In situ conservation surveys of iron shipwrecks in Chuuk Lagoon and the impact of human intervention

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Abstract
Regular site inspections are an integral part of the overall management strategy for a submerged site. The primary focus of an on-site corrosion survey is to collect as much pertinent information as possible to assist in ascertaining the extent of deterioration and structural integrity of a site. Further inspections are then required at regular intervals so any changes in the integrity of the site are noted by direct comparison with earlier surveys. The more surveys carried out, the better, as they will provide more information regarding the rate of deterioration and the inherent stability of a site, which will assist in recognising which sites are a priority for future implementation of appropriate in-situ conservation management strategies. Hence, as an example, over a five-year period, a series of in situ conservation surveys were performed on a selected number of World War II Japanese wrecks located in Chuuk (Truk) Lagoon, in the Federated States of Micronesia. During World War II, the Japanese established their principal military naval base at Chuuk (Truk) Lagoon but in February 1944, American forces attacked the base and consequently, many of their ships were sunk and a number of aircraft were lost in the lagoon. These wreck sites have become very popular dive sites and therefore, Chuuk Lagoon has become one of the major recreational dive destinations in the world. As unsustainable fishing practices have become more prevalent in this area and with the downturn in the tourism industry due to the global economic crisis, it is very important to monitor the archaeological, biological and structural integrity of the wrecks in Chuuk Lagoon, so early intervention may prevent loss of these internationally significant underwater cultural and natural heritage sites, which are intrinsically linked to the economic future of the local Chuukese people.

Keywords: corrosion, conservation surveys, shipwrecks, World War II, Chuuk Lagoon, Federated States of Micronesia, in-situ preservation, underwater cultural heritage

Introduction

Chuuk is geographically part of the larger Caroline Islands and is situated in the south-western part of the Pacific Ocean, about 7° north of the equator and on the 152° east line of longitude. It comprises the most populous of the four states of the Federated States of Micronesia (FSM), along with Kosrae, Phonpei and Yap. Chuuk Lagoon is approximately 64km in diameter and has been formed by a barrier reef enclosing an area of 2125 km^2 (Figure 1).

During World War II, a significant portion of the Japanese fleet was based in Chuuk Lagoon. In February 1944, the United States of America commenced a major strike, code-named Operation Hailstone, on this strategic Japanese base. The sustained attacks by US Navy carrier-based aircraft obliterated the fleet and resulted in the sinking of more than 65 enemy military and armed merchant vessels including hundreds of aircraft. These submerged sites are a significant part of World War II history, and they are the only historic sites listed as a USA National Historic Landmark in Micronesia. More importantly, these shipwrecks and submerged aircraft are the main tourism attraction in Chuuk, which is, in fact, the state's only major industry. It is therefore imperative that appropriate management plans are implemented to ensure the future preservation of these underwater cultural heritage sites, which are intrinsically linked to the economic future of the local Chuukese people.

In the early 2000s, a number of concurrent projects were initiated by Dr William Jeffery to record the natural and cultural attributes of the wrecks and the integrity of these underwater archaeological sites. More importantly, the projects provided essential funding to provide the local FSM National Historic Preservation Office (HPO) staff with the appropriate resources and

Figure 1. Map of Chuuk Lagoon, Federated States of Micronesia, showing the main islands and the general location of the wrecks (Google Earth 2009).

training to continue the regular and effective documentation and monitoring of their submerged historic and cultural heritage. It is considered that the documentation of the important archaeological, biological and corrosion aspects of these sites will assist in ascertaining site values and management requirements and therefore, allow for more effective and timely implementation of sustainable mitigation strategies integral for their future preservation.

In 2002, the first systematic in situ conservation/corrosion survey was undertaken by the authors to assess the current state of deterioration of the wrecks, with financial support from the Department of the Interior, National Parks Division. Additional sites were visited during the Earthwatch Foundation funded program in 2006, 2007 and 2008, which resulted in additional wrecks and aircraft being assessed as well as repeat visits being made to those reviewed in the initial study in 2002. It is well understood that the rate of decay of historic submerged resources such as the aircraft and the iron shipwrecks is the net result of a combination of marine biological, chemical, oceanographic and meteorological processes. Since the level of complexity of the wrecks and their interactions with the local marine environment is high (e.g. the description of the sedentary epifauna and the fish life and their interactions with the historic man-made substrates), it is not possible to cover all aspects in a single paper. Thus only the results of the on-site corrosion surveys performed on a selected number of World War II Japanese wrecks will be presented and based on these results, the future preservation of the shipwreck sites discussed.

Corrosion mechanism

The degradation of metals in a marine microenvironment is controlled by a large number of factors, the major variables being water depth, the amount of dissolved oxygen in the seawater, the amount of water movement, salinity, temperature and the composition of the metal. Interwoven with these physical parameters are the marine environment and its complex interaction with the metallic substrates. Since there are only small annual variations in water temperature and salinity in Chuuk Lagoon, these factors, which dominate the amount of dissolved oxygen in the marine environment, are not major site variables. The corrosion rate of metals on shipwrecks sites is very dependent on water depth and the flux of oxygenated seawater over the objects lying proud of the seabed. In warm tropical waters, iron alloys will actively corrode, creating iron corrosion products that stimulate marine growth, and the surfaces become rapidly encapsulated by encrusting organisms such as coralline algae and bryozoans (North 1976). Consequently, the WWII iron shipwrecks in Chuuk Lagoon are generally characterised by a rich, thick and variable layer of marine biota. This interaction causes the initial corrosion rate to fall to a steady state value after the first few years of immersion in the marine environment.

The primary effect of this marine growth, or concretion, is to separate the metal from direct access to dissolved oxygen. The marine concretion separates the anodic reaction, or oxidation of the metal occurring underneath the concretion from the cathodic reaction, or oxygen reduction occurring on the outer surface of the concretion. Under these conditions the rate-determining step is not the oxidation of the metal but the rate of reduction of the dissolved oxygen at the concretion/seawater interface. The corrosion process causes the inward diffusion of chloride ions from the sea, through the semi-permeable concretion layer to the corroding metal and the outward diffusion of the metal ions towards the sea surface resulting in an increase in the concentration of chloride ions and acidity underneath this marine growth (North 1982). Typically the initial oxidation of iron in seawater leads to the formation of ferrous chloride ($FeCl_2$), which is subsequently hydrolysed to a mixed iron (II) hydroxyl chlorides (Equation 1).

$$2FeCl_2 + 2H_2O \rightarrow [Fe(OH)_2.FeCl_2] + 2H^+ + 2Cl^- \quad (1)$$

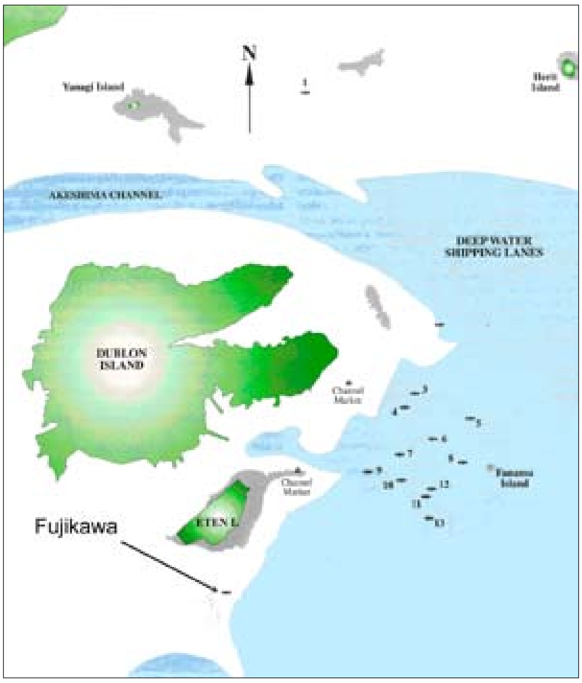
Corroding iron on shipwrecks has characteristic potentials that are a mixed voltage due to the combination of the oxidation (metal dissolution) and oxygen reduction reactions that characterise this overall corrosion process. After decades of immersion, metals are corroding at a quasi-equilibrium state 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 deterioration of the wreck. However, removal of the protective concretion layer provides direct access for the dissolved oxygen to the chloride-rich acidic corroded surface, which will normally lead to increased corrosion and ultimately, to the loss of archaeological information.

Experimental

The surface pH of the iron elements was determined by using a BDH GelPlas flat surface pH electrode connected to a Cyberscan 200 pH meter sealed inside a custom-built plexiglass waterproof housing. The corrosion potential (E_{corr}) was determined with a high impedance digital multimeter mounted in the same waterproof housing, connected to a platinum working electrode and a $Ag/AgCl_{seawater}$ reference electrode. The reference electrode was calibrated by measuring the voltage difference between a standard $Ag/AgCl_{3M\ KCl}$ electrode that had been previously calibrated using a standard saturated quinhydrone solution in a pH 4 buffer solution. For comparative purposes all voltages in this paper are reported relative to the normal hydrogen electrode (NHE).

The procedure for measuring surface pH and E_{corr} was to drill through the concretion and corrosion layers on the artefact until the residual metal surface was reached. Penetration of the concretion was effected using a 16mm masonry drill bit attached to a pneumatic drill powered from a scuba tank. Immediately after removal of the drill bit the pH electrode was inserted and held against the metal surface until the minimum pH reading was recorded. The E_{corr} was measured by establishing electrical contact between the metal and the platinum electrode that had been placed into the drill hole. The E_{corr} values were characterised by a steady voltage that varied by only one millivolt. After the corrosion parameters were measured, the total corrosion/concretion depth (d_{total}) was determined with vernier callipers. The water depth was measured with a divers depth gauge. Finally the drill holes were filled with a hand-kneadable underwater curing epoxy.

Figure 2. Location of the Fujikawa Maru (Bailey 2000).



