The effects of storms and diving activities on the corrosion rate across the SS *Yongala* (1911) site in the Great Barrier Reef

Ian D. MacLeod*
Western Australian Museum

Andrew Viduka
Australian Government Department of Sustainability, Environment, Water, Population and Communities

*corresponding author: ian.macleod@museum.wa.gov.au

Abstract

The initial assessment of the condition of the wreck of the SS Yongala (1911) took place in 2005 and was followed with additional in-situ measurements on three field trips in 2007. Analysis of the corrosion potential, pH and plate perforation data confirmed that the superstructure, deck and hull plates are highly corroded and that the most extensive corrosion is on the port side gunwale. The high corrosion rates found at the forward end hull/forecastle deck level and at the stern near the rudder are consistent with the exposed locations which lie proud of the seabed and are subject to significant water movement across the site. Comparison of the original structure and its present condition with site records from previous visits suggest that the wreck is following the Riley waterline theory with the port side frames eventually collapsing and the bow and or stern section breaking off from the vessel. This collapse could happen at or near hold 3 and or around holds 1 and 2. Currently the bow is corroding at a higher rate than the stern end. Changes in the souring of the site and past practices of tying up to the wreck have been significant factors in accelerating the corrosion of this historically significant iron shipwreck.

Keywords: conservation, shipwreck, SS Yongala, in-situ corrosion measurements.

Introduction

The wreck site of SS *Yongala* is socially significant in terms of it being the gravesite of the 122 passengers and crew who were lost during a cyclone in 1911 and because it is currently one of Australia's most popular shipwreck dive sites (MacLeod 2008, Viduka 2008). The wreck lies in the open waters of Cape Bowling Green Bay in the central section of the Great Barrier Reef Marine Park at latitude 19° 18.268 S and longitude 147° 37.337 E (WGS 84) in 27–30m of water. The wreck sits approximately 14m above the seafloor leaning to starboard. Its geographic location has resulted in a heavily colonised site that is a veritable cornucopia of marine life (Viduka 2007a).

The *Yongala* was built in 1903 by Armstrong, Whitworth and Co. in Newcastle-on-Tyne, England for the Adelaide Steamship Company. The vessel was classed as an A1 screw steamer and was constructed primarily of steel, iron and timber. The *Yongala* had a raised poop, central citadel, winch and forecastle decks. The stern had an elliptical shape and internally there were four bulkheads. The hull construction was clincher built with riveted steel plates, and its overall dimensions were 363 feet long, its extreme breadth 45 feet 3 inches and the moulded depth 26 feet 9 inches. The draught of the vessel was 24 feet 3¾ inches, and it had a storage capacity of 8,139 cubic feet. Its physical size alone means that the wreck is significant in the national context of historic iron shipwrecks. A measure of the popularity of the wreck is that it received an average of 7,774 visitors per year between 2002 and 2005 (GBRMPA 2005). Between 1981 and 2001 the shipwreck suffered from its then growing popularity as one of the 'world's top 10 dive sites' from a combination of divers and, more particularly, anchor damage from charter boats removing the protective concretions. The Museum of Tropical Queensland (MTQ) developed a management and conservation plan for the site which proposed prohibiting vessels from anchoring near or tying off on the wreck site via the installation of a set of moorings to facilitate diving tourism (Moran 2001). The moorings were established in 2002 and charter vessels were subsequently prohibited from tying off to the wreck or anchoring within the declared inner 500m portion of the protected zone (Viduka 2006a). The *Yongala* site is adjacent to a major shipping channel with shipping traffic passing on

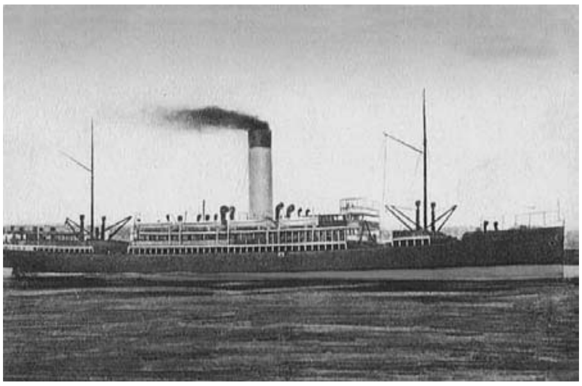

Figure 1a (above left). Illustration of the 'Yongala' during service, AD Edwards, State Library of South Australia.
Figure 1b (above right). A model by John Riley based on a site visit in 2004.

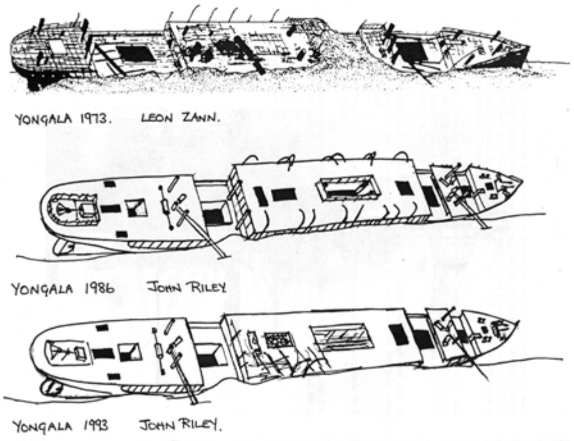

Figure 2. Isometric projections of the 'Yongala' showing progressive deterioration of superstructure and sand coverage-scouring episodes.

both the east and west of the site and it is clearly marked on all nautical charts as an historic shipwreck (Viduka 2006b). Since pre-disturbance chemical, biological and electrochemical surveys are one of the most useful ways of assessing the full potential of a wreck site to provide information on the nature of the processes involved in site deterioration, it was decided to complete a detailed examination of the site (MacLeod North & Beegle 1986). Results from such surveys describe not only the nature of the site but also the way in which the forces of decay have worked to bring about the present distribution of the archaeological deposit. This work reports the results of the first in situ corrosion survey of the SS *Yongala*.

