amount of water. If you have a 1-inch (2.5-cm) diameter hole, 20 feet*

(6 meters) below the water line, that hole will let in over 89 gallons (338 litres) of water per minute. This equates to 744lbs (338 kgs) or over one third of a ton of water per 1-inch (2.5-cm) hole per minute!"

Thus, those last six near misses and the one bomb hit produced the flooding that was enough to erode the ships limited residual stability. The torpedo hits had put *Prince of Wales* in a sinking condition – this bomb attack delivered the coup de grace.

The question remains why the port shaft flanges came apart while the starboard shaft, although twisted underneath the inner shaft, appears not to have failed, even though its 'stopping' was more abrupt. The answer may reside in possible undetected shock damage from the German bomb attack. Although the propellers were not fitted at the time of this attack, the shafts were installed. The shock response of a bomb exploding only 3 meters from the ship may have weakened the bolted connections. There is also the possibility of a metallurgical flaw in the bolted materials.

The torpedo defense system in way of "B" Turret performed well, with one exception. Part of the gas jet from the torpedo explosion did vent into the Seamen's Mess Deck over the impact area near Frame 109. Unlike American warships of that period which were fitted with the same type of sandwich torpedo protection, the British system was unable to contain the explosion completely within the system. American battleships had a void over the system that was designed to contain structural debris or prevent the gas jet from reaching spaces within the ship. USS *North Carolina* was the only new American battleship tested in combat by a torpedo – a Japanese Type 95 submarine torpedo, with an explosive charge of 405-kilograms that exceeded the explosive force that the system was designed to defeat. Despite being of riveted construction, the American system performed rather well.

The two torpedoes that struck *Prince of Wales* aft of "Y" Turret (and the one at the very bow) were in regions of the ship where there was no multi-layer torpedo defense system. Although these aerial torpedoes had small charges compared with those carried by Japanese surface ships and submarines (as well as the maximum design charge used in *Job-74*[33]) they nevertheless caused grievous damage.

[33] Job 74 was a series of tests done on a series of caissons built to model hull sections of the *King George V* class battleships so as to establish the design and arrangement of their Side Protective Systems against underwater attack. The charges used in these test were up to 1,000 pounds (454 kilograms) of TNT and the SPS design was, at the time, found to defeat them.

The parting of five sections of shafting at their flange connections can be attributed to the shaft rotating out of center and the subsequent loss of the port outer propeller and strut. The bolted connections were designed for a torque loading, not a combination of tensile and torque loads that led to their failure.

Conclusions

The loss of *Prince of Wales* and *Repulse* on 10 December 1941 was a tremendous shock to the whole world, and especially to Prime Minister Churchill and Admiral Pound on both a strategic and personal level. This event, coupled with the Japanese attack on Pearl Harbor a few days before, led naval leaders to rethink the role of battleships in their fleets. These two British capital ships were vastly outnumbered by the forces the Japanese had in the area and the presence of one aircraft carrier may not have been enough to prevent their loss, as that carrier probably also would have become a victim of this Japanese assault. *Prince of Wales* and *Repulse* were the first capital ships to be sunk solely by air attack while underway at sea and fully prepared for action.

The exploration of the *Prince of Wales* wreck by Kevin Denlay and his associates has revealed much new information on the loss of this ship, and it also has confirmed the testimony of Stoker James as to the massive, unexpected failure in the shafting that had never been confirmed – as a matter of fact it had been seriously doubted − until this exploration took place. The degree of damage from near-miss bombs, also a new discovery on the wreck, is consistent with the Marine Forensics Committee’s analyses of other ship wrecks with riveted construction. Riveted connections were susceptible to failure under shock loading, whether caused by explosions or impact, such as those failures in RMS *Lusitania* and RMS *Titanic*.

The shaft disintegration that Expedition ‘Job-74’ uncovered was in all probability the result of a massive energy spike traveling along the shaft, which overwhelmed its designed strength. This energy spike, also aided by the shock response of the ship, was sufficient to shear the bolts for the shaft flanges and also sheared the bolts securing the plummer block to the line shaft. These bolts were not load bearing and their failure freed the shaft segments from all their restraints. With the line shaft no longer secured, they expended their energy in flailing against local structures, such as shaft seals (glands) in the transverse bulkheads within the shaft alley, while also moving somewhat aft. Important to note is they were in tension when the bolts failed.

Evidence from the wreck site revealed no hull damage in the immediate vicinity of where the port outer propeller itself was located, confirming that the wrecked propeller made no contact with the hull structure. We cannot be sure of the exact time of the shaft strut failure, but it was a key event in the failure of the port outer shaft. The shafting, no longer restrained by its connections to the plummer blocks, destroyed bulkhead stuffing glands and severely damaged the structure of each transverse bulkhead that it passed through.

The impact of this energy spike on the thrust bearing within "B" Engine Room cannot be evaluated. However, it can only have been severely damaging, as was discussed by Vice Admiral Wildish and author William Garzke in 2008. The impact of the energy spike on the stern gland is known to have been catastrophic, as the ship's hull around the stern tube was torn open. The damage visible in imagery suggests massive misalignment of the still-rotating shaft which physically displaced the shaft inwards by some fractions of a meter. It then 'reamed out' the stern gland perhaps in one rotation. With the torpedo explosion impacting the stern tube, it created an intense energy spike. This theory would only be confirmed by finding the stern tube and the rest of shafting to the propeller and subjecting them to a forensic examination.

The effects of the energy spike on the reduction gear also would have been similarly damaging. The authors have queried a number of technical experts regarding the extent of the damage to the reduction gear. Estimates regarding the damage range from broken gear teeth, at a minimum, to broken gear wheels at maximum. There is cautious and qualified agreement that the noise that the then LT. Wildish heard and felt when re-starting the shaft may have been gear box rumble due to internal gearbox damage. Every mechanical engineer spoken to has remarked how important it would be to see what was in the internals of the reduction gear box. We do know from the photography of Mr. Challen that the line shafting became decoupled from the Thrust Block.

Admiral Wildish has expressed his conviction that the shaft was still turning when he left the control platform. However, with the rapid flooding of his space, he was unable to know if the shaft was still turning when he emerged from the hatch in the deck above. We believe, based upon testimony taken at the Bucknill Committee, that all the boilers in "B" Boiler Room providing steam flow to the turbines in "B" Engine Room were secured during his escape from the Boiler Room. With no steam, the turbines could no longer power the outer shaft. The shaft may have been turning when then LT Wildish left the Control Platform, but its energy at that time was being expended in damaging structure, decoupling the shaft from the thrust bearing, and possibly damaging the gearing in the reduction gear until its steam supply was cut off. This latter action prevented an over speeding of the turbines.