Results and discussion

Fujikawa Maru

The *Fujikawa Maru* was built in 1938 as a passenger-cargo ship and was requisitioned by the Japanese Navy for use as an armed aircraft ferry in 1940. The vessel (159.45m length, 21.3m breadth, 9.48m depth)

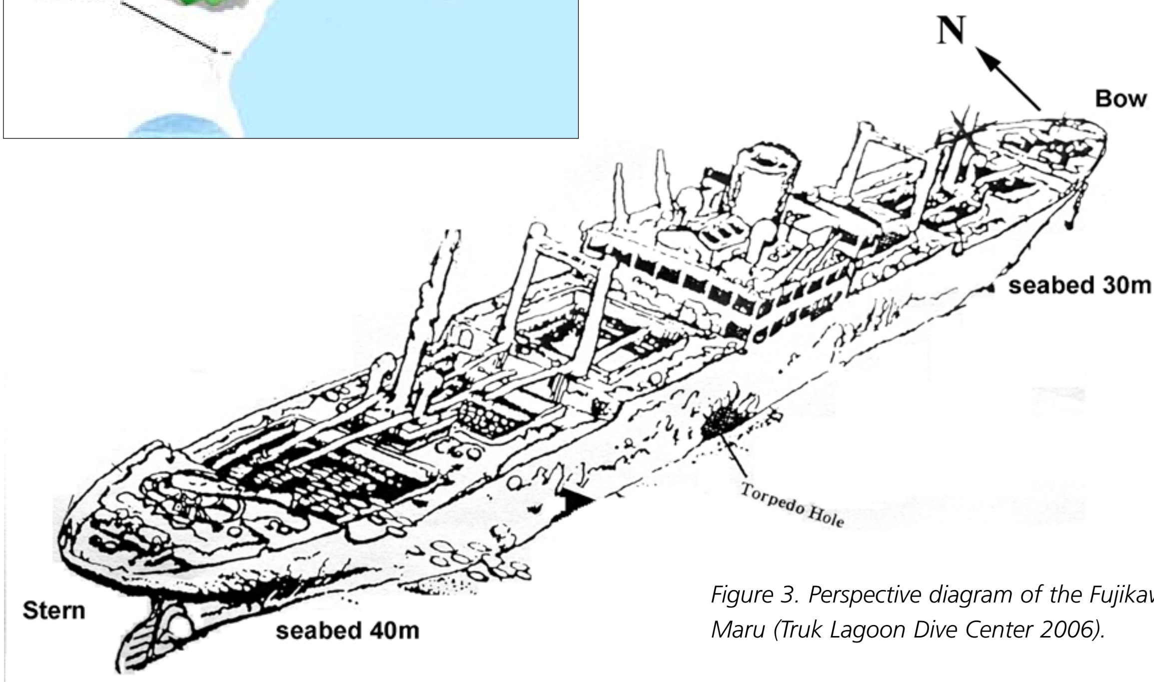


Figure 3. Perspective diagram of the Fujikawa Maru (Truk Lagoon Dive Center 2006).

is located in the channel between Fefan and Tonoas (or Dublon), south of Eten Island (Figure 2) and lies upright and proud of the seabed (Figure 3). The bow points east-south-east and the seabed slopes slightly to stern, where the depth to seabed is 40m, compared to the bow at 30m. The wreck lies in the natural channel between several islands, therefore the currents associated with the diurnal tide variations of ±0.5-1m has a relatively small impact on the extent of corrosion.

The *Fujikawa Maru* is one of the most popular dive sites in Chuuk Lagoon. This frequent visitation has taken its toll on the encrusting biota over the last 30 years, which could also have some effect on the corrosion rate. However, most importantly, the site has been systematically subjected to explosive 'dynamite' fishing practices, which has led to a series of multiple deconcretion events. The local community members use old WWII explosives collected from land sites or from the munitions on the shipwrecks to create "dynamite bombs" in order to capture the fish that live in abundance around the wreck site. Site inspections over the past six years have shown areas of the wreck denuded of concretion by these explosive events and this has resulted in the increased corrosion of this iconic vessel. There are regions of the wreck where the terraces of regrowth are clearly visible, i.e. some upper areas of the wreck have been blasted at least six times in the recent past. Under these conditions it is possible to discern systematic differences in the localised corrosion rate in the area of measurement. Since the E_{corr} data describes the electrochemical environment of the steel that is electrically connected to the measurement point, it is not as sensitive to localised corrosion processes as the value of the pH recorded at the same point. It has been shown that pH data is a useful guide to the corrosion rate, since the pH is controlled by the dynamic equilibrium between the concentration of the Fe^{2+} ions and their acidic hydrolysis products (Equation 1) and is therefore more sensitive to changes in apparent corrosion rate (MacLeod 1995, 2002). The pH data on the *Fujikawa Maru* have been analysed and the results can be viewed in terms of both the regrowth of the concretion and the sensitivity of the pH to the impact of dynamite fishing.

A plot of the metal surface pH versus water depth on the *Fujikawa Maru* (Figure 4) shows a systematic trend of increasing pH with water depth and this is simply a reflection of the fact that the rate of corrosion, as measured by the amount of acid produced from metal ion hydrolysis, is logarithmically decreasing with increasing water depth (MacLeod 2005). This graph also shows that the dynamite fishing affects the pH particularly in the shallower water range down to 15m, which covers the depth of the forward midships and bow sections of the vessel. Extensive exfoliation of the concretion has been noticed on the forward deck by the bow gun and on deck plates leading back to the bridge superstructure. The pH and depth data for the April 2002 field season has been reported previously in MacLeod (2005) but with the additional data collected over a further four seasons (July 2006, November 2006, August 2007, August 2008) it has become clear that it is possible to discern not only two types of concretion and pH relationships, but in fact there are three

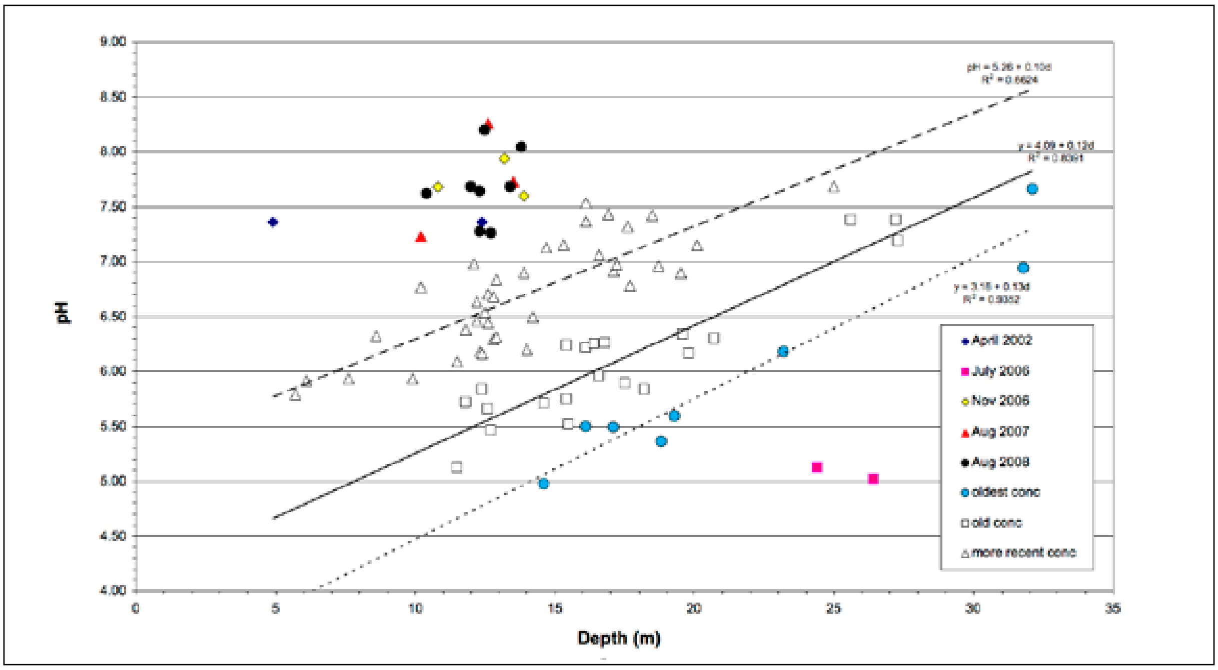


Figure 4. Plot of metal pH versus water depth on the Fujikawa Maru.

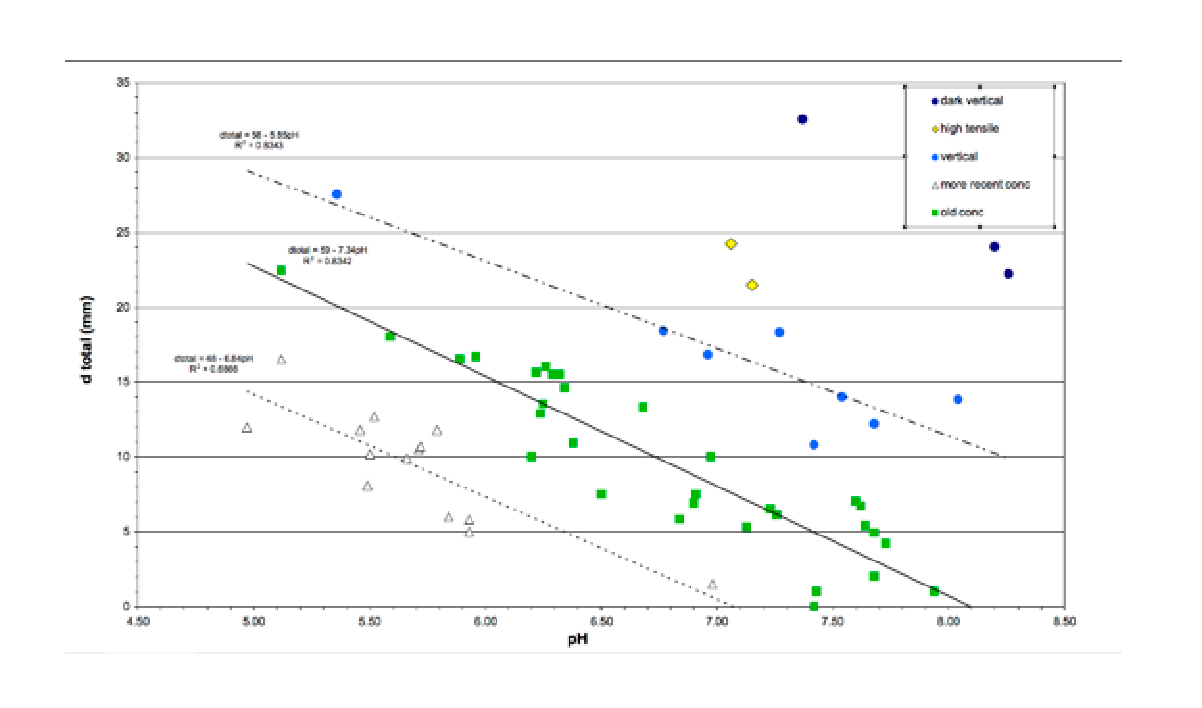


Figure 5. Plot of total concretion thickness versus metal pH on the Fujikawa Maru.