Local environment conditions

The seafloor surrounding the wreck is open and sandy. A large current gyre occurs in the area and the wreck is subjected to characteristic 2-knot flows throughout the year running along the length of the vessel (Malcolm et al. 1999). Wave action at depth from the 25–30 knot trade winds is significant and the odd gale force winds produce destructive swells that last for several days (Gould 2001). Periodic cyclonic activity has left its mark on the wreck; when tropical cyclone Aivu crossed the site in 1989 it dislodged the memorial plinth that had been cemented to the bow and scoured a large area of the wreck. In 2006, Cyclone Larry caused loss of concretion on the stern revealing new holes in the remaining deck 'plate' (Crocombe and Batrick 2007). The wreck currently sits intact on the seabed, listing to starboard on an angle of 60°–70° with the bow pointing in a northerly direction (Riley 1993) as indicated in the model of the wreck shown in Figure 1b. The upper sections of the wreck lie approximately 16m below the surface. Strong currents scour the area periodically exposing or covering parts of the starboard side gunwale and decking.

Severe scouring of the site can at times lead to major sections of the vessel being unsupported which places it under considerable mechanical stress, for although corrosion will have thinned the metal, the resulting matrix of remaining hull and associated concretions will be significantly heavier than the original design ever envisaged, and the reduced metal thickness becomes increasingly unable to sustain the increased stress loads (MacLeod & Romanet 1999). Once the combined effects of corrosion and concretion formation render the component elements unable to be sustained, parts of the wreck break away. Scouring events, such as those of May 2007, result in parts of the vessel losing support from the surrounding sediment (e.g. the starboard side gunwale was predominantly exposed in areas outside the citadel or mid-ships during this scour event). The progressive degradation of the site has been mapped through a series of isometric sketches in 1973, 1986 and finally in 1993 (Figure 2). A significant amount of deck plate has corroded away and it is possible to swim the length of the vessel with views inside, as reported by Cropp in 1976 (Cropp 1980). The scouring had also fully exposed areas under the bow and stern and

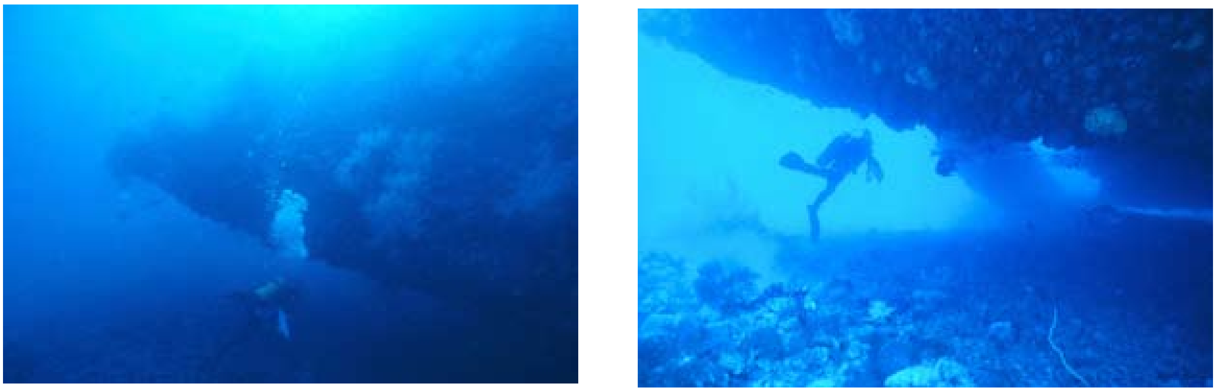

Figure 3. Images of 'Yongala' showing major scouring events had taken place prior to a 2001 site visit. Photos: Bill Jeffery.

at times, nearly the entire forecastle deck of the vessel was suspended above the seafloor as evidenced through Bill Jeffery's photographs taken in 2001 (Figure 3). The removal of the bronze propeller by a salvage company in the 1970s removed a large weight from the stern end of the vessel and removed the detrimental effects of galvanic and proximity corrosion (North 1989).

After 1981 site management practices were improved with penetration diving being banned (Gesner 1992, Moran 2001). Penetration diving led to an accumulation of expired air at the underside of concreted plates and frames which exacerbated localised corrosion. Diver activity inside the hull also caused mechanical damage and losses to concretions which were normally protected from scouring episodes by the completeness of the hull (Viduka 2008). Following the introduction of the moorings in 2002, the primary significant negative cultural activity of anchoring or tying up to the vessel was stopped. Permits issued to charter operators to access the site were directly linked to their monitoring diver behaviour and carrying out appropriate pre-dive briefs. Linking the sites preservation and the commercial interests of charter operators has significantly decreased negative cultural activity from divers (Viduka 2007b, 2008).

Site temperatures show a seasonal range between 23°C–26°C while data from the Hydrolab Datasonde conductivity measurements gave a salinity of 36.1‰, a pH of 8.02 and a temperature of 24.3°C; the dissolved oxygen was 6.59 ppm which shows the site is well oxygenated (Janz and Singer 1975). The depth profile of the wreck is between 16–27m and Figure 4 shows the false colour of the varying depth of the elements of the wreck at which corrosion measurements were made. Most of the data was recorded in the pink-red-orange zone of the side scan sonar image at an average depth of 20.0m ± 3.7m.

Corrosion measurements on concreted marine iron

In warm tropical waters, corroding iron and steel in seawater rapidly becomes encapsulated by encrusting organisms such as coralline algae and bryozoans (North 1976). This encapsulation begins the process of separating the anodic and cathodic sites of the corrosion cell, with oxygen reduction generally occurring on the outer surface and oxidation of the metal occurring underneath the marine growth (MacLeod 1989a). Under such conditions the anodic, or oxidation, reaction is not the rate-determining step in the overall corrosion process; the controlling factor is the rate of reduction of the dissolved oxygen. The variations in seawater temperature and salinity determine the maximum amount of dissolved oxygen while biological consumption and the flux of water moving across the concreted surface determine the corrosion rate since cathodic reduction of oxygen is generally found to be the rate determining step in the overall corrosion mechanism. The corrosion processes result in the inward diffusion of chloride ions from the sea, through the marine growth to the corroding metal, and the outward diffusion of the metal ions towards the sea surface. Hydrogen ions are produced by the hydrolysis of the corrosion products.