After considerable study and discussion with relevant experts, the authors have determined a possible scenario and timeline of events (Appendix B) for the torpedo and bomb damage and the flooding, based on both official reports by officers and men aboard *Prince of Wales* and the detailed published reports of the surveys of the wreck in 2007 and 2008.

Based on the new evidence detailed in the foregoing and Appendix B, we can reasonably address the question: “What deficiencies were there in the design of *Prince of Wales*?”

The failure of internal communications after the first torpedo hit reflected an inexcusable design flaw – it negated much of the skill and training of the crew to keep the ship afloat. Critical decisions had to be made without proper knowledge of events outside confined spaces.

Centerline machinery space bulkheads were incorporated to enhance survivability, but such subdivision actually decreases it. Although smaller machinery spaces can limit the amount of flooding, this advantage is more than offset by the effects of off center flooding, leading to devastating lists. A survey of damage to World War II Japanese cruisers, which had centerline bulkheads in their machinery spaces, noted they behaved very poorly when they sustained damage on one side. Only one ship managed to limp back for repairs, while sixteen others capsized and sank. The decision to use centerline bulkheads in the *King George V* Class was a serious design flaw. American and French designers avoided centerline bulkheads like the plague in their contemporary battleship designs, opting for large machinery spaces that would flood without creating damaging lists. It was not until the design of the battleships of the proposed *Montana* Class (BB67-71) with beams of 122 feet (37.2 meters) that the U.S. Navy would accept longitudinal bulkheads in their machinery spaces. *Prince of Wales* and her sisters were too small to tolerate extensive longitudinal bulkheads.

The experience of flooding in the USS *Pennsylvania* from a stern torpedo hit hints that one cause of extensive flooding in the stern of *Prince of Wales* was due to failed rivets, parted seams and failed caulking. This allowed massive flooding to occur on the port side aft.

Another major fault in the design was the inadequacy of the ventilation system in the machinery spaces. Admiral Tovey protested the assignment of this battleship to tropical regions because *"recent operations in the Mediterranean made it clear that, when underway, ventilation in the King George V class is most inadequate in a hot climate and health and efficiency of the ship's company will be seriously affected, which will be aggravated by lack of awnings and side screens in harbour.*[34]*"* Tovey's remarks proved to be correct, as officers and crew alike were overcome by heat exhaustion during the 10 December engagement with Japanese aircraft. These shortcomings were also evident during the voyage from Capetown to Singapore.

The torpedo defense system in way of "B" main battery turret did appear to function more or less as intended. The presence of water in the inner and outer layers of the side protection system - due to counter-flooding to correct the port list - did allow damage to extend into spaces above (over) the system following the subsequent damage at that point from the torpedo hit. Placing a void over the system would have possibly prevented this from occurring, however the ship was already seriously damaged and this design defect did not materially contribute to her loss.

The experience of *Prince of Wales* had a profound influence in the design, construction, and outfitting of HMS *Vanguard*, the Royal Navy's last battleship that was under construction at the time of this incident. The light antiaircraft armament was changed to incorporate a battery of 40-mm Bofors machine guns instead of the obsolete and inadequate 2-pounder Pom-Pom mounts; there were dual steam-line connections to the steering gear for emergency steering; and the shafting arrangement was revised for increased separation between the inner and outer shafts.

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[34] Public Record Office ADM 199/2232 and *Battleship* by Middlebrook and Mahoney, page 52.

Appendix A: The Gamble

Prior to the deployment of the *Prince of Wales* and *Repulse* to the Pacific, the Royal Navy had been operating for over two years (September 1939 - December 1941) in the Mediterranean in the face of intensive attacks from German and Italian land-based aircraft. These airplanes were able to damage the convoys but not totally stop them. British battleships had been repeatedly attacked but never sunk. Based on that recent war experience, it certainly appeared risky but possible to operate in waters covered by enemy land-based air. What was not understood, due to a serious intelligence failure, was the fact that the Japanese bombers based in Indo-China were not an ordinary formation of aircraft but were a force especially trained and equipped for "ship killing". These planes were specifically stationed there because of the predicted arrival of *Prince of Wales* and *Repulse* in Singapore. No other enemy or allied air force had this equivalent capability at the time. As the war progressed, ordinary land-based bombers (US B-17s, the Germans and Italians in the Mediterranean) continued attacking ships at sea with limited success. The RAF, using torpedo and rocket-equipped twin engine planes against German coastal convoys, and USN carrier-based planes (using torpedoes and bombs) and USAF B-25s, using skip bombs against Japanese coastal shipping, would finally gain the equivalent potency of these Japanese land-based aircraft later in the war.

The Japanese were not deterred by witnessing the destruction of the British ships deployed with inadequate air cover – they used the same tactic of sending surface ships against invasion forces later in the war. There was one success late in 1942 – driving the U.S. Navy's amphibious ships away from Guadalcanal, leaving the Marines precariously exposed until the American Navy could regroup. There was one near success – only a desperate defense by US light forces and confusion in the Japanese command prevented the Japanese battleships from reaching the transports at Leyte Gulf in 1944. The disastrous deployment of the battleship *Yamato* in April 1945, admittedly a one-way suicide mission, was a mirror image of the British loss, sailing southbound against a naval air arm especially trained to kill ships.

In an unnoticed small bit of revenge, *Prince of Wales'* sister ship *King George V* joined USN battleships in 1945 daylight bombardments of the Japanese main islands. This British battleship could sail close to Japan regardless of any ad hoc attacks by Japanese aviation. The Japanese specialist ship killer planes had long since been lost and their highly-trained pilots killed without replacement.

Appendix B: Timeline of Events

(Based on Reports of the Power Control Room and Compass Platform)

1113 5.25-inch guns open fire at Japanese high-level bombers attacking *Repulse.*

1117 Shafts of *Prince of Wales* are making 204 revolutions (25 knots).

1141½ *Prince of Wales* opens fire at nine torpedo bombers approaching from port.

1144 A torpedo strikes the ship a few meters aft of where the port outer stern tube exits the hull, bending the shaft enough so that it causes instantaneous damage to both strut arms of the outboard port shaft. Pieces of hull plating or strut come loose that foul and chip the blades of the port inner propeller causing it to rotate with a blade imbalance. **(**No. 2 Steering motor was stopped and No. 1 slowly failed.**)** Turbine in "B" Engine Room begins to vibrate badly and the Power Control Room notes that the revolutions on port outer shaft ("B" Engine Room) are dropping. "Y" hydraulics is shut down. There is no steam pressure from "Y" Boiler Room to its Engine Room. Glands in the various bulkheads along the shaft are damaged as shaft begins to rotate out of centre.