subgroups of data. When the scattered data points are statistically analysed the slopes of the three data sets are identical, indicating a common corrosion mechanism but the intercepts values at zero depth are different. The more acidic intercepts reflect less disturbed areas of the site, therefore the oldest concretion had the most acidic intercept value of 3.18 ± 0.31, the old concretion intercept was 4.09 ± 0.21 and the more recent concretions had the most alkaline intercept at 5.26 ± 0.18. The scattered data above the regression line of the more recent concretion simply reflects the impact of recent deconcreting events. For example, a 'dynamite fishing' event took place only weeks before the 2008 season (Mailo). It was noted during the measurements that the impact of the explosions was far from uniform, and the protection offered to some areas by nearby elements of the vessel's structure was quite significant, which would account for some of the data variability. For example, within 1m of a zone that showed terraced, multiple stages of regrowth and a total concretion thickness of 12mm, there was a protected section behind a box structure that had 28mm of concretion.

It has been reported previously (MacLeod et al. 2007) that the thickness of concretion is an important factor in determining how effective the marine growth is in establishing separation of the anodic and cathodic sites of the corrosion cell and this, in turn will be reflected in the pH values. On wreck sites where there have been episodes of either natural deconcretion events during storms or site disturbances, such as 'dynamite fishing', it takes some time for the marine organisms to regrow, and the rate of regrowth is dependent on a variety of interrelated factors. Thus, when measurement points are accessed there is a chance that the pH recorded is not fully representational of the underlying degree of corrosion. This, in turn, causes the pH values to be more alkaline than the underlying long term corrosion rates would indicate. However, generally, measurements on the total thickness of concretion and corrosion products, $d_{total} = d_{concretion} + d_{corrosion}$ have shown that the pH systematically falls with increasing thickness of the concretion up to a point where there is sufficient coverage of the underlying metal to reflect the pseudo-equilibrium state (MacLeod et al. 2007). In simple terms, more recently deconcreted and recolonised areas tend to present more alkaline pH values, whereas the fully matured sections possess more acidic values. It is important not to confuse alkaline pH values with low corrosion rates, for without knowledge of the thickness of concretion and the environmental history of the vessel, it is not wise to apply simplistic interpretation of the data—this can imply that the rate of corrosion is low whereas it can be quite high in these particular areas.

When all the total concretion and corrosion thicknesses (d_{total}) were plotted against the corresponding metal pH values (Figure 5) it was found that there were three main groups of data which correlated with the old concretion, the more recent concretion and the concretion found on vertical surfaces. Outlying data points on the more alkaline pH values and representing thicker concretion values were associated with the vertical surfaces that lay in shadow zones cast by the

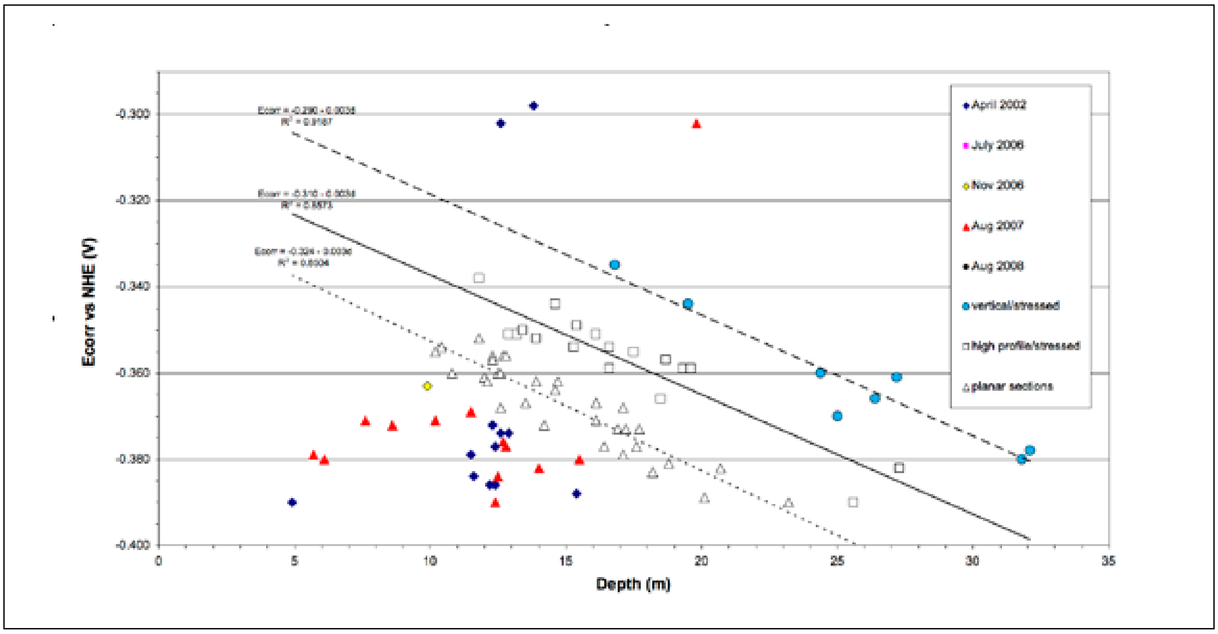


Figure 6. Plot of corrosion potential versus water depth on the Fujikawa Maru.

structure of the vessel and typically these were found on the hull plates directly below the more protective gunwales. It was also noted that the lifeboat davit and the kingpost were located in more alkaline equivalence for their concretion thicknesses than the other vertical elements and this was due to the difference in their metallurgy and chemical composition since they would have had to be made of a steel with a higher tensile capacity than the standard mild steel deck plates, frames and other fittings.

The slopes of the old, more recent and vertical concretions had the same values, within experimental error, of -6.60 ± 0.67 mm.pH^{-1}. Therefore, the values of d_{total} for each concretion type can be calculated from the regression equations at the average pH of 6.63 ± 0.81, representative of 85 pH readings measured over the five field seasons (April 2002, July 2006, November 2006, August 2007, August 2008). The calculated values were 19mm for the vertical structural elements and 11mm for the old concretions whilst the more recent concretions had a value of 3mm. This data is consistent with the anecdotal evidence from the Chuukese divers of the frequent use of 'dynamite fishing' on the *Fujikawa Maru* as the more recent concretion is roughly one quarter the thickness of the old concretion. Hence, the vertical surfaces on the site are less damaged by explosive fishing practices and diver interference than other more planar and higher profile surfaces.

Previous reports on the overall corrosion processes on iron shipwrecks in Chuuk Lagoon (MacLeod 2006) have shown that the logarithm of the corrosion rate (d_g), measured in mm of graphitisation per year of immersion in mm.yr^{-1}, for the shallower wrecks (0-20m) decreases linearly with depth as shown in the general equation (2)

$$\log d_g = -0.7314 - 0.0181\, d \qquad (2)$$

where d is the water depth at which the depth of graphitisation of cast iron structural members were measured. Furthermore, there is a direct relationship between the logarithm of the corrosion rate and the corrosion potential (E_{corr}) with site specific equations of the form (3)

$$\log i_{corrosion} = a\, E_{corr} + b \qquad (3)$$

where the constants, a and b, are site-specific variables. The value of a is primarily dependent on the temperature and the amount of dissolved oxygen and the b value relates to the overall turbulence factors associated with the site, i.e. includes the impact of vessel orientation (e.g. lying upright, upside down or on its side, etc), being in a lee-shore environment, etc. Therefore based on equations 2 and 3, it is a natural consequence that the E_{corr} values will be linearly dependent on water depth.

When the E_{corr} data from all field seasons for the *Fujikawa Maru* is plotted versus water depth (Figure 6), it is found that the voltages cluster according to a combination of the physical position on the wreck and the associated mechanical stresses on the elements. The vertically positioned and physically stressed (e.g. near the torpedo damage) sections of the ship have the highest, i.e. the least negative, E_{corr} values which are 20mV more anodic than the areas which can be described as having a high physical profile; many of these sections are also

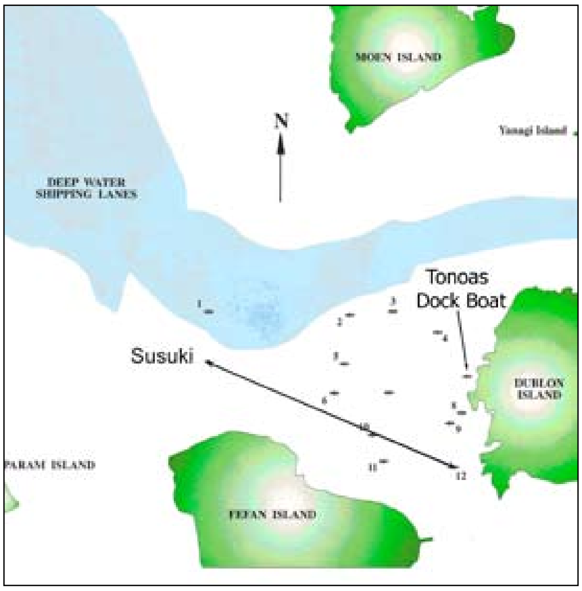


Figure 7. Location of the Tonoas dock boat and the Susuki patrol boat no. 34 (Bailey 2000).

associated with manufacturing and constructional stresses. The difference of 20mV means that the vertically stressed members are corroding at a 15% faster rate. This calculation is based on a combination of experimental testing of concreted corroded marine iron and the empirical observations of how the slope of the log corrosion plots are dependent on E_{corr} (MacLeod 1995). In a similar fashion the least stressed sections of the ship, such as vertical walls and deck plates, are 13mV more cathodic than the high profile sections and thus are corroding at a 10% slower rate. The three clusters all show the same dependence of E_{corr} on water depth, with a mean slope of −0.003 ± 0.001 volt.m^{-1}, which again indicates that all parts of the vessel have the same underlying corrosion mechanism.