For metal that is totally buried in the sediment and is not electrically connected to iron that is exposed to oxygenated waters, the major cathodic reaction will be the reduction of water and the associated evolution of hydrogen. Under such circumstances, the corrosion process is often dominated by microbiological activity (Fischer 1983) since the presence of dehydrogenase enzymes will often control the rate of hydrogen evolution (Sequeira 1988). After nearly 90 years of corrosion in the warm tropical waters of the Great Barrier Reef, the net effect of the concretion acting as a semi-permeable membrane results in a substantially different microenvironment being established around the metal itself compared with the surrounding sea. Chloride concentrations can be three times that of the surrounding seawater and the pH can fall from 8.2 to 4.2 (MacLeod 1986). Removal of the protective concretion layer provides direct access for the dissolved oxygen to the chloride-rich corroded and acidic metal surface, which will normally lead to the loss of archaeological values (MacLeod 1981, 1987). Reports from dive boat operators had noted that there had been spontaneous deconcretion episodes on the *Yongala* site after very heavy storms and this will exacerbate corrosion on the shipwreck.

Experimental

Corroding pieces of iron on shipwrecks have characteristic potentials that are a mixed voltage because of the combination of the oxidation (metal dissolution) and oxygen reduction reactions that characterize the overall corrosion process. For fully buried iron objects the corrosion potential (E_{corr}) is the mixed potential of the oxidation of metal and reduction of water, which is the cathodic process. For iron objects lying proud of the seabed, the voltage for concreted iron is controlled by the rate of reduction of dissolved oxygen at the concretion/seawater interface. The acidity of the underlying corrosion interface is measured by gently and quickly inserting a flat surface pH electrode into the space created by drilling through the marine growth, using a compressed air-driven drill and a masonry bit, then recording the minimum value prior to the influx of alkaline seawater. A standard high-impedance digital pH meter housed in a waterproof box is connected to the electrode. Corrosion potentials are measured by reading the voltage recorded by a digital voltmeter housed in its waterproof case. The measured voltage refers to the difference in electrical potential of a reference electrode, such as a silver chloride electrode in the seawater, and a platinum working electrode. Platinum is used because it is electrochemically inert and therefore the measured voltages refer to the object itself and are not part of the nature of the experimental apparatus. Placing the platinum electrode into the hole with the reference electrode adjacent to the point of measurement and recording the voltage measures the corrosion potential at that location. Correct determination of the corrosion potential is indicated by steady voltage, i.e. a reading that varies by only 1 to 2mV over several minutes.

After decades of immersion, metals are corroding at a quasi-equilibrium state and the data represent a steady long-term rate of decay. Thus determination of corrosion potentials prior to any site disturbance provides a unique insight into the nature of the processes controlling the decay of the wreck. All voltages in this report, unless otherwise stated, are relative to the silver/silver chloride $Ag/AgCl_{sea}$ reference electrode. The silver chloride electrode was calibrated against a standard hydrogen electrode by using a secondary standard of a saturated solution of quinhydrone in a pH 4.0 buffer solution. The minimal impact of such measurements on the integrity of an archaeological site is supported by the observation that repeated measurements on the boiler of the SS *Xantho* (1872) in coastal Western Australia have shown that there has not been any measurable impact on the overall corrosion process (MacLeod 1992).

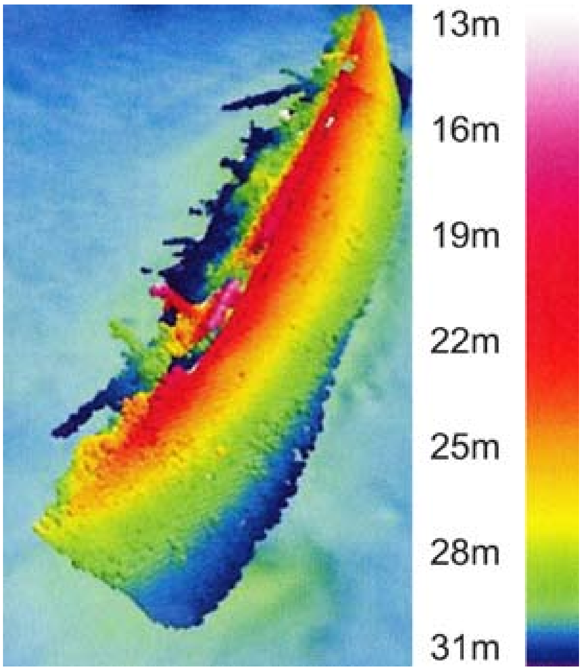

Figure 4. Multibeam bathymetry image of the wreck site showing main structural elements at depth (Courtesy of Thomas Stieglitz, James Cook University).

By drilling through corroded cast iron with a small diameter steel drill bit, it is possible to obtain a direct measure of the depth of corrosion or graphitization of the partially deconcreted cast iron object. Owing to the low carbon content of steel and the absence of major amounts of graphite and the iron carbide cementite, Fe_3C, it is normally not possible to obtain a non-destructive measure of the long-term corrosion rate on steel. Both in situ and laboratory measurements have shown that the E_{corr} value is directly related to the logarithm of the annualized corrosion rate of iron (MacLeod 1989b). In order to obtain these data in situ it is necessary to remove a small section of the marine growth to expose the original degraded surface. The annualized corrosion rate dg (mm/year) is obtained by dividing the depth of graphitization (d, mm) by the number of years since the ship was wrecked, which in the case of the *Yongala* is 95 years.