1146 LT Wildish in "B" Engine Room realizes the necessity of a quick decision in this emergency, as the shaft started to turn with difficulty. He then orders the Mechanic A. Handley, manning the throttle to shut off the steam immediately by tripping the emergency bulkhead stop valve in the steam line from "B" Boiler Room to the turbine in "B" Engine Room. E.R.A. Greenwood discovers water rising in the bilges. The fire and bilge pumps which were on the fire main are changed to bilge suction.

1147 LT Wildish uses steam at a pressure of 100-pounds (45-kilograms) to the astern turbine to bring the outer shaft to a halt in "B" Engine Room. When LT Wildish brings the shaft to a stop**,** the propeller evidently hung from the ship**,** still turning slowly due to ship's forward motion. All of this puts tension on the bolts for the coupling of the line shaft to the stern tube. LT Wildish had Chief Stoker Hooper check with personnel in "B" Boiler Room to determine if there were any problems with equipment there. Hooper reports back that there was no apparent damage there.

Comment: Stopping a shaft rotating at 204 revolutions per minute takes considerable power, and a steam pressure of 45 kilograms was probably insufficient for the task. The shaft was trailing after the action with the astern turbine and led LT Wildish to believe he still had a propeller on his shaft.

1149 LT Wildish, not knowing the conditions of his shaft outside his space, wants to provide some power from his shaft as the ship is under attack. He increases revolutions to 158 rpm and steam again begins flowing freely to "B" Engine Room. However, the Power Control Room notes that the "B" Engine Room shaft speed is decreasing.

Comments: The decision to restart the shaft of "B" Engine Room continues the process of deforming bulkheads and destroying stuffing glands in the transverse bulkheads within the outer port shaft alley. Water begins to flood even more rapidly up the shaft alley and "Y" Action Machinery Room gradually begins to flood. The port outer strut assembly had been damaged by the torpedo explosion. Within several minutes of that explosion and once the shaft is restarted, the outer propeller and strut hub begin to pull away from the hull, causing the strut arms to fail singly or possibly both at the same time. The propeller droops and also begins to spin wildly without support from the strut arm. Vibrations and other forces begin to flow up the shafting, distorting bulkhead glands in several bulkheads forward within the outer port shaft alley. A horrendous knocking noise can be heard in this section of the ship that many equated to a second torpedo hit. The magazines of the two aft 5.25-inch dual-purpose mounts, P3 and P4, are flooded by their crews.

Circa 1150 Stoker James notices that the shaft is rotating out of center and immediately leaves "Y" Action Machinery Room after the steam to the turbo-generator is shut down. From an overhead hatch, he then witnesses an unsupported line shaft come apart between the plummer blocks[35] in this space. It falls onto the turbo-generator.

1151 Revolutions ceased on the inner port shaft ("Y" Engine Room) due to vibrations in its turbine. Power Control Room narrative notes that starboard shaft revolutions are at 158**;** no revolutions are shown for the port shafts **Comment:** These vibrations probably resulted from debris from the hull plating, the outer strut and outer propeller damaging the blades of the inner port propeller. Chipping of its blades was observed and photographed by Expedition 'Job 74' divers**.**

1152 Regulating Chief Stoker Glanville reports to the Power Control Room that there is damage in "Y" Action Machinery Room and a hatch to Number 12 Ring Main Breaker Room is still open.

Comment: Shafting flanges had already failed by this time and flooding was occurring in the "Y" Action Machinery Room and the Diesel Dynamo Room. Water rushes into the "Y" Action Machinery Room and, with the overhead watertight hatch not closed, allows flooding of spaces over. Water floods the Diesel Dynamo Room – albeit at a slower rate - from an opening made in the bulkhead around the gland by the shaft that was rotating out of center. .

Circa 1154 LT Wildish goes aft to make an inspection of the Thrust Block where the 17.5-inch 44.5-cm) diameter shaft passed through the aft bulkhead of "B" Engine Room into the Diesel Dynamo (Generator) Room immediately behind - and from there on through there into "Y" Action Machinery Room further aft. Arriving at the recess in the bulkhead for the Thrust Block, he finds that the bulkhead stuffing gland was wrecked and there was nothing that he could do to stop the water pouring through the Thrust Block pocket.[36] The shaft had been and still is running out of center. LT Wildish realized that something serious has probably happened to his propeller, which had caused the whole line of shafting to run eccentrically under enormous power, destroying the watertight integrity along the entire length of shafting. There was nothing now that could be done about that either. LT Wildish immediately returned to the control platform, where the turbine throttles were located.

1155 Water is rising fast in the Engine Room's bilges; therefore, LT Wildish orders starting the emergency pump and that the fire and bilge pumps should be on bilge

[35] Pedestals in U. S. Navy terminology.

[36] For this to occur the Diesel Dynamo Room, the "Y" Action Machinery Room and the shaft alley all the way aft to the ripped open stern tube gland *must* already be fully flooded at this time

suction. The water level still keeps rising so he orders E.R.A. Greenwood to shut the sea inlet so that the main circulator could be changed from sea suction to bilge suction (the high volume pump moving water to the main condenser under its main turbine). With the water level still rising, Wildish realizes that the situation in his Engine Room was clearly getting out of hand; evacuation of the space is mandatory. He decides to let the turbines continue in operation with the machinery prepared to run underwater by increasing gland steam to the turbines and speeding up the auxiliaries. Once the water was over the platform where the controls were, Wildish then orders all remaining personnel out of the space.

1157 Damage is reported abreast of M/C Shop, port side. Repair parties are urgently summoned.

1202 LT Wildish is the last man out of B Engine Room and as he dogged down the hatch some water was oozing out.[37] CDR Goudy was on the scene and Wildish gave him his report that his turbine is still running, full gland steam on, and that all personnel are out of the space.

1202 Emergency lighting is extinguished in the Power Control Room. Both port engines have stopped. Port inner shaft is trailing at 60 revolutions.

Comment: Note that there is no report that there is trailing in the port outer shaft because the port outer propeller has already broken away from ship.

1203 Electrical fire is reported in Harbour Machinery Room. CDR. Goudy went there and detected only smoke that had resulted from an electrical fire there. He also reported that there was eight feet of water in this space, but both fore and bilge pumps were pumping into the bilge.

1204½ Lights are back on in Power Control Room.

1209 Electrical fire in Harbour Service Room is reported to be extinguished.

1210 Hoisted signal, “Not under Control.”

1212 There are now only 60 Revolutions on starboard engines. The Regulating Chief Stoker reports that S3 and S4 5.25-inch magazines were not flooded, but water is coming in.