Many of the measurement points in the lower E_{corr} and shallower depth area of the graph came from data collected in 2002, which was when the *Fujikawa Maru* demonstrated a different corrosion mechanism to the other Chuuk wrecks assessed during the latter field seasons (MacLeod 2005). When the site was revisited in 2006 it was noted that the originally observed slopes of the Pourbaix plots of the E_{corr} values against pH had changed from −59mV in 2002 to −28mV, which is the value commonly observed on all exposed historic iron shipwrecks in marine environments (MacLeod 2006). Another contributing factor to the apparently low corrosion rate, based simply on a comparison of the E_{corr} values of the measurements points in the shallow waters in 2002 and in 2007, lies in the fact that when freshly reconcreted marine iron is measured the voltages are more negative than adjacent sections of the vessel that have not been subjected to exfoliation. The reason for this lies in the fact that the microenvironment underneath the fresh concretion is not the same as that under well established colonization.

Tonoas dock boat

In 2006 some Chuukese children from Tonoas Island showed the expedition leader, Bill Jeffery, the location of a previously undisturbed and unidentified wreck site, a relatively unique occurrence in Chuuk Lagoon. This vessel appeared to be a small fishing vessel (~30m length) lying close to shore in the lee of Tonoas (Dublon) Island (Figure 7). However, most importantly for the biological and corrosion surveys, the site had

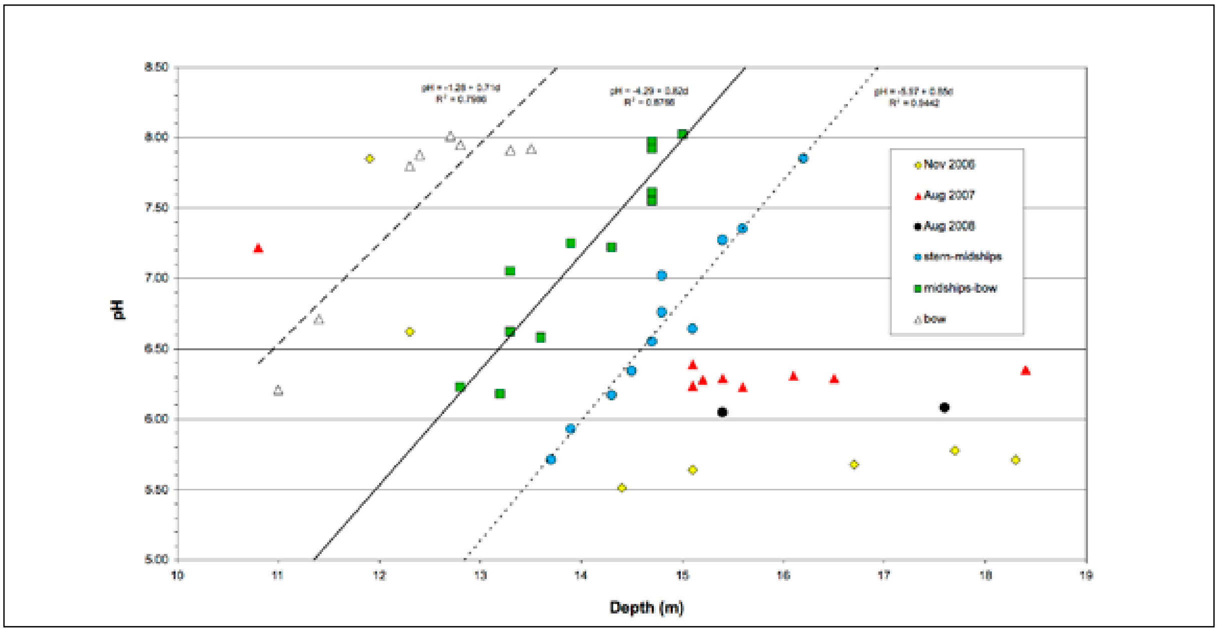


Figure 8 Plot of metal pH versus water depth on the Tonoas dock boat.

not been subjected to the ravages of dynamite fishing or other physical damage associated with the anchoring of dive charter boats or frequent diver visitation so the results could be used in comparative studies with the other more disturbed shipwrecks in the area.

The pH versus water depth graph for the Tonoas dock boat (Figure 8) exhibits the same trend of increasing pH with increasing water depth as was evident on the *Fujikawa Maru* (Figure 4) for the same underlying reasons (i.e. decreasing corrosion rates with increasing depth), and the slopes of the three separate clusters of data points were the same within experimental error, indicating the same mechanism is controlling the corrosion rate. However, the average slope of the pH versus depth plots of the three data clusters observed from 56 measurement points on the Tonoas Dock Boat was 0.80 ± 0.08 which is much steeper than that observed on the *Fujikawa Maru*, where the mean slope of the pH versus depth plots was 0.12 ± 0.01. The slope of the pH versus depth plot for the Tonoas dock boat was almost seven times that observed on the heavily disturbed *Fujikawa Maru* site. Given that the mean depths of both sites are quite similar at 15.4 ± 5.2 m for the *Fujikawa Maru* and 14.4 ± 1.7 m for the Tonoas Dock Boat, the significantly greater sensitivity of the Tonoas Dock Boat pH is likely to be a reflection of the underlying susceptibility of the iron corrosion mechanism to changes in the local micro-environment in the absence of a series of 'dynamite fishing' or similar deconcreting events such as occur during typhoons. This observation is supported by the intercept pH values of the three data sets at zero depth, which are significantly more acidic than the intercepts of the data point clusters measured on the *Fujikawa Maru*.

Furthermore, it appears that the metal pH increases, albeit non-uniformly, from the stern area towards the bow; in the absence of any major deconcreting events on the site, this may indicate a slight decrease in the corrosion rate as the vessel is traversed forward towards the bow. Unlike other shipwreck sites in Chuuk Lagoon and on other open ocean wreck sites, the drilling of the stern sections on the Tonoas dock boat resulted in voluminous clouds of red-brown rusty corrosion products, and appreciable amounts of gas emanating from the drill holes in the stern area are indicative of very active iron corrosion. Previous studies on the gas composition have shown that it is mainly composed of hydrogen, methane and nitrogen (MacLeod 1988). This gas was responsible for the forced release of the ferrous chloride/hydroxide solutions from under the concretion and their concomitant oxidation and precipitation in the oxygenated water column formed the red-brown plume.

Review of the deeper stern data, located below the stern-midships regression line in Figure 8, showed that instead of the normal trend of increasing pH with water depth, the pH is essentially independent of depth. This indicates that the stern section of the vessel has a slightly different corrosion mechanism to that which has been commonly observed on other historic iron shipwreck sites. It is possible that the stern hull plates and general surroundings are electrically connected to the rudder and propeller that may be of different metal compositions and/or the engine, which remains intact inside the stern section of the wreck. It is therefore likely that the combination of galvanic coupling and the direct physical connection with the whole of the

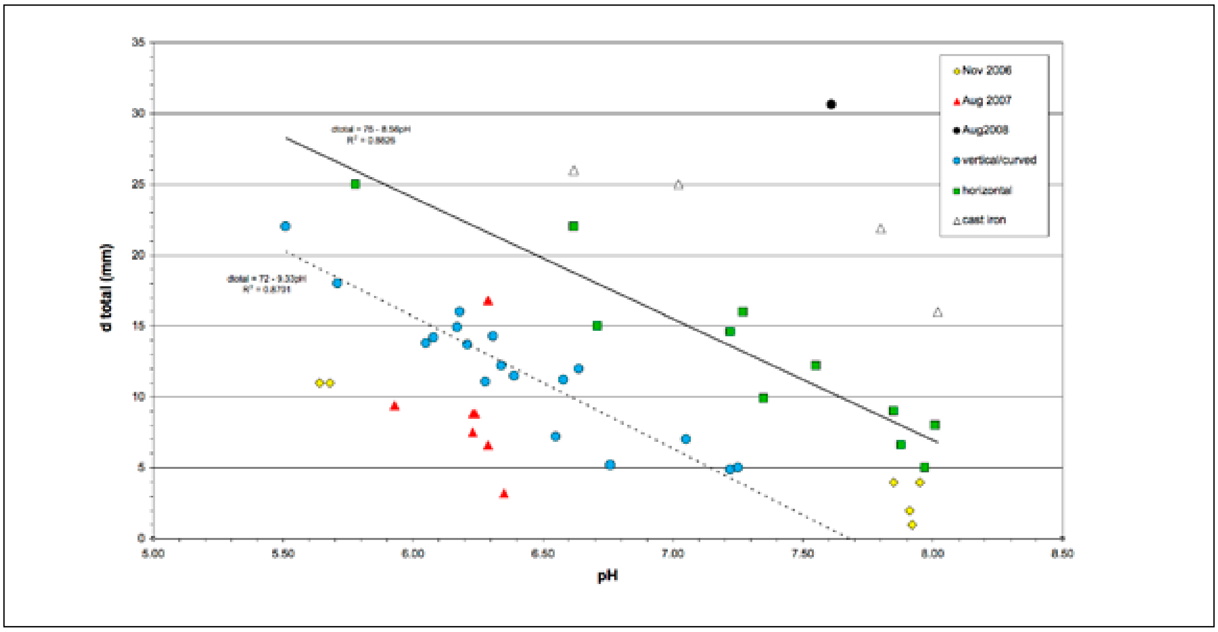


Figure 9. Plot of total concretion thickness versus metal pH on the Tonoas dock boat.

engine room interior will be the factors controlling the overall corrosion mechanism of the rear of the vessel. In support of this supposition there were no voluminous clouds of corrosion products released from drill holes on the forward part of the vessel.