Results and discussions

A series of measurements were conducted on the remains of the SS *Yongala* in February 2005 which acted as a baseline. Repeated visits in January, May and July 2007 were used to assess if any changes were occurring. In analysing the data from the wreck it is important to

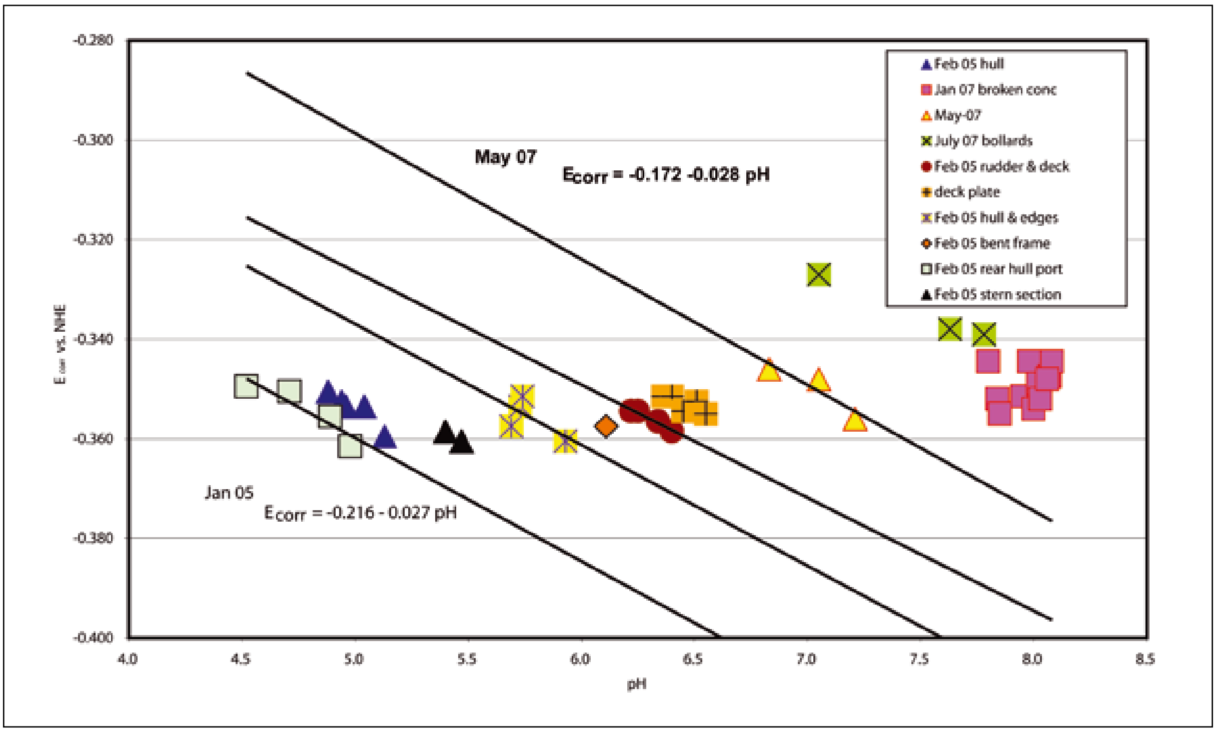

Figure 5. Plots of the E_{corr} and pH data showing different corrosion microenviornments

understand that the composition of the steel can also bear significantly upon the overall corrosion process. The amount of carbon and phosphorus in the matrix have subtle effects on the supply of micronutrients which manifest themselves in thicker concretions (MacLeod 1988). Plots of the E_{corr} and the pH of the corroding elements of the wreck can provide direct insight into the corrosion mechanism if the vessel is in a state of quasi-equilibrium. Pourbaix used plots of Eh vs. pH to characterise the corrosion behaviour of all metals and published the summary of years of work in his seminal book (Pourbaix 1974).

Plots of the corrosion potential, measured against the $Ag/AgCl_{sea}$, but standardised against the Normal Hydrogen Electrode (NHE), show that the measurements fall into a series of parallel lines, as shown in Figure 5. The same slopes indicate a common corrosion mechanism. When parts of the site have the same voltage but different pH values, the more alkaline pH points generally reflect a lower corrosion rate. The pre-disturbance data shows that the most acidic points are located at the rudder post and hull plates just aft of the citadel due to localised turbulence despite the protective concretion cover (MacLeod et al. 2007). Thus the sheltered horizontal deck plates had a mean pH of 6.43±0.07 while the hull plates had a mean pH of 4.99±0.10 due to differences in the flow of oxygenated seawater over the concreted surface. All the in situ data from the 2005 and the 2007 surveys had the common slope of slope of –0.026 ±0.003 which is consistent with the corrosion mechanism on historic iron shipwrecks over 70 years of age shown in equation 1. The acidity of the metal-concretion interface is due to the hydrolysis of ferrous chloride which produces a mixed iron (II) hydroxychloride species, which is represented in equation 1:

$$2\,Fe + 2Cl^- + 2\,H_2O \rightarrow \{Fe(OH)_2Fe(Cl)_2\} + 2H^+ + 4\,e^- \quad (1)$$

The E_h and pH data from 2007 have generally less negative voltages and lower pH which shows the site is corroding at an increased rate. Substantial concretion losses occurred when storms on 26th March 2006 from Cyclone Larry tore off the protective marine growth at the bow and other locations. The impact of the cyclone damage is equivalent to a 37% increased corrosion rate as seen in the 44 mV separation of the intercept values for the E_{corr} and pH data shown in Figure 5. The cyclone also caused premature failure of a dive boat mooring buoy and dive operators in April 2007 reported losses to the metal hull and deck plate (Crocombe & Batrick 2007).