1217 No. 1 Steering Gear motor is off. The Engineer’s Office reports through Chief Stoker Glanville that No. 2 Steering motor cannot be started.

1218½ 90 Revolutions on starboard engines.

1219 120 Revolutions on starboard engines.

1219½ 150 Revolutions on starboard engines.

1220 224 Revolutions on starboard engines.

1223 Watchkeeper reports that the Transfer pump is unable to stop flooding below. Pump is stopped.

1222½ 220 Revolutions on starboard engines.

1223 Two torpedo hits on the starboard side, a few seconds apart.

Comment: Two torpedoes struck, or *appeared* to have struck the ship, almost simultaneously. One hits the bow at about Frame 8, the other in “*the after part of the ship*”. This ‘other’ one *may* have exploded prematurely just off the side of the ship in the area abaft the mainmast, or, *perhaps*, have hit at Frame 296 **(**causing the failure of the outer starboard shaft strut and bending the shaft so that the outer

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[37] As this is an ‘over’ or above hatch, for water to be oozing out indicates that ‘B’ Engine Room is now flooded to the deckhead (i.e. fully flooded).

propeller is wedged under the inner starboard shaft). However, there is still debate / conjecture with regards this being the hit that bent the shaft, as some survivor reports claim that the torpedo that hit furthest aft (the one that bent the shaft) was the last torpedo to strike the ship.

1223½ One torpedo hit to starboard under Compass Platform.

Comment: This is the torpedo hit near "B" Main Battery Turret confirmed at Frame 109 by Expedition 'Job 74'.

1224 "A" Engine (starboard outer shaft) stopped. Shaft at zero revolutions.

1225 Half lights out in Power Control Room.

1226 S.P.O. Dingle reports that After Steering Compartment is flooded.

1227 Torpedo hit reported forward of Frame 119? Starboard. Oil leaks.

Comment: The report of a torpedo hit in this position on the starboard side was in error: Expedition 'Job 74' found no evidence of a torpedo hit in this vicinity. However, although the time is wrong (i.e., too late) this report may relate to either the last torpedo to strike the ship (at Frame 296) or one that may have detonated outboard of the hull in the vicinity of the mainmast. Although there are only three confirmed hits to starboard, many survivors reported a hit abaft the mainmast; however Expedition 'Job 74' proved that there was no hit there either.

1230 "X" Engine Room only one in service.

1230 Nine Japanese bombers approach from port bow.

1232 Damage between A.1 to 5 oil fuel tanks.

1234 120 Revolutions on starboard inner engine ("X" Engine Room – inner starboard shaft).

1238 90 Revolutions.

1241 Attack on *Prince of Wales* by eight high-level bombers approaching from the port bow.

1244 One 500-kilogram bomb hits the ship, and there were six near misses, port and starboard. Lights out. **Comment,** One of the eight bombers fails to drop its bomb due to a faulty release mechanism.

1245 50 Revolutions on inner starboard shaft; list is now 3 degrees to port and increasing.

Comment: Flooding of port outer voids in side protective system through parted seams and failed rivets is the cause of the increasing list to port. This damage was observed and filmed by Kevin Denlay and his colleague Dr. Andrew Fock during Expedition 'Job 74'.

1250 Radio message sent to Singapore for tug assistance.

1300 Destroyer *Express* alongside starboard side to evacuate all non-essential and injured personnel.

Circa 1310 All shafts not in operation – Abandon Ship starts.

1315 List to port begins to increase rapidly.

1324 *Prince of Wales* capsizes and sinks. Capsizing was so rapid that the battleship's bilge keel catches the one on *Express* causing the destroyer to heel alarmingly to starboard.

Appendix C: The Puzzling Port Outboard Shaft Failure

The 2007-2009 diving expeditions to the wreck of *Prince of Wales* clarified many questions regarding the loss of this British battleship. By a large margin, the unexpected discovery of the multiple failures of the port outboard propeller shaft has tantalized engineers and analysts, effectively addressing the challenge to "explain the inexplicable."

Although the exact sequence of events in this area of the ship will always be unknown, using the techniques of marine forensics, we have developed a likely sequence of events based on survivor testimony and several inspections of the wreck. (Late in World War II, the U.S. battleship *Pennsylvania* sustained a similarly-located torpedo hit. Analysis of this damage is relevant to understanding the situation of *Prince of Wales* in 1941. Refer to Appendix D for details of the 1945 *Pennsylvania* damage incident.) The torpedo detonated forward of the port strut in close proximity to the stern tube of the outboard shaft that received its power from the turbines in "B" Engine Room. All survivors noted the heavy shaking of the ship. The torpedo explosion under the stern had the tendency to lift the stern, but the inertia of the barbette armor and the aft quadruple turret resisted the tendency of the stern to lift, causing deformation of the surrounding structure and perhaps failed riveted seams. (This type of damage was experienced by the USS *Pennsylvania* when she was hit by a torpedo in the stern while at anchor in Buckner Bay, near Okinawa, on 12 August 1945[38].)

The outboard shaft strut arms were weakened by the force of the explosion and a ragged hole was torn in the hull plating approximately four meters high and six meters wide just abaft the stern tube, and the shaft itself was damaged. The stern tube was also damaged (See Figure 1), but its degree of damage is not known, nor will it be until that missing section of shafting and the associated stern tube structure is found for further examination. The outer port propeller continued to rotate at high speed and, turning out of center, started to wobble and vibrate, putting additional stress on the weakened strut.

In order to better understand this event, it is necessary to refer to Figure 11, which is duplicated below:

[38] See Appendix D

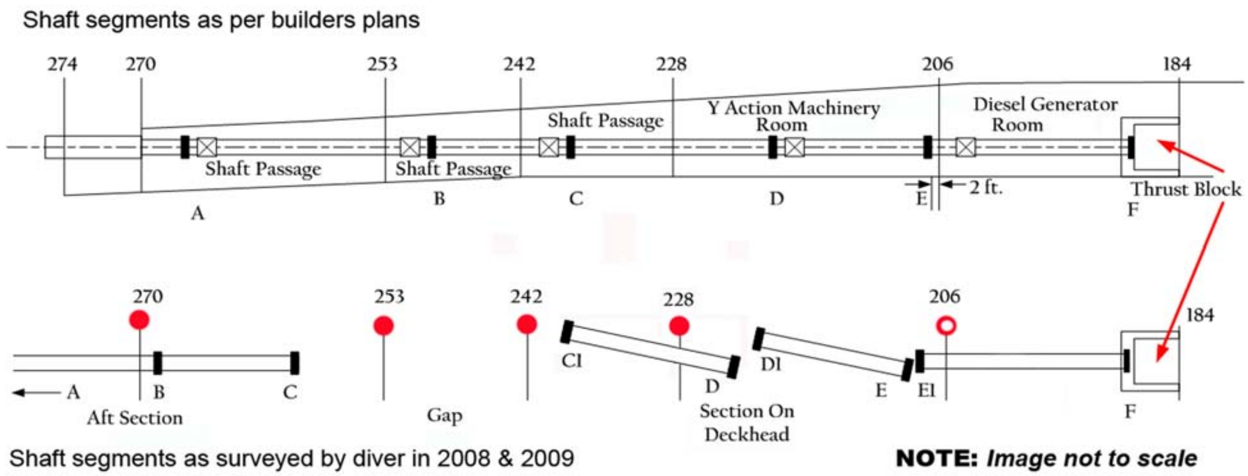


Figure 11 – Illustration Comparing the Port Outboard Propeller Shaft

A comparison of the intact port outer shaft (upper) and the separated sections as surveyed (lower), with bulkhead frames numbered and flanges marked A, B, C, D, E, F. Flange B is the *only* flange that remains intact aft of the Thrust Block itself; the length of shafting missing (approximately 17-meters) aft of Flange A having separated with the propeller when it broke away. The distance across the gap between separated Flange C is approximately 14-meters (C to C1). Solid red dots indicate the destroyed bulkheads along the shaft tunnel, while the outlined red dot (frame 206) indicates a partially destroyed bulkhead.

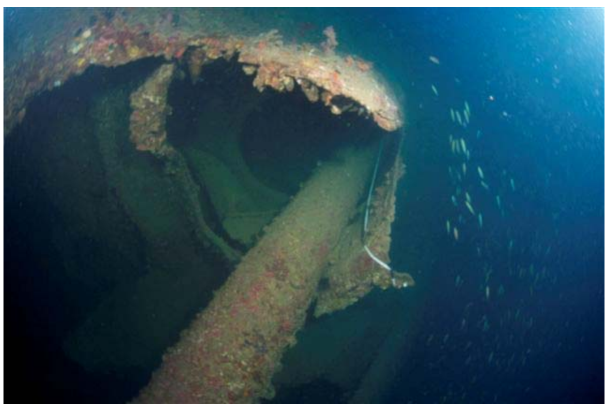
With the failure of the shaft strut, the fast-turning propeller shaft is now unsupported. This caused massive shock loadings and vibrations up the entire length of the shaft, ripping out the supporting plummer blocks (which had already been damaged by the initial energy spike caused by the torpedo detonation.) Inevitably, this process heavily stressed the several flanges joining the various segments of the propeller shaft. Numerous bolts, possibly already weakened as a result of shock damage caused by the near-miss bomb event of August 1940, began to fail. With no strut to support the propeller, still turning at high speed, the shaft and propeller assembly began to pull aft.

With all these various forces at play, the first flange to separate is Flange C, as hinted by the available forensic evidence. With no structure holding the three lengths of shaft aft of Flange C in place (propeller to Flange A, A to B, and B to C) they all begin to pull out aft as one continuous piece, with enough force to rip out the stern tube in the process. As all this is happening, the shaft is still spinning with considerable momentum, separating at Flange A right after it passes out through the web frames.

This structural failure leaves two lengths of shaft (from Flange A to Flange C) where we see them now, with the intact Flange B caught in the web frames, where the stern tube had been, which stopped the shaft segment from sliding out any further aft.

After this chain of events, there is a large gap which we now can see between the separated halves of Flange C (C/C1).

At the same time that all the foregoing was happening aft of Flange C, the shafting forward of Flange C starts flailing and begins to separate at all its flanges (D, E, F). However, given the failure at Flange C, there is no force available to pull these sections aft, so they basically fell in place, where we see them now and there are only small gaps between the several flange halves. This process happened almost instantaneously, hence with less and less damage to the bulkheads the further forward you go.



Port outer shaft where it now exits the hull. Torpedo hole is to left. Flange A is out of picture lower left.

Flange B, now just inside hull where stern tube should be, is the only remaining intact flange on entire shaft.

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Looking forward at destroyed bulkhead at Frame 270. White 'line' right is the survey measuring tape.

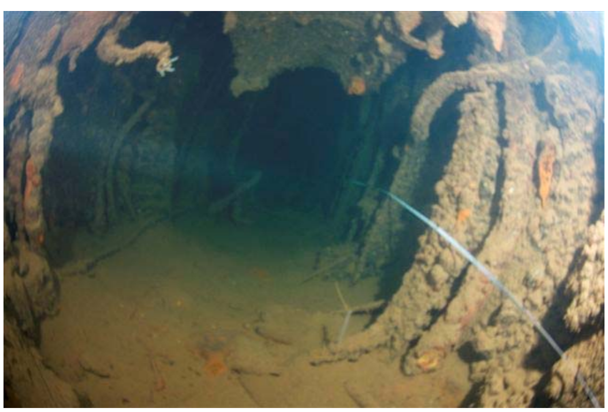
Lower arrow points to an open hatchway in deckhead, upper arrow to the remains of a Plummer Block.

Looking towards / past Flange C.

Flange C.

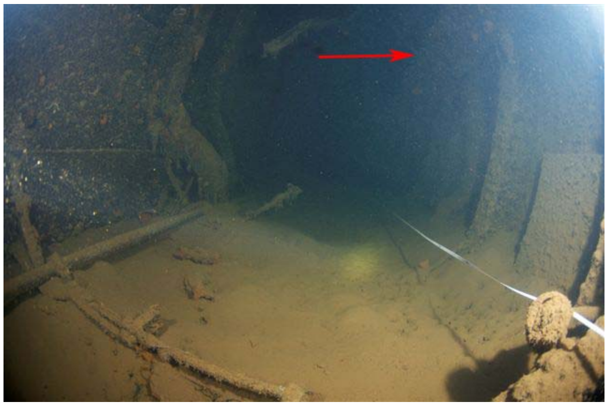
Flange C just out of picture lower right corner; start of large gap between C/C1. Note gaps in deckhead (arrows).

Looking towards remains of bulkhead (upper arrow) at Frame 253. Gaps in deckhead lower arrow.