When the data on the total thickness of concretion and the corrosion products (d_{total}) is plotted as a function of pH (Figure 9) there are two main lines at the upper and lower sections of the graph which clearly conform to a linear relationship between d_{total} and pH. That is, the pH of the corroding residual metal interfaces decrease linearly with increasing total thickness of the corrosion product layer and the encapsulating concretion. The line with the highest d_{total} intercept at a formal zero pH (equation 4) relates to sections of the vessel that are primarily horizontal plates or surfaces (e.g. deck plates, etc) while the lower line (equation 5) corresponds to sections of the vessel which have either a vertical or a curved nature i.e. the gunwales, the hull plates and other related structural members.

$$^{horizontal}d_{total} = 75 - 8.56\ \text{pH} \quad (4)$$

$$^{vertical/curved}d_{total} = 72 - 9.33\ \text{pH} \quad (5)$$

Although a difference of approximately 3mm in concretion thickness at zero pH between these two different structural orientations is relatively small, it is a reflection of the greater ease of juvenile marine organisms to settle on horizontal rather than curved or near vertical surfaces. The values of d_{total} for each concretion type can be calculated from their corresponding regression equations at the average pH of 6.70 ± 0.79. The calculated value for the horizontal surfaces was 17mm, while for the more vertical and curved areas the d_{total} was 8mm, compared to the d_{totals} calculated for the *Fujikawa Maru*, where the vertical elements had the thickest calculated d_{total} of 19mm and 11mm and 3mm for the old and more recent concretion, respectively. Therefore, these calculated concretion thickness results indicate that the Tonoas dock boat is a relatively pristine, undisturbed site with the thicker concretions evident on the horizontal surfaces as compared to the thinner coverage on more vertical structures, which is totally consistent with natural colonisation processes (MacLeod et al 2007). In comparison, the *Fujikawa Maru*, which has been subjected to extensive human interference, has the thickest concretions on the vertical surfaces as these areas tend to be least damaged by 'dynamite fishing' and diving practices.

The scatter associated with the pH measurements on the Tonoas dock boat is reflected in the R^2 values, and statistical analysis shows that the two pH slopes of $\partial d_{total}/\partial pH$ are the same, within experimental error. This supports the supposition that the thicker the marine concretion, the greater the capacity of this semi-permeable membrane to separate out the anodic and cathodic sides of the corrosion cell, and the pH values will more accurately reflect the underlying corrosion rates at those measurement points, unlike the more disturbed *Fujikawa Maru*.

The data points with the thickest concretion cover, lying above the regression line for the horizontal

Figure 10. Plot of corrosion potential versus water depth on the Tonoas dock boat.

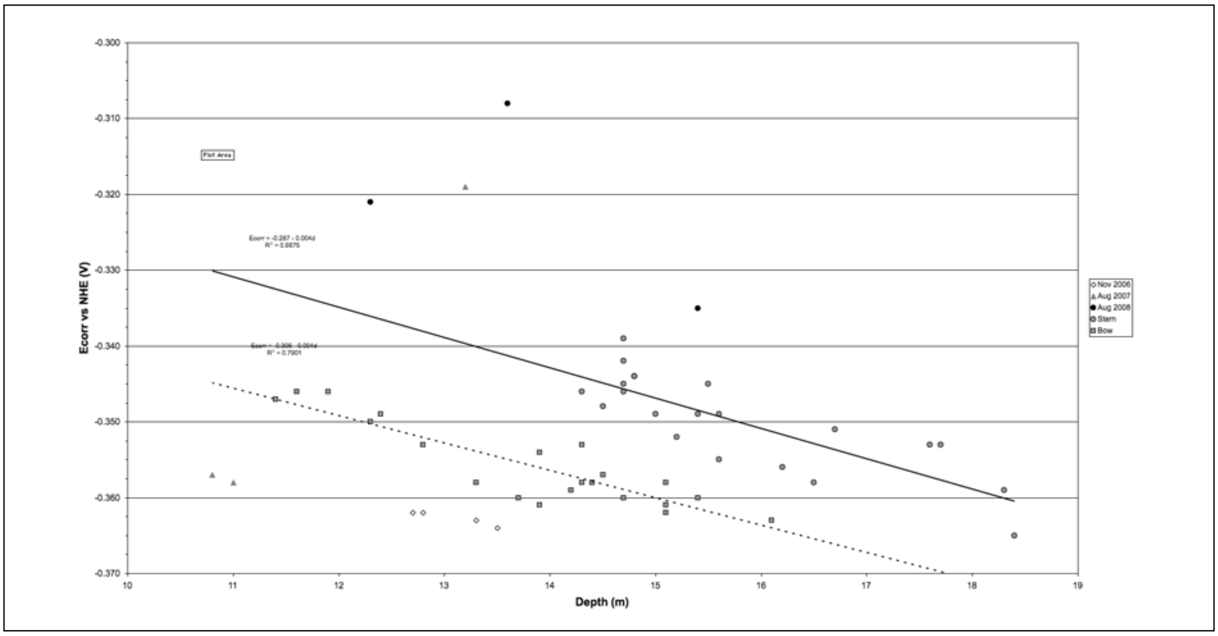


Table 1. Mean E_{corr} for the wrecks for each site inspection.

Wreck	Mean E_{corr} vs NHE (V)				
	April 2002	July 2006	Nov 2006	August 2007	August 2008
Fujikawa Maru	–0.377 ± 0.018	–0.359 ± 0.009	–0.365 ± 0.008	–0.372 ± 0.010	–0.352 ± 0.014
Tonoas dock boat	nd	nd	–0.355 ± 0.006	–0.355 ± 0.010	–0.340 ± 0.013
Susuki patrol boat	–0.370 ± 0.005	–0.337 ± 0.004	–0.316 ± 0.004	–0.355 ± 0.002	nd

nd: not determined

Table 2. Mean pH for the wrecks for each site inspection.

Wreck	Mean pH				
	April 2002	July 2006	November 2006	August 2007	August 2008
Fujikawa Maru	6.73 ± 0.57	5.95 ± 0.79	7.32 ± 0.80	6.43 ± 0.84	7.12 ± 0.62
Tonoas dock boat	nd	nd	6.95 ± 0.98	6.37 ± 0.35	7.07 ± 0.66
Susuki patrol boat	7.13 ± 0.69	6.22 ± 0.90	5.61 ± 0.48	6.41 ± 0.77	nd

nd: not determined

surfaces, are associated with measurements on cast-iron structures. This increase in d_{total} is consistent with cast iron having higher phosphorus contents than steel and wrought iron. Previous studies (MacLeod 1988) have shown that anaerobic bacteria convert the insoluble phosphorus impurities present as iron phosphide, Fe_3P, into a volatile phosphine, which diffuses through the concretion and provides an extra nutrient source to the colonising marine organisms. The other data points lying to the more acidic pH values and at generally lower d_{total} relate to sections of the vessel which are either on heavily curved areas of the gunwale, on the rudder and/or on near vertical hull plates and these results are consistent with the argument presented above for the other vertical and curved surfaces.

When the E_{corr} data for the three field seasons on the Tonoas dock boat were plotted against water depth (Figure 10) it is obvious that there are two distinct clusters of data points. The data set with the highest (least negative) E_{corr} values were those measured around the stern and the engine house area and were about 20mV more anodic than the other data set measured predominantly around the bow area possessing lower (more negative) E_{corr} values. The more anodic values reflect a 15% increase in the corrosion rate, based on calculated values for the difference in the voltage intercept values and the known average value of 320mV difference in voltage equating to a ten fold difference in corrosion rate (MacLeod 1995). This indicates that the stern section is corroding at a faster rate than the bow area, which can be explained by the fact that there is obviously some form of galvanic corrosion occurring around the stern area with this aft section being in direct electrical contact with the engine, the propeller shaft and the propeller that remain within the stern hull structure.

The points that had the highest recorded E_{corr} values (most positive) and also recorded corresponding low pH values and high d_{totals} were very high-profile points located at the stern (e.g. on top of gunwale on the transom) and hence, had a higher water flux over their surfaces and therefore, greater dissolved oxygen impingement, thus significantly increasing the localised corrosion rates in those particular areas. Other points that recorded high E_{corr} values but did not possess correspondingly acidic pH values were associated with the totally corroded wheel-like structure located near the bow. Iron artefacts that have very little or no residual metal remaining no longer have the driving force to maintain the lower pH and E_{corr} values associated with corroding iron inside the concretion and the solution gradually equilibrates to the local environmental values (more positive E_{corr} and more alkaline pH). In these situations, where very little residual metal remains, the drill bit often penetrates the structure and the voltages are not true corrosion potentials but are more indicative of redox voltages i.e. those that relate to the ratio of the Fe (III) to Fe (II) ions in the corrosion product matrix.