The alkaline pH data obtained in May 2007, after Cyclone Larry, is an artefact of insufficient concretion cover to allow for an acidic microenvironment to build up that is commensurate with the underlying corrosion rate (MacLeod et al. 2007). The cast iron bollards are 21±2 mV more anodic than steel plates at the same pH, and this is due to the high carbon content which moves the corrosion potential in a more noble direction (MacLeod 1989a). It is possible that cracks in the protective concretion layer allowing penetration

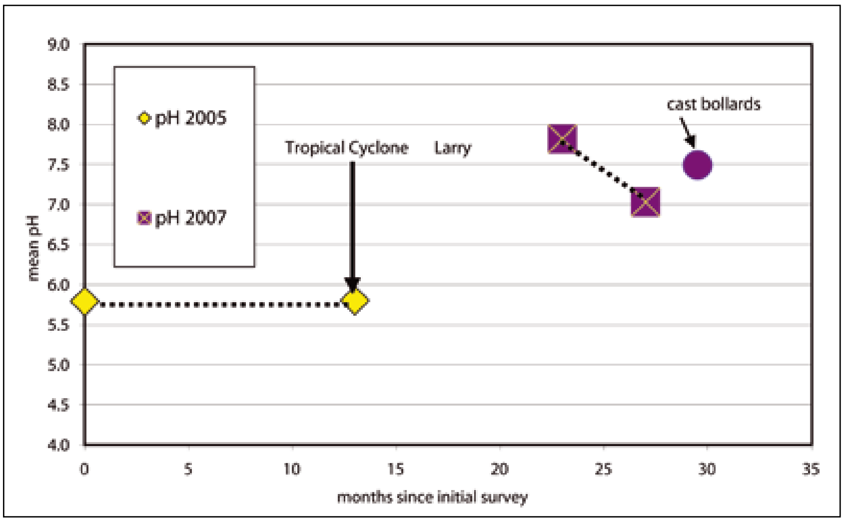

Figure 6. Plot of mean pH of steel plate and cast iron before and after Cyclone Larry in 2006.

of the alkaline seawater are the reason why the January 2007 data has very alkaline pH values. The trend in pH values can be seen in Figure 6, which shows that the cyclonic concretion damage was responsible for the initial alkalinisation of the pH but renewed colonisation by marine organisms saw the underlying acidity increase as the system moved back towards its previous dynamic equilibrium.

At the initial rate of recovery it is estimated that the site will take 20±4 months to recover from the cyclonic damage which is consistent with iron shipwrecks in Chuuk Lagoon recovering from damage to concretion from dynamite fishing (MacLeod and Richards 2010).

Effects of depth and concretion formation on surface pH

The acidity or pH of the microenvironment under the concretion is a useful guide to the local corrosion rate, since the pH is controlled by the dynamic equilibrium between the concentration of the Fe^{2+} ions and their hydrolysis products (MacLeod 1995, 1998 2002). Comparison of how the pH changes with depth on the wrecks provides a useful guide to the nature of the corrosion processes affecting the site and is summarised in Figure 7.

The main feature of the pH vs. depth data (Figure 7) is that much of it falls along parallel lines which show the same depth dependence and hence they have a similar local corrosion microenvironment. Eight data sets gave a mean slope of $+ 0.40 \pm 0.02$ $pH.m^{-1}$ which is the same as the *Gosei Maru* and the *Hino Maru* in Chuuk Lagoon in the Federated States of Micronesia. Since the pH is a logarithmic function of the hydrogen ion concentration which is directly linked to the concentration of $Fe^{(II)}$, it follows that the logarithm of the corrosion rate decreases linearly with depth (MacLeod 2006). As previously noted cyclonic damage to the wreck site means that pH data near the bow and along the port side of the citadel are not reflective of the underlying corrosion rate. The well scoured stern had the highest acidity because its concretion had not been damaged by the cyclone whereas the bow and the citadel areas had been significantly affected. The entire near vertical hull plates and sections of the bridge have pH values 1.6 more alkaline than other nearby structural elements which means they have a noticeably lower corrosion rate. High profile areas such as the funnel opening in the raised central citadel, the starboard side of the citadel structure and the promenade deck have higher corrosion rates because of the greater profile they present to the movement of the sea water.

Effect of water depth on corrosion potentials

The E_{corr} data was plotted against both the as recorded values from the $Ag/AgCl_{sea}$ reference electrodes and also against the Normal Hydrogen Electrode and the results are essentially the same in that the voltages became increasingly negative with increasing depth. The greater sensitivity of the E_{corr} values to water depth on the *Yongala* of -4.2 ± 0.2 mV per metre compared with -2.2 ± 0.2 $mV.m^{-1}$ for the Japanese wrecks in Chuuk Lagoon is likely due to the more exposed nature of the site in the open ocean waters. (MacLeod 2006). The most corrosive areas of the wreck were located at the bow at the port bollard, low down on the stem and also at the port side of the hull at the bow and also at the stern the voltages were also high at the counter stern and around the rudder (see Figure 8).

The most and least corrosive areas of the wreck are separated by a difference of 35 mV or 29% different corrosion rates at the same depth between the lower hull plates and the high profile areas in and around the stern. It is likely that one of the reasons why the vessel has remained intact is because of the massive amount of marine concretion covering the wreck which provides mechanical strength to overcome the weakness of the metal that has been lost through 92 years of corrosion.