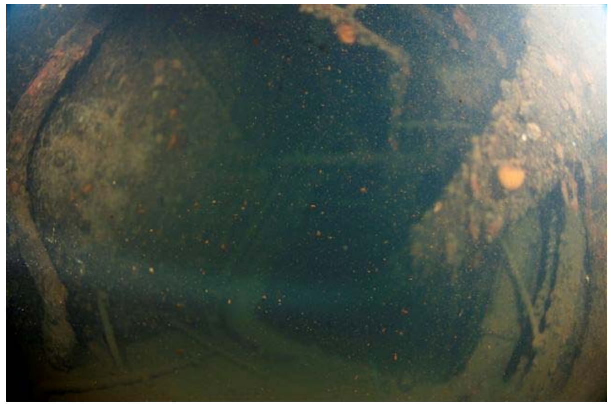


Approximately halfway between bulkhead at Frame 253 and bulkhead at Frame 242

Bulkhead at Frame 242. Arrow points to an open deckhead hatchway. Another deckhead hatchway also remains open just behind (forward of) Frame 242

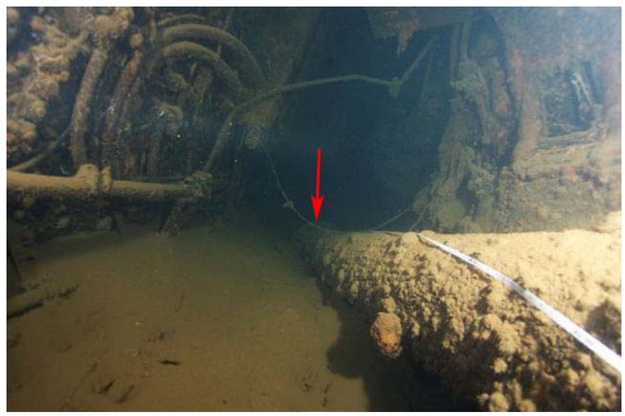


Arrow points to Flange C1, barely visible in upper right center

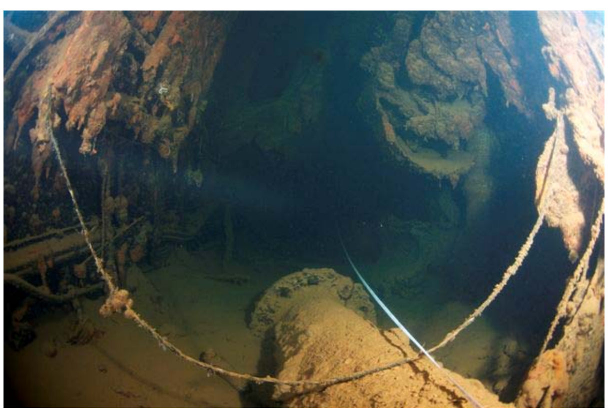


Shaft on angle at right, Flange C1 is just out of picture in upper right corner.   .

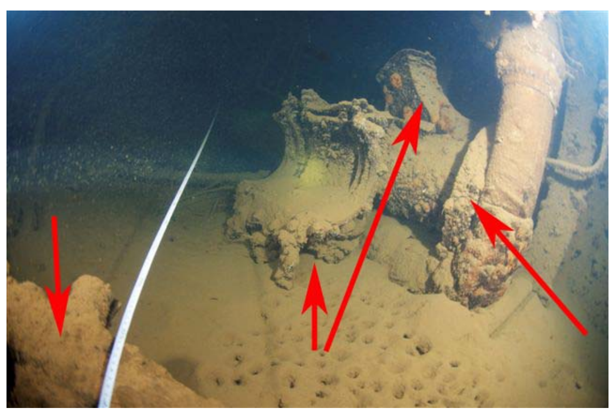
Aft bulkhead (Frame 238) of Y Action Machinery Room.



Arrow points to Flange D



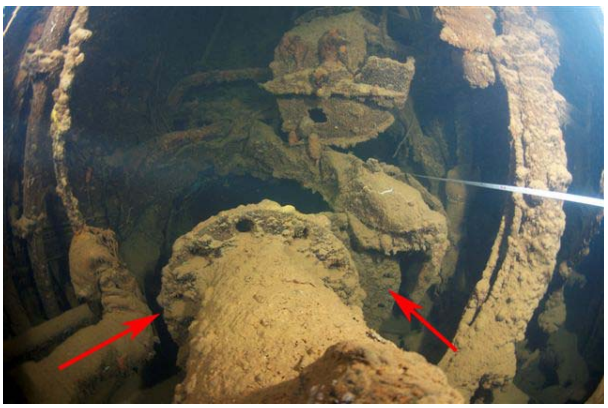
Flange D center, inside Action Machinery Room.



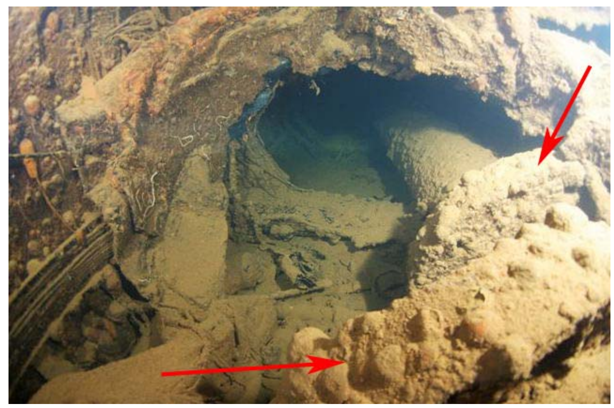
Flange D, left arrow: Remains of Plummer Block, centre two arrows: Flange D1, right arrow.

Shaft in Action Machinery Room

Arrow points to Flange E



Flange E, left arrow: Flange E1, right arrow. Bulkhead at Frame 206 in background.

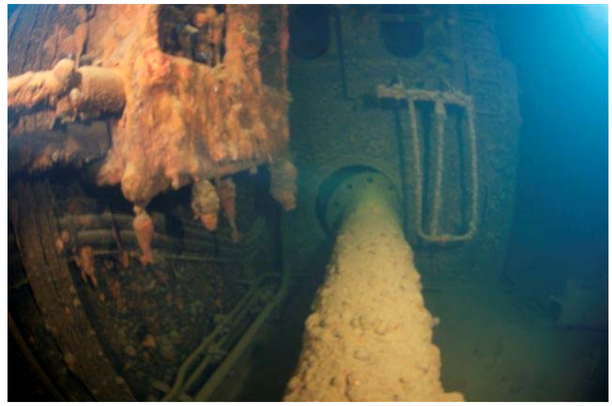


Flange E, left arrow: Flange E1, right arrow. Elongated gland in aft bulkhead to Diesel Dynamo Room (Frame 206) which survey diver squeezed through in 2009 (to continue his 2008 survey) in centre background.