The data points that were corroding the least (most negative E_{corr}) were either very well protected under the gunwales in the bow area or they were in direct electrical contact with the totally corroded wheel-like structure located at the bow. Clearly this cast iron, circular structure has been corroding in preference to the surrounding support structure. This is a form of cathodic protection and is caused by the differences in the microstructure of the cast iron. The more noble carbon-rich phases present

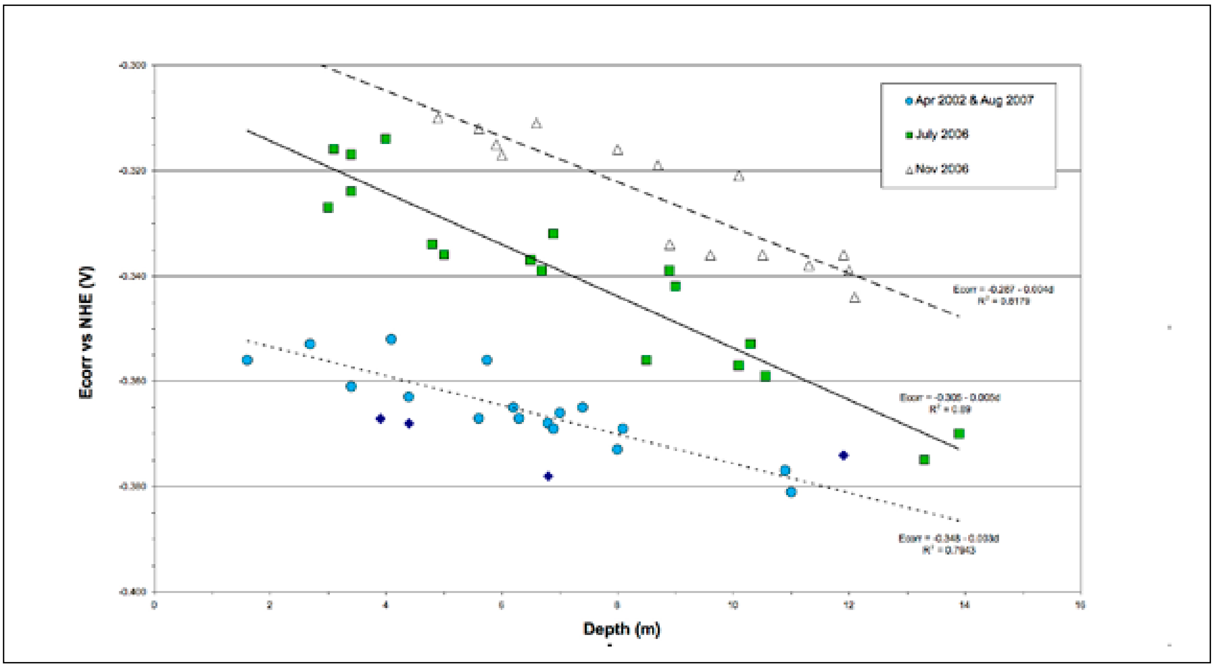


Figure 11. Plot of corrosion potential versus water depth on the Susuki patrol boat.

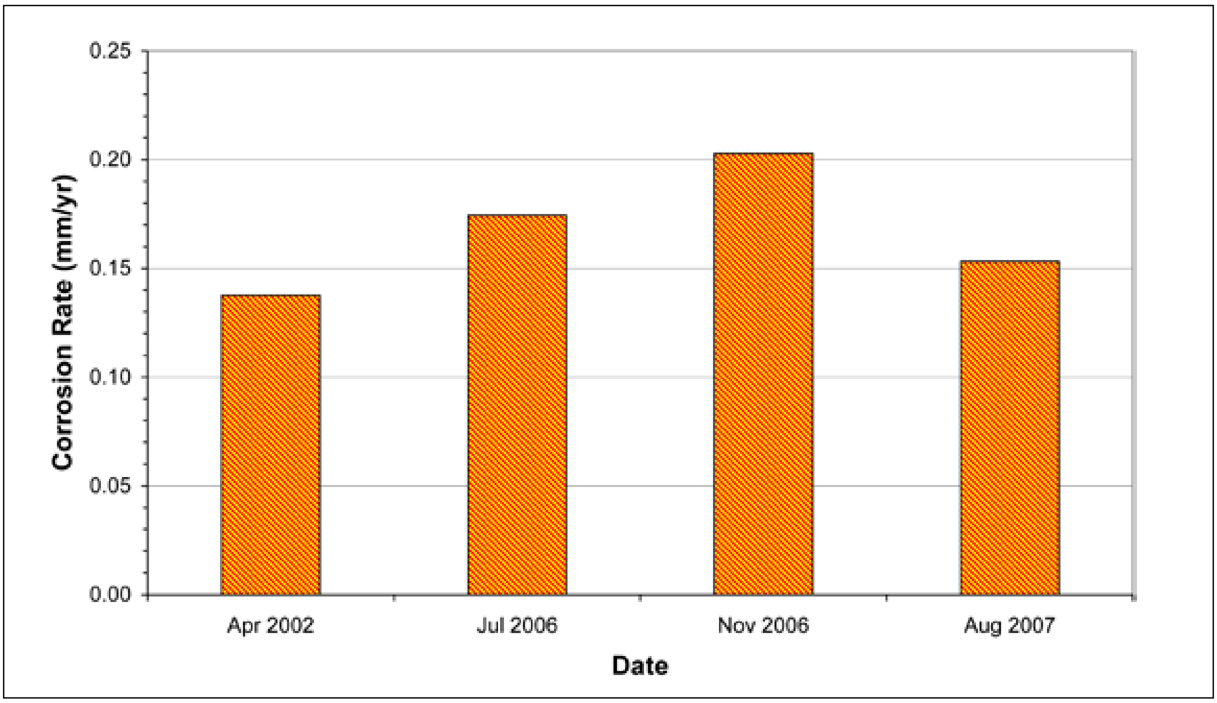


Figure 12. Plot of Susuki corrosion rate versus time.

in the microstructure exacerbate the corrosion of the ferritic phases and so if there are structural elements of mild steel electrically connected to the objects, such as the support structure, then they will be inherently protected by the more exposed and more internally corroded cast iron wheel-like structure.

Susuki patrol boat

The wreckage of the *Susuki* patrol boat lies on the west side of Dublon or Tonoas Island (Figure 7) and is more commonly known as patrol boat no. 34. The vessel is 84m long and 8m wide, with a draught of 3m. The shallowest part of the wreck is in 3m and the bottom of the keel at the stern is at 14m. Originally built in Tokyo in 1921, it was repaired in Chuuk after a collision with a large Japanese warship off New Guinea. This involved a total reconstruction of the forward parts of the ship. The vessel was finally sunk during an aerial attack on

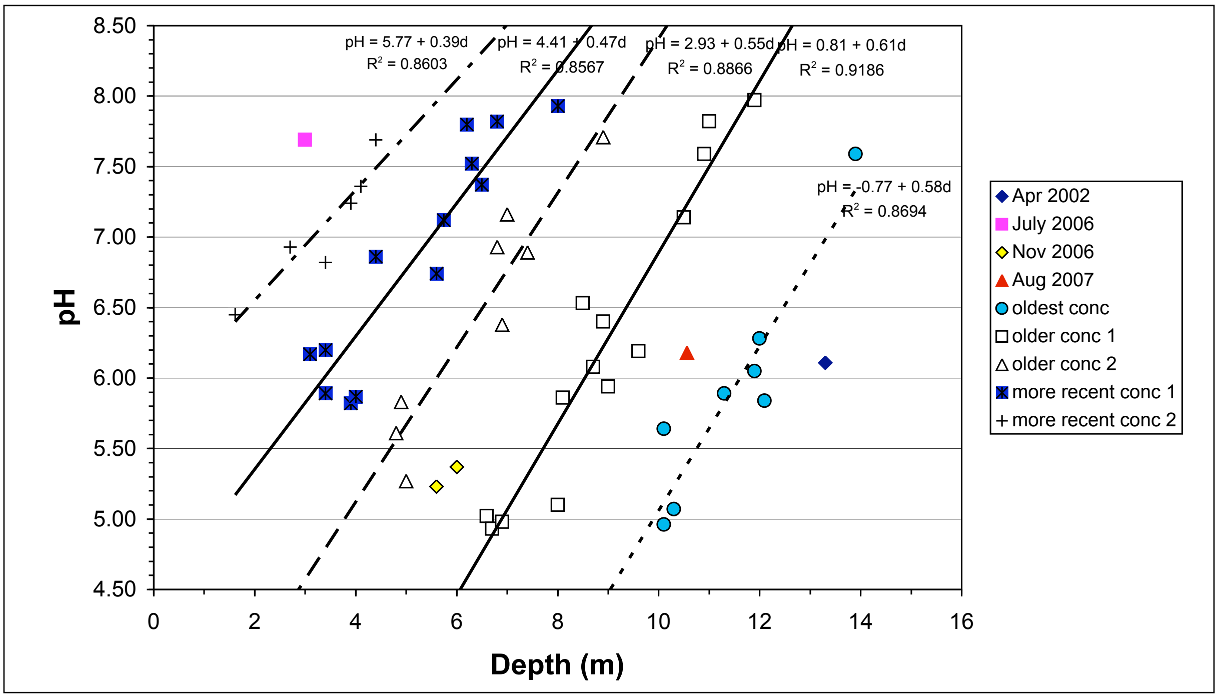


Figure 13. Plot of metal pH versus water depth on the Susuki patrol boat.

3 July1944, five months after the devastation of Operation Hailstorm. This wreck provides a very good example of the challenges associated with effective management of underwater cultural heritage in the absence of effective implementation of the protective legislation in Chuuk Lagoon. In order to facilitate comparisons with the other wrecks all the relevant data is summarised in Tables 1 and 2.

The complexities of the *Susuki* site are shown in Figure 11, which shows the E_{corr} vs. depth data for 56 measurements. The data shows that the site disturbances that were reflected in the two sets of measurements in 2006 resulted in a 64% increased sensitivity of the E_{corr} to water depth when compared with the initial 2002 and the final data set in 2007. The changing nature of the *Susuki* site over several years is also reflected in the mean E_{corr} and pH values shown in Tables 1 and 2. Inspection of the data shows that between the initial measurements in 2002 and the subsequent data set collected four years later, the site had undergone accelerated decay during this period as indicated by the less cathodic E_{corr} value and the more acidic mean pH. The data recorded only four months later in November 2006 showed a continuing movement in the E_{corr} to more anodic values and the pH continued its acidic trend, which indicated a further increase in corrosion rate. In August 2007 the mean E_{corr} had moved to more negative values and the pH had also increased thus the overall site condition appeared to be moving back towards the 2002 values. This indicated that the site was recovering from human intervention activities such as diving tourism and 'dynamite fishing' through recolonisation of the corroded iron structures.