Data from temperate open ocean shipwreck sites showed that the corrosion rate, as measured by the depth of graphitisation, was logarithmically dependent on the water depth (MacLeod 2006), as shown in equation 2:

$$^{Open-ocean}\log d_g = -0.630 - 0.0156\,d \quad (2)$$

Using a mean depth of the *Yongala* measurement

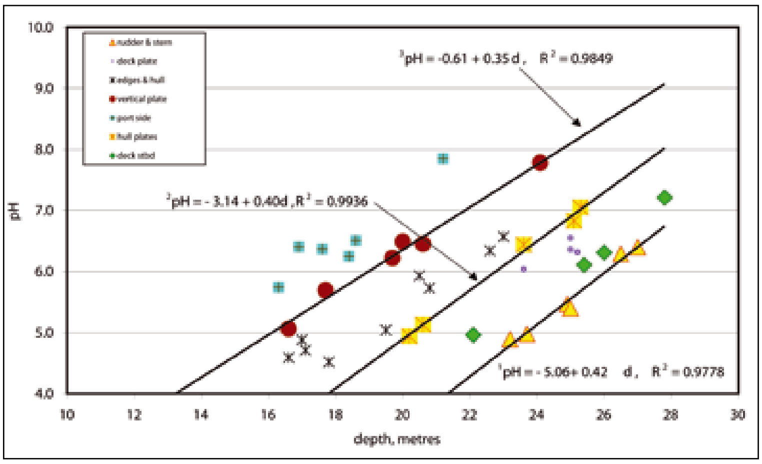

Figure 7. Plot of pH as a function of depth, location and aspect.

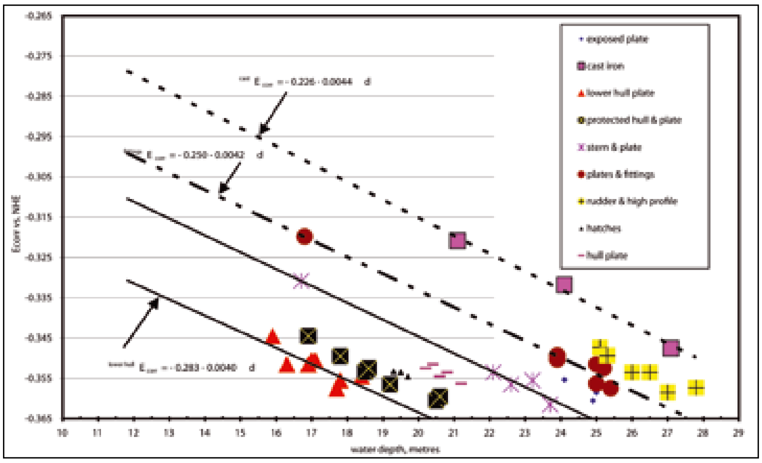

Figure 8. Plot of E_{corr} vs. depth for the 'Yongala' site over all seasons.

points of 21.0 ± 3.6 metres in the equation, the calculated rate is 0.110 ± 0.015 $mm.yr^{-1}$ equates to 10.8 mm metal loss during the time of immersion in the waters of the Great Barrier Reef Marine Park. This metal thickness is greater than the original thickness of the deck plates, which explains the holes in the structure and why many of the measurement points had insufficient metal in them to provide a real E_{corr} value and were reported as redox potentials. As has been previously observed on corroded cast iron cannon from a number of wreck sites (Carpenter and MacLeod 1993) there is a fine balance of corrosion rates increasing as a result of the strong currents creating a greater flux of dissolved oxygen in warmer water temperature which is balanced out by the increasingly protective nature of the massive amount of marine concretion growing on the wreck in warm and well-oxygenated seawater.

Five of the corrosion measurement points gave E_{corr} values that were 400 mV more anodic than nearby sites which indicates that the voltages are not true corrosion potentials but that they are redox voltages of corrosion cells where most of the iron has corroded away (Heldtberg MacLeod & Richards 2004, MacLeod 2009). Pourbaix plots of these data points showed that the slope of – 0.024 volts per pH is consistent (MacLeod 2006) with the commonly observed equation 1.

Apart from there being not enough solid metal at these test points to provide a standard E_{corr} measurement there were three other sites where the drill bit totally penetrated the concreted matrix. These locations were on the port side garboard strake at the intersection hull and decking, decking amidships aft of the citadel, and on the port gunwale opposite the other holes. Of the 56 measurement points, five gave data that reflected redox couples and in three areas the drill bit penetrated through both side of the concretion so $^1/_7$ or 14% of the *Yongala* sites were totally corroded. Technical difficulties prevented the development of a site specific corrosion equation for the *Yongala* since only two bollards gave a reasonable depth of graphitisation. The 19mm of corrosion on the cast iron port bollard at the bow gives a local corrosion rate of 0.198 $mm.yr^{-1}$, compared with the predicted rate of 0.128 $mm.yr^{-1}$ which is consistent with a very high local corrosion rate around the bow, owing to the scouring of this section of the wreck which has left it free standing. The scour is responsible for the 55% increased corrosion rate over and above the predicted level of decay. The starboard bollard at the stern had 10 mm of graphitisation which gives a local corrosion rate of 0.104 $mm.yr^{-1}$ which is very close to the predicted rate of 0.099 $mm.yr^{-1}$for the 24.1m depth using equation 2.

Interpretation of the E_{corr} values into actual corrosion rates is facilitated by use of site specific corrosion equations (MacLeod 1996, 2002) which enables calculations of the corrosion rate directly from the potentials recorded on site. From the recorded values of temperature and salinity on the *Yongala* site the amount of dissolved oxygen on the site can be calculated and the slope of the corrosion equation calculated according to the relationship (MacLeod 1995)

$$\partial \log_{dg} / \partial E_{corr} = 10.33 \log [O_2] - 4.57 \quad (3)$$

which gives a slope of 2.45 which is similar to that of the wreck of the *Lively* (1820), located on the edge of a continental atoll more than 400 km off Broome, which had an empirical slope of 2.82 and a mean annual water temperature of 29°C. The local corrosion equation for the *Yongala* is

$$\log_{dg} = 2.45\ E_{corr} + 0.479 \quad (4)$$

which is based on the corrosion rate of the stern starboard bollard. Use of equation 4 enables the range of corrosion rates to be calculated directly from the E_{corr} readings, thus the most corrosive area of the wreck is at the bow in 16.9m where the corrosion rate is 0.119 $mm.yr^{-1}$ whilst the least corrosive is 0.095 $mm.yr^{-1}$ at the rudder post at a depth of 23.7m. The calculated corrosion rates based on the measured E_{corr} values varies by 18.4%. This result is exactly the same as the calculated corrosion rate based on the mean water depth as being 0.110± 0.015 $mm.yr^{-1}$ which is based solely on long term corrosion rates based on a large number of cast iron graphitisation measurements on at least 20 wreck sites.