Photo taken immediately after survey diver maneuvered through elongated bulkhead gland at Frame 206

Shaft (at bottom) further into the Diesel Dynamo Room

Still further inside the Diesel Dynamo Room



Looking further along shaft to Thrust Block enclosure

Shafting leading to dislocated Flange F inside Thrust Block enclosure

Flange F can be seen here completely ‘dislocated’ from the Thrust Block.

Alcove on outboard side of the Thrust Block enclosure. Behind ladder is the bulkhead to B Engine Room, Frame 184. Under the ‘drum’ in image on right is a deckhead hatchway.

Appendix D: USS Pennsylvania Torpedo Damage

On the evening of 12 August 1945 a Japanese plane equipped with a torpedo slipped into Buckner Bay, Okinawa without being detected and launched a torpedo at the battleship USS *Pennsylvania* (BB 38) which lay at anchor. The torpedo struck well aft on the starboard quarter, causing extensive damage to the stern and shafting. The explosion was either a non-contact type or it hit the starboard outer shaft, propeller, or strut some 20-25 feet below the water surface. There was a severe whipping response, lifting the ship vertically. Inspection of the hull in dry dock afterwards revealed a vertical tear in the hull plating. This damage was apparently caused by the outboard edge of a heavy athwartship bulkhead that acted like knife shearing the shell plating vertically. The shell plating was also ruptured horizontally along the structure that supported the armor belt. The size of this hole was some 30 to 32 feet long.

All four propellers were affected. The explosion sheared the starboard shaft at the after end of the stern tube bearing and destroyed the starboard outer strut. The starboard inner strut was ripped loose (one leg was pulled clear of the side of the ship and the other member was ruptured a few inches below its mounting pad). The starboard propeller and shaft were bent downward at an angle of 30 degrees with the bend beginning at the after end of the stern tube bearing. One blade of the outboard starboard propeller was projected vertically into the ship, which may have caused an unusual vertical rupture of the shell plating in that area. The starboard inner propeller was forced out of line. The port inner shaft was inoperable. There was no steering control, although the rudder had no apparent damage. However, being anchored and her propellers immobile at the time of the hit, she did not sustain severe damage to her shaft alleys as did *Prince of Wales*.

A centerline bulkhead in the area of the explosion was badly distorted to port and ruptured to port as was the aft bounding bulkhead to the affected compartment over the propeller and strut. The deck over in that compartment was badly buckled with many rivets missing. The frames, longitudinals, the light deck structure of the platform over the compartment, and a portion of the shell over the point of impact were all pushed up to the overhead and ruptured. Compartments adjacent to the hit had distorted bulkheads, warped decks and loosed rivets. Inspection of surrounding bulkheads around the two after main battery turrets revealed the inertia of the barbettes and other heavy structural members caused damage to light bulkheads, bounding angles, caulking, and riveted connections. This was the consequence of a shock response and the resultant stern whipping from the torpedo explosion. The main battery turrets and barbettes were not so easily excited, causing connections around them to fail. A similar occurrence probably occurred from the stern torpedo hits in *Prince of Wales*.

Many compartments were flooded in the region where the torpedo hit. The battleship settled heavily by the stern. The flooding was brought under control by an intensive effort by repair parties of *Pennsylvania,* coupled with the prompt assistance of two salvage tugs. She was towed to shallower water, where salvage operations were continued. Twenty men were killed, as well as ten injured, including Admiral Oldendorf. She was later towed by two salvage tugs to a floating dry dock at Guam, where a temporary patch was fitted over the torpedo hole. Other repairs were made to allow her to steam to Puget Sound for permanent repairs. While enroute on 17 October, her No. 3 shaft suddenly carried away inside the stern tube and the shaft slipped aft. It was necessary to send divers down to cut through the shaft, letting the shaft and propeller drop into the sea. Shipping water and with only one screw turning, *Pennsylvania* limped into Puget Sound Navy Yard.

USS *Pennsylvania*, BB-38, in a floating dry-dock somewhere in the Pacific, circa 1944.

Acknowledgements

The authors would like to thank Vice Admiral D.B.H. Wildish (Royal Navy, Retired) for his assistance in the preparation of this paper and permission to use his personal monograph, which provided details on his actions during the loss of his beloved battleship. The contributions of Admiral Wildish illustrate the value of an experienced engineering officer as a source for a marine forensic analysis. Such an officer is trained to be analytical and to understand physics. He was an eyewitness to the events that unfolded during the sinking of *Prince of Wales* and was a key asset in our marine forensics analysis and reconstruction of events. The information gleaned from the 1966, 2007, and 2008 survey dives was discussed with the former LT Wildish and his keen insights were invaluable to the conclusions that we have reached. It should be noted however, that in a letter to author William Garzke dated July 2009, Admiral Wildish still maintained that when he left his Engine Room at 1202 the turbines were driving his shaft.

We also would like to thank marine engineer Dennis Breen for his assistance in developing some of the technical details regarding the failure of the shafting, fellow Forensics Committee member Philip Sims for his contributions to this paper, and Dr. Andrew Fock for sharing with us his own unpublished Expedition 'Job 74' survey report. Also, thank you to Stefan Draminski **(** **http://bismarck3d.pl/** **)** for the astonishingly realistic 3D renditions that he constructed of the wreck of HMS *Prince of Wales* specifically for this paper using Expedition 'Job 74' survey images in close cooperation with author Kevin Denlay. A very special thanks is also due to John Roberts for being the one to notice the shaft flange that should not have been located 'outboard' on the wreck – and immediately perceiving just what that meant in terms of the shafting damage - that in turn lead directly to the discovery of the separated sections of shafting in the shaft alley. And last but not least to Craig Challen for going above and beyond the call of duty during his subsequent solo penetrations into the shaft alley itself.

All photos - and stills pulled from video imagery - of the wreck contained herein are courtesy of author Kevin Denlay, except for the photographs of the interior of the shaft tunnel which are courtesy of Craig Challen.