The changing corrosion rate at the various measurement intervals is illustrated in Figure 12 where the initial rate of 0.14 $mm.yr^{-1}$ increases to 0.17 then 0.20 and finally falls to 0.15 $mm.yr^{-1}$ in 2007. The initial corrosion rate was calculated using equation 1 for shallow wrecks in Chuuk Lagoon (MacLeod 2006), based on mean water depth of the site, and the subsequent measurements were calculated according to the standard change of 320 mV in E_{corr} for a tenfold increase in corrosion rate (MacLeod 1995). The greatest difference between the mean E_{corr} values April 2002 and the data in November 2006 represents a 47% increase in corrosion rate. The trend in the corrosion rates of the vessel is also reflected in the way in which the mean pH decreases, i.e. as the corrosion rate increases the concentration of Fe^{2+} ions underneath the protective layer of concretion increases and the extent of hydrolysis concomitantly increases and so the pH falls. This data shows that wreck sites are in a dynamic equilibrium with the marine environment and that when damage occurs there can be relatively rapid recovery to pre-disturbance levels.

The cause of these very large changes in site conditions is associated with concretion loss. Such losses can either have resulted from natural storm activities and/or from human intervention on the site. The following scenario is a likely calendar of events, which is corroborated by local Chuukese heritage divers.

The site was relatively undisturbed for some years when first visited in 2002. Some time prior to the measurements in July 2006 there was a 'deconcreting'

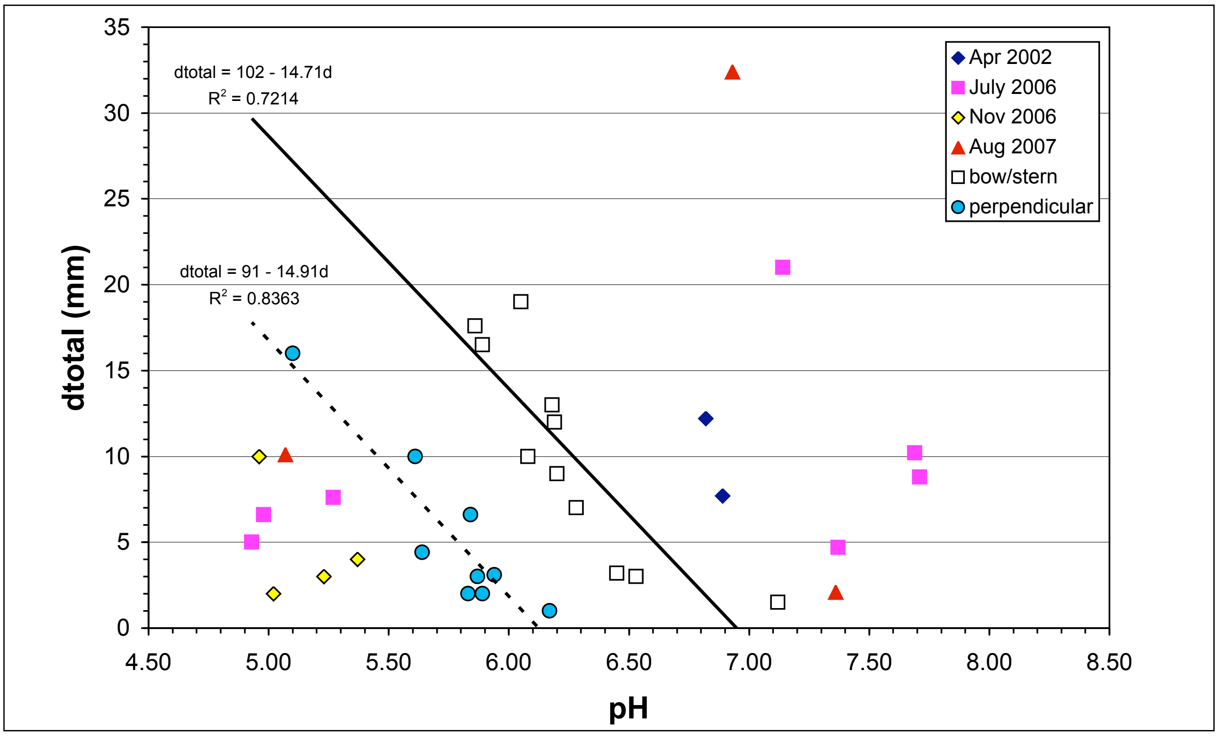


Figure 14. Plot of total concretion thickness versus metal pH on the Susuki patrol boat.

Table 3. Rate of change of pH with depth on the Susuki Patrol Boat site.

Description	Slope of pH vs depth	pH at mean depth (7.2m)
Oldest concretion	0.583	3.43
Older concretion 1	0.608	5.19
Older concretion 2	0.548	6.88
More recent concretion 1	0.472	7.81
More recent concretion 2	0.391	8.58

event, and by the time the data was collected there had been a partial recovery of the wreck in terms of the concretion layer rebuilding as a result of natural colonisation processes. When additional data was gathered in November 2006 it was very clear that a deconcreting event had taken place within the preceding few months. This showed directly the huge impact that 'dynamite fishing' can have on a shallow wreck site that is also subjected to the activities of inexperienced tourist divers, who often have difficulty in adjusting their buoyancy in shallow waters. One direct result of the buoyancy problem is that divers grab hold of corals and other organisms to stabilise themselves underwater and this normally results in the marine growth being wrenched off the site. An additional complication for the *Susuki* wreck site is that the vessel is often used for night diving and, under these conditions, the accidental concretion damage is exacerbated.

The plots of the pH versus depth in Figure 13 show a series of parallel lines of essentially the same slope, which shows that the site pH is being controlled by the same fundamental electrochemical processes over all the seasons. From the regression equations for lines of best fit for the different aged concretions it is possible to calculate the pH at the average site depth of 7.2 metres (Table 3).

The oldest concretion line has the most acidic value at pH of 3.43 while the most recent concretion has the least acidic value of 8.58, which is very close to that of the surrounding seawater at pH of 8.20. This data shows that there appears to be a minimum thickness of concretion needed to allow the re-establishment of the dynamic equilibrium between the pH due to hydrolysis of the corrosion products and the movement of alkaline seawater from the general environment through the semi-permeable concretion layer. The older concretion layers have had sufficient time to allow the pH to be representative of the underlying corrosion rate as compared with the more recent concretion layers which are too thin to have values that are truly indicative of the corrosion rate of the underlying metal.

When the thickness of concretion on the *Susuki* is plotted as a function of pH (Figure 14) the same types of relationships observed with the *Fujikawa Maru* and the Tonoas dock boat were found for the older concretions which represented more than half of the measurements. There was a linear increase of d_{total} with the increasing acidity of the metal interface as seen in the two trend lines illustrated in Figure 14. The thicker concretions

Table 4. Summary of average in situ corrosion data for the three Chuuk shipwrecks.

Wreck	No. of measurements	Mean depth (m)	Mean E_{corr} vs NHE (V)	Mean pH	Mean d_{total} (mm)
Fujikawa Maru	85	15.5 ± 5.2	–0.367 ± 0.017	6.63 ± 0.81	12.0 ± 6.7
Tonoas dock boat	56	14.4 ± 1.7	–0.351 ± 0.011	6.79 ± 0.79	13.3 ± 7.6
Susuki patrol boat	56	7.2 ± 3.1	–0.347 ± 0.021	6.46 ± 0.92	8.9 ± 6.8

Table 5. Summary of observed and predicted corrosion rates for the three Chuuk shipwrecks.

Wreck	Mean depth (m)	Mean depth graphitisation (mm)	Calculated corrosion rate ($mm.yr^{-1}$)	Observed corrosion rate ($mm.yr^{-1}$)	Percentage corrosion rate increase
Fujikawa Maru	15.4	8.3 ± 2.4	0.098	0.143	46
Tonoas dock boat	14.4	5.0 ± 1.7	0.102	0.081	-20
Susuki patrol boat	7.2	10.0 ± 3.4	0.138	0.161	17

are associated with structures such as davits, which have a different chemical composition from the other steels on board. This sensitivity to substrate composition and microstructure was also noted on the *Fujikawa Maru*. Additionally thicker concretion was associated with planar decking surfaces as was also observed on the Tonoas dock boat. The next most concreted areas were associated with structures near the bow and the stern which are subject to a more turbulent flow of water and associated flux of nutrients around the forward and rear ends of the vessel. Other high concretion values were associated with cast iron structures on the ship, such as bollards. The less concreted zones of the wreck were associated with the more perpendicular sections of either the superstructure or the hull plates. As previously noted in the case of the Tonoas dock boat these areas provide less opportunity for colonisation of the marine organisms and so the concretion cover is thinner.

Comparison between the wrecks

The value of having data from several shipwrecks in the same location which have all been underwater for the same period is that it is then possible to examine the impact of water depth and anthropogenic activities such as 'dynamite fishing'. The average values for E_{corr} and pH measured over all seasons are listed in Table 4 and the mean corrosion parameters are listed in Table 5.

The trends in E_{corr} for the three wrecks show a systematic shift to more negative, less corrosive, voltages with increasing depth, as shown in Table 4. If the pH values were truly reflective of a dynamic corrosion equilibrium they would be expected to show the reverse trend i.e. the mean pH values would be less acidic for deeper wrecks. Although the scatter of the pH data is high, owing to the range of concretion thicknesses and the effects of 'dynamite fishing' previously noted, the mean pH of the three wrecks are statistically indistinguishable. Previously published data on the Chuuk iron shipwrecks (MacLeod 2006) has shown that the corrosion rate is logarithmically dependent on water depth.