Conclusion

Analysis of the corrosion data collected over several seasons on the Yongala wreck site has demonstrated that it is possible to obtain a good insight into the present and past rates of deterioration from a combination of historical corrosion rates deduced from graphitised cast iron and the present corrosion cells. The data also points to the value of conducting a series of measurements on the same wreck to assess site stability.

Owing to the complexity of the remnant structure of the wreck the E_{corr} values often relate to localised corrosion cells but the in-situ pH data gives a useful guide to the prevailing corrosion rate at that point of measurement. The wreck site is subject to periodic spontaneous deconcretion events and the long term corrosion rate at the bow, as indicated by the 19 mm depth of graphitisation of the port bollard, is 67% greater than the present corrosion rate of 0.119 $mm.yr^{-1}$ which shows that the vessel when last measured was in a more benign corrosion microenvironment than its long term history indicates. It is likely that the main causes for this include below average conditions at the bow when the measurements were recorded, previous episodes of boat and diver damage which would have caused increases in corrosion rate through loss of concretion and from storm or cyclonic activity. The in-situ measurements have shown that the combination of pH and E_{corr} measurements provide a very sensitive tools that enable the present state of the wreck to be determined.

Postscript

The devastating impact of Cyclone Yasi on the Queensland coastal communities and hinterland in February 2011 has been well-documented in the local media and has earned its own place in the archives of the Bureau of Meteorology. Although the cyclone struck the land 300–400 km north of the wreck its impact was enough to dramatically alter the Yongala shipwreck which now leans over at 70°–80° from the vertical, compared with 60°–70° before the cyclonic winds and wave action wrought their havoc 27m down to the ocean bed. As predicted from the in situ corrosion survey, the bow area had been suffering from significant corrosion and it has now collapsed and dropped several metres to rest on the seabed. Artefacts have spilled out from the bow end of the shipweck through tears in the previously complete hull plating. The concreted hull plates have collapsed, distorted and folded in sections and this has opened up the interior of the wreck to direct action of the prevailing currents. Without direct intervention and active site management the wreck will now undergo a relatively dramatic change in its physical form as elements begin to become disconnected and move across the site. There has been massive exfoliation of the protective concretion and this will also exacerbate the corrosion of the vessel in its 100th anniversary year.

Biographies

Dr Ian MacLeod is a corrosion chemist and materials conservator who has worked for the Western Australian Museum for the past 30 years. He pioneered the use of in situ corrosion measurements on historic shipwrecks, with particular emphasis on the use of sacrificial anodes to preserve materials on the seabed. He has studied the microstructure of metals covering a wide range of ferrous and non-ferrous alloys and has learned how changes in the formulation of alloys and the work history of the objects predisposes them to particular patterns of decay.

Andrew Viduka is a qualified conservator and maritime archaeologist. Among other positions both in Australia and abroad, he worked at the Museum of Tropical Queensland in Townsville where he treated artefacts from historic shipwrecks in Queensland's north. He is presently the Assistant Director Maritime Heritage in the Australian Government Department of Sustainability, Environment, Water, Population and Communities.

References

Carpenter, J and MacLeod, ID 1993, 'Conservation of corroded iron cannon and the influence of degradation on treatment times', *ICOM-Committee for Conservation, Preprints 10th Triennial Conference*, Washington, vol. 2, pp. 759–66.

Crocombe, P, and Batrick, H 2007, *Yongala* charter boat operators, personal communication.

Cropp, B 1980, *This rugged coast—adventures around Australia's coastline,* Rigby Publishers Limited, Australia, pp. 57–9.

Fischer, KP 1983, *Microbial Corrosion,* Metals Society, London pp. 1–110.

Gesner, P 1992,'SS *Yongala* (1903–1911) Draft Management Plan', unpublished report, Queensland Museum, Brisbane, Australia.

Gould, P 2001, Townsville Metrological Office, personal communication.

Great Barrier Reef Marine Park Authority—Environment Management Charge data for *Yongala* 2002–2005.

Heldtberg, M, MacLeod, ID and Richards VL 2004, 'Corrosion and cathodic protection of iron in seawater: a case study of the James Matthews (1841)', J Ashton and D Hallam (eds), *Metal 2004: Proceedings of the International Conference on Metals Conservation,* Canberra, October 2004. National Museum of Australia, pp. 75–87.

Janz, GJ and Singer, SK 1975,'Copenhagen Standard Sea Water; conductivity and salinity', *Journal of Solution Chemistry,* vol. 4, no. 12, pp. 995–1003.

MacLeod, ID, North, NA and Beegle, CJ 1986,'The excavation, analysis and conservation of shipwreck sites', *Preventative measures during excavation and site protection,* ICCROM, Rome, pp. 113–32

MacLeod, ID, and Romanet, A-S, 1999 'Effects of pH and stress on the corrosion of copper and its alloys in seawater' Preprints of the ICOM-CC 12th Triennial Meeting, Lyon, September 1999. James & James, London, pp 828–33

MacLeod, ID, 1981 'Shipwrecks and applied electrochemistry', *Journal of Electroanalytical Chemistry,* vol. 118, 291–304.

MacLeod, ID, 1986 'Conservation of the steam ship Xantho', *ICCM Bulletin,* vol. 12, nos 3–4, pp. 66–94.

MacLeod, ID 1987,'Conservation of corroded iron artefacts -new methods for on-site preservation and cryogenic deconcreting', *International Journal of Nautical Archaeology,* vol. 16, no. 1, pp. 49–56.

MacLeod, ID 1988,'Conservation of corroded concreted iron', *Proceedings of Conference 28, Australasian Corrosion Association,* Perth 1, 2–6, pp. 1–9

MacLeod, ID 1989a 'The electrochemistry and conservation of iron in sea water', *Chemistry in Australia,* vol. 56, pp. 227–9.