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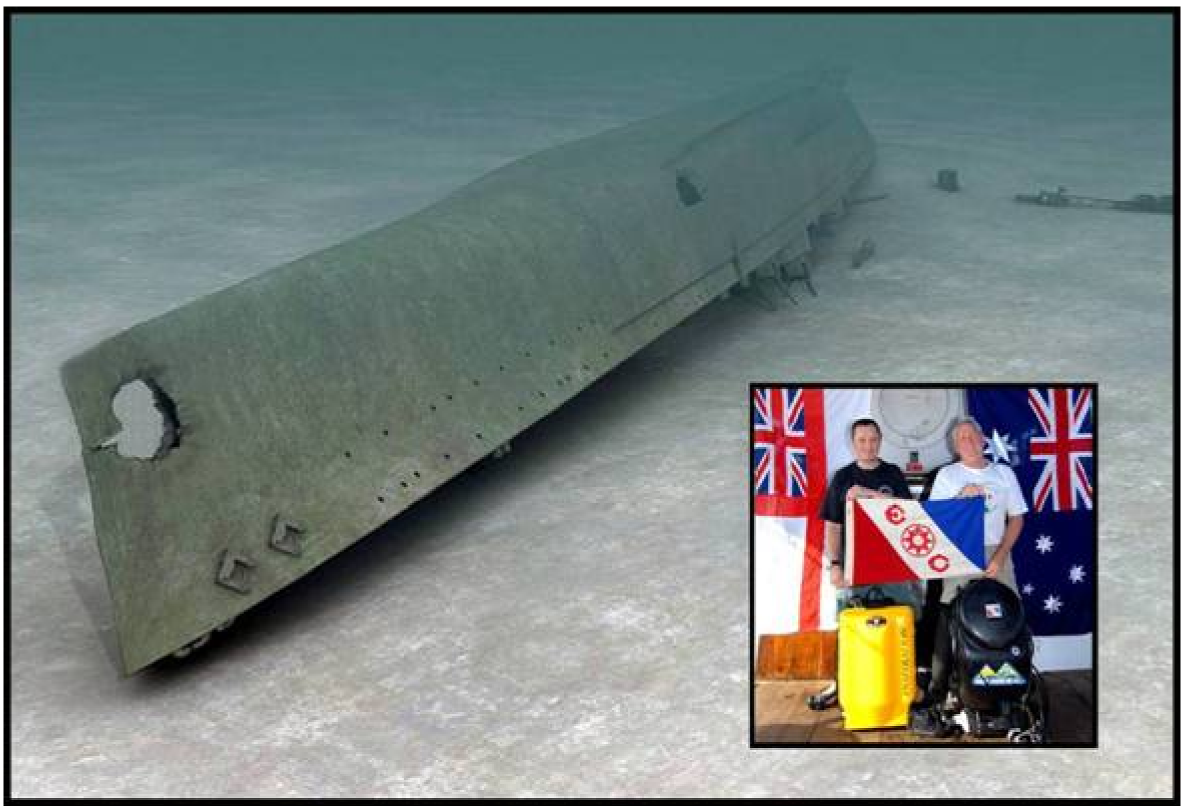
http://www.pacificwrecks.com/ships/hms/prince_of_wales/pow-hull-damage.pdf



Inset: Co-author Kevin Denlay (right) and Dr Andrew Fock displaying Explorers Club Flag #118 at the completion of *Expedition 'Job 74'*, May, 2007.

The Authors

WILLIAM H. GARZKE, JR., is a graduate of the University of Michigan with a degree in Naval Architecture and Marine Engineering. He also attended the Massachusetts Institute of Technology for graduate studies in Naval Architecture. He has a Masters degree in Applied Mathematics from Adelphi University. He is a member of the Society of Naval Architects and Marine Engineers, which have awarded him the Vice Admiral Cochrane Award for the best technical paper presented at a local sectional meetings in 1974 and 1995 as well as the Joseph Linnard Prize for the best paper presented at their Annual Meetings in 1981 and 1997. He and Mr. Dulin are authors of the trilogy of books on modern battleships of World II, published by the Unites States Naval Institute Press. Mr. Garzke is currently the chairman of their Marine Forensics Committee and has served in that capacity since 1995 when it was the Marine Forensics Panel. He is also a member of the Marine Technology Society, the American Society of Naval Engineers, and the Society of Allied Weight Engineers. Mr. Garzke is widely recognized as an expert on warship design. Not only did he research the design and operation of World War II battleships, but he also took part in specialized destroyer-design studies for the U.S. Navy and forensic studies of the RMS *Titanic*, HMHS *Britannic*, SS *Andrea Doria*, and the RMS *Lusitania*. Some of these findings can be found in the book, *Titanic Ships, Titanic Disasters*, published by the Society of Naval Architects and Marine Engineers that was co-authored with Professor John Woodward.

ROBERT O. DULIN, JR., graduated from the United States Naval Academy in 1961. After three years of service in the destroyer *Mullinnix* (DD-944), Ensign Dulin entered the Massachusetts Institute of Technology, from which he graduated in 1967, having received a Master of Science degree in Naval Architecture and Marine Engineering and the Professional Degree, Naval Engineer. He then served for two years at the U.S. Naval Ship Repair Facility at Subic Bay in the Philippines, and for four years with the office of the Supervisor of Shipbuilding, Conversion, and Repair, Third Naval District, Brooklyn, New York. The last three years of his service in the latter billet were as Supervisor (Commanding Officer). After retiring at the rank of Commander in the U.S. Navy, Mr. Dulin specialized as a management consultant. His clients have included the Naval Supply Systems Command, the Naval Sea Systems Command, and the U.S. Coast Guard. For several years, Mr. Dulin developed comparative naval architectural analyses of Soviet warship designs for the Navy. Prior to his recent retirement, Mr. Dulin consulted with the Missile Defense Agency for the past five years.

KEVIN V. DENLAY, is a Fellow International of The Explorers Club (New York) and a member of the SNAME Marine Forensics Committee's Diving Panel. He has been actively involved in shipwreck exploration and documentation since 1995 when he conducted the very first scuba dive on USS *Atlanta*, which sunk in 130 metres of water off Guadalcanal in the Solomon Islands. Besides extensive shipwreck exploration around Guadalcanal, Mr. Denlay has also dived and explored countless shipwrecks in such diverse locations as Australia, USA, PNG, Bikini Atoll, Baltic Sea, Java Sea, Red Sea, South China Sea and the Malacca Strait, and has participated first hand in numerous shipwreck discoveries in Asia aboard the dive vessel MV *Empress*. Some of these include the discovery of and very first dives on such notable WWII warships as Hr Ms *De Ruyter*, Hr Ms *Java*, Hr Ms *Kortenaer*, HMS *Electra*, HMS *Exeter*, HMS *Encounter*, USS *Perch*, HIJMS *Itsukushima* (all lost in the Java Sea), HIJMS *Haguro* and HIJMS *Kuma* (both lost in the Malacca Strait). Closer to his home in Australia Mr. Denlay was also involved in the discovery of and first dive on SS *Keilawarra*, a steamship sank in tragic circumstances in the mid 1800's. His articles and underwater photos from many of these discoveries have been published worldwide in magazines and books and are on various web sites, and his video footage used in TV documentaries. For many years a closed circuit rebreather and mixed gas instructor trainer with the International Association of Nitrox and Technical Divers and Technical Diving International, both technical diver training agencies, he now no longer trains divers but concentrates solely on shipwreck exploration and documentation.