Data on the combined thickness of concretion and corrosion product layers, d_{total} is characterised by large standard deviations of the mean values. This is a reflection of the natural and anthropogenic deconcreting events. It has also been found that the substrate profiles (horizontal, curved, vertical, etc) and the microstructure and chemical composition of the iron alloys all have a significant impact on the encrusting marine organisms and the extent of their coverage on the wreck. For example the growth rate of concretions is dependent on the flux of micronutrients in the flowing seawater and from sources, such as phosphines and hydrocarbons coming from the underlying corrosion processes. For photosynthetic marine organisms, however, the water depth is the main factor controlling growth rates.

It is possible to use the way in which the observed corrosion rate varies with water depth to calculate the expected corrosion rate on each of the wrecks, using the mean depth of the sites. The data was calculated using equation 2 and the results are presented in Table 5. The observed corrosion rate of 0.161 $mm.yr^{-1}$ on the *Susuki* is 17% higher than the calculated value based on the mean depth. In a similar fashion the corrosion rate on the *Fujikawa Maru* is 46% above that which would be predicted on the basis of water depth. Both the *Susuki* and the *Fujikawa Maru* have suffered from increased corrosion as a result of multiple deconcretion episodes. A contributing factor to the greater increase in corrosion rate on the *Fujikawa Maru* site is because of its location

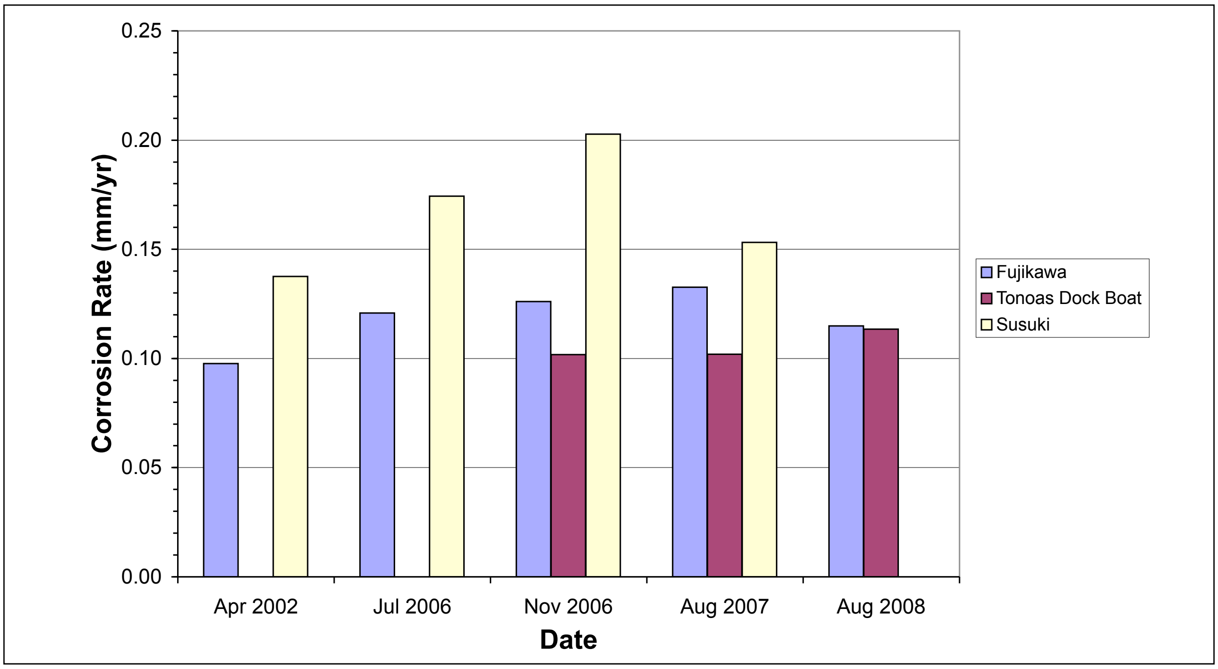


Figure 15. Plot of corrosion rate on all wrecks versus time.

in the shipping channel and the greater amount of water flux over the site. In addition the nature of the ship construction and form provides much greater habitat variation for all colonising organisms therefore it is much more densely populated with fish and is thus more attractive to the dynamite fishers. It also has to be remembered that the *Fujikawa Maru* is the most popular wreck site in the lagoon and is thus subjected to inadvertent diver damage.

In contrast, the recently discovered Tonoas dock boat had a 20% less observed corrosion rate than predicted because it is a pristine wreck and there was no evidence the site had been subjected to 'dynamite fishing' or visited by diving tourists. The corrosion rates were calculated from the raw data previously recorded on eight shipwrecks in the lagoon which had been presumed to be 'normal'. However when the data from the pristine wreck site of the Tonoas dock boat is used as the baseline it can be seen that all the other wrecks showed some signs of deconcretion episodes.

When comparing the mean values of the slopes of the pH vs. depth plots for the three wrecks it was noted that the Tonoas Dock Boat had the greatest sensitivity with a mean slope of 0.8 ± 0.08 $pH.m^{-1}$ while the *Susuki* had a mean value of 0.52 ± 0.09 $pH.m^{-1}$ and the *Fujikawa Maru* had a much lower average slope of 0.12 ±0.01 $pH.m^{-1}$. The interpretation placed on this data is that the undisturbed Tonoas dock boat wreck shows the inherent sensitivity of pH, and thus corrosion rate, on water depth because of its pristine condition, which has allowed the dynamic corrosion equilibrium to achieve a steady state. Although the *Susuki* is at roughly half the depth of the Tonoas dock boat, it does not have a higher pH versus depth slope because of the site history of multiple deconcretion episodes. In a similar vein, the slope of the *Fujikawa Maru* at 0.12 $pH.m^{-1}$ is in part due to the multiple episodes of deconcretion and also due to its greater depth.

Since corrosion on iron shipwrecks is controlled by the flux of dissolved oxygen to the concreted metal surface the way in which the concentration of oxygen changes with water depth is going to be critical in determining the sensitivity of pH with depth. For the three wrecks plots of dissolved oxygen versus depth had characteristic sigmoidal curves with asymptotes at 9 ± 2 metres for the Tonoas Dock Boat and *Susuki* while the *Fujikawa Maru* had a turning point at 30 metres. This simple physico-chemical parameter explains the basic differences in sensitivity of the pH to water depth since the shallower wrecks will exhibit a greater change in corrosion microenvironment with depth than the deeper sites, such as the *Fujikawa Maru*.

The impact of 'dynamite fishing' on the wrecks can be seen in the way in which the mean E_{corr}, and the associated corrosion rate, changes with the seasons of measurement due to deconcreting events (Table 1 and Figure 15). The corrosion rate for the Tonoas dock boat is constant within experimental error, which is in marked contrast to the *Fujikawa Maru* and the *Susuki* patrol boat. For the *Fujikawa Maru* the 2002 mean E_{corr} was −0.377± 0.018 V, which increased to −0.359± 0.009 V in July 2006, a 14% increase in corrosion rate probably caused by a 'dynamite fishing' event. Within the space of five months the E_{corr} fell to −0.365± 0.008 V (5% decrease in corrosion rate) which indicated that the site was beginning to recover. The recovery process continued for some time since by August 2007 the E_{corr} had fallen further to −0.372 ± 0.010 V, which was an additional 5% decrease in corrosion rate. One year later in 2008 the E_{corr} had risen to −0.352 ± 0.014 V which equates to a 15% increase in the corrosion rate, similar to the July 2006 data where the impact of a deconcreting event was evident. The changing impact of deconcreting events and recolonisation processes is even more pronounced on the *Susuki* patrol boat where the corrosion rate increase by 27% between the initial measurements in 2002 and the July 2006. This was followed by an additional 16% increase by November 2006 and then it decreased by 32% over the ensuing 12 months.

Conclusion

Observations of varying thicknesses of the concretion layers indicated that there had been episodic localised loss of this protective layer of marine concretion from the surface of the vessels. The data collected on these wreck sites show the detrimental impact of the combination of natural deconcretion events associated with typhoons during the Monsoonal period, 'dynamite fishing' and diving tourism. The *Fujikawa Maru* is the most seriously affected site with an estimated increase of 46% in the corrosion rate compared with what is expected for a wreck at that depth. The continued practice of 'dynamite fishing' results in permanent damage to the longevity of the wrecks subjected to this form of intervention. Sustained corrosion activity at levels which are typically 30–50% higher than predicted will result in premature collapse of these iconic cultural objects. Based on results from corrosion data collected in 2002, many of the wrecks in Chuuk Lagoon will begin to undergo significant collapse in the next 10 to 15 years. This has major implications for the management of the sites and for the safety of divers undertaking penetration dives.

The only effective method for reducing corrosion rates on these historically significant shipwrecks is to improve management practices such as provision of permanent moorings and improved policing of the existing protective legislation. In addition, education training programs for dive tourism operators to move towards a more sustainable interaction with the wrecks would greatly assist the recovery of the wrecks from past damage and intervention. In addition, there is the risk of perforation of fuel bunkers on some vessels, possibly releasing petrochemicals into the fragile ecosystem potentially causing significant environmental damage in Chuuk Lagoon. Hence there is an urgent requirement for additional funding to be provided to the Chuukese government to enable longer in situ corrosion monitoring and the installation of cathodic protection systems to be installed onto 'at risk' wrecks.

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Author 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.

Vicki Richards is a research chemist/conservation scientist in the Department of Materials Conservation at the Western Australian Museum. Her research activities have primarily concentrated on understanding the degradation mechanisms and improving the current treatments for metal impregnated organic materials and metal/organic composite artefacts recovered from underwater cultural heritage sites, investigating post conservation degradation problems and prospective treatments for acid-deteriorating polyethylene glycol–treated waterlogged wood, such as the *Batavia*, monitoring the corrosion and environmental impact of decommissioned vessels as artificial reefs and performing extensive on-site conservation surveys to establish the extent of deterioration of underwater cultural heritage sites and using this information, devising and implementing appropriate on-site management plans for the long-term *in-situ* preservation of these sites and their associated artefacts.

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