MacLeod, ID 1989b 'The application of corrosion science to the management of maritime archaeological sites', *Bulletin of the Australian Institute of Maritime Archaeology,* vol. 13, no. 2. pp. 7–16.

MacLeod, ID 1992,'Conservation management of Iron Steamships—The SS Xantho (1872)', *Multi-Disciplinary Engineering Transactions GE* No. 1, pp. 45–51.

MacLeod, ID 1995,'In-situ corrosion studies on the Duart Point wreck 1994', *International Journal of Nautical Archaeology,* vol. 24, pp. 53–9.

MacLeod, ID 1996,'An in-situ study of the corroded hull of HMVS Cerberus (1926)', *Proceedings of the 13th International Corrosion Congress,* vol. 25, pp 1–10.

MacLeod, ID 1998,'In-situ corrosion studies on iron shipwrecks and cannon: the impact of water depth and archaeological activities on corrosion rates', W Mourey and L Robbiola (eds), *Metal 98: Proceedings of the ICOM-CC Metals Working Group Conference,* Draguignan-Faginère France, James & James, London, pp 116–24.

MacLeod, ID 2002,'Conservation of the iron shipwreck *City of Launceston* (1865) and modelling its decay', *Preprints for ICOM-CC Triennial Meeting,* Rio de Janeiro, Brazil, September, vol. 2, pp. 871–7.

MacLeod, ID 2006,'Corrosion and conservation management of iron shipwrecks in Chuuk Lagoon', *Conservation and Management of Archaeological Sites,* vol. 7, pp. 203–23.

MacLeod, ID, Beger, M, Richards, V, Jeffery, B, and Hengeveld, M 2007,'Dynamic interactions of marine ecosystems with wrecks in Chuuk Lagoon, Federated States of Micronesia', *Metal 07, Preprints of the ICOM-CC Metals Working Group* meeting, Amsterdam, C Degrigny, B Ankersmit, I Yolanda and R van Langh (eds), vol. 3, pp. 51–54.

MacLeod, ID 2008,'Shipwreck graves and their conservation management', *AICCM Bulletin,* vol. 31, pp. 5–14.

MacLeod, ID 2009,'Dynamic interaction of an historic iron shipwreck with the marine environment: a 16-year study of the of City of Launceston (1865) in Port Phillip Bay', *Australasian Institute for Maritime Archaeology.*

MacLeod, ID, Morrison, P, Richards, V and West, N (2004), 'Corrosion monitoring and the environmental impact of decommissioned naval vessels as artificial reefs', *Metal 2004: Proceedings of the International Conference on Metals Conservation,* Canberra, October 2004, J Ashton, D Hallam (eds), National Museum of Australia, pp 53–74.

MacLeod, ID, Beger, M, Richards, V, Jeffery, B, and Hengeveld, M 2007,'Dynamic interactions of marine ecosystems with wrecks in Chuuk Lagoon, Federated States of Micronesia', *Metal 07: Preprints of the ICOM-CC Metals Working Group* meeting, Amsterdam, C Degrigny, B Ankersmit, I Yolanda and R van Langh (eds), vol. 3, pp. 51–4.

Malcolm, H, Cheal, AJ and Thompson, AA 1999,'Fishes of the *Yongala* Historic Shipwreck', CRC Reef Research Technical Report No. 26.

Moran, V 2001,'SS *Yongala* (1903–1911): A Conservation and Management Plan December 2001', Unpublished Report, Museum of Tropical Queensland, Townsville, Australia.

North, NA 1976,'The formation of coral concretions on marine iron', *International Journal of Underwater Archaeology and Underwater Exploration,* vol. 5, pp. 253–8.

North, NA 1989,'Proximity corrosion in seawater', *Corrosion Australasia,* vol. 14, no. 5, pp. 8–11.

Pourbaix, M 1974,'Atlas of electrochemical equilibria in aqueous solutions', 2nd edn, NACE, Houston.

Riley, J 1993 'SS *Yongala* site inspection 5 December 1993', Queensland Museum internal report, Museum of Tropical Queensland.

Riley, JP & Skirrow, G (eds) 1975, *Chemical Oceanography,* vol.

1, 2nd edn, Academic Press, London.

Sequeira, CAC and Tiller, AK (eds) 1988, 'Microbial Corrosion—1', *Proceedings of the First European Federation of Corrosion Workshop on Microbial Corrosion*, Elsevier Applied Science, London and New York.

Viduka, A 2006a, 'IDM, DAPS, Pickups and Risers—*Yongala* moorings site management', *Iron Steel and Steam: A progressive seminar on developments 'down under'*, 23 June–1 July 2007, Fremantle, Melbourne and Sydney, Michael McCarthy (ed.).

Viduka, A 2006b, 'Managing threats to underwater cultural heritage sites—The *Yongala* as a case study', *Underwater cultural heritage at risk: managing natural and human impacts*, R Grenier, D Nutley and I Cochran (eds), ICOMOS, pp. 61–3.

Viduka, A 2007a, SS *Yongala* (1911) Corrosion Survey and Condition Assessment, Latitude 190 18.268 S Longitude 1470 37.337 E, Site Number 508, Report for Department of Environment and Heritage Commonwealth Historic Shipwrecks Program, Queensland Historic Shipwrecks Officer, 27 June.

Viduka, A 2007b, 'Managing underwater cultural heritage: A case study of SS *Yongala*', *Extreme heritage: managing heritage in the face of climatic extremes, natural disasters and military conflicts in tropical, desert, polar and off-world landscapes*, 2007 Australian ICOMOS National Conference, Cairns, Queensland, 19–21 July, <http://www.aicomos.com.files/viduka*Yongala*.pdf>.

Viduka, A 2008, 'SS *Yongala*—a vested interest commercial utilisation model of public access site management', unpublished thesis for Masters of maritime archaeology, Flinders University.