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# Corrosion and conservation management of iron shipwrecks in Chuuk Lagoon, Federated States of Micronesia

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## ABSTRACT

A series of *in situ* corrosion measurements on World War II Japanese merchant and military vessels sunk in Chuuk (Truk) Lagoon in 1944 was conducted in 2002 as part of a study of the cultural heritage values of the wreck sites. The data provide evidence of episodic loss of the protective layer of marine concretion, which directly increases corrosion of the underlying metal and removal of the archival microenvironment record. It is likely that dynamite 'fishing' is the most likely cause of such losses. All the vessels, apart from the *Fujikawa Maru*, showed a corrosion mechanism that is common to historic iron shipwrecks. The apparent sensitivity of the corrosion potentials and the pH of the corroding interfaces to water depth have been interpreted in terms of the overall amount of water movement and the aspect or orientation of the wrecks with regard to being horizontal, upside down or inclined. Corrosion rate equations predict that many of the wrecks in Chuuk Lagoon will retain their existing integrity for the next ten to fifteen years before undergoing significant collapse. The corrosion rates in Chuuk Lagoon were between 26% and 30% lower than the iron shipwrecks at the same depth in open-ocean waters.

## INTRODUCTION

It is essential to conduct pre-disturbance chemical, biological and electrochemical surveys to assess the full potential of a wreck site to provide information on the nature of the processes involved in site deterioration. 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 submerged vessels from World War II in the waters of Chuuk state, which is located approximately in the middle of the Federation States of Micronesia (FSM), just over 7°N of the equator and on the 152°E line of longitude. It represents the first stage of a full survey of the submerged cultural heritage resources of the island state. Chuuk or Truk Lagoon is approximately 64km in diameter and has been formed by a barrier reef enclosing an area of 2125km$^2$ (Figure 1) [1]. It is the most populated region of Chuuk, enclosing nineteen high volcanic islands with lush tropical vegetation, warm and clear waters with a great abundance of fish. 'Truk' was the spelling adopted during the German annexation of Micronesia (1898–1914). Truk reverted to its traditional pronunciation and spelling of Chuuk in 1986. The *in situ* corrosion studies were conducted at the request of the Chuuk government to see if estimates of corrosion rates could be used to predict the future of their shipwrecks and submerged aircraft. The corrosion assessment team visited a number of wreck sites during two weeks in April–May 2002 under the guidance of Bill Jeffery [2–4].

The wreck sites were chosen to reflect differences in orientation (flat bottom, upside down vessel, sloping), calming effects of nearby islands and previous work history (torpedoed, collision damage). Apart from these variables the principal difference between the sites was the depth of water. Since there are only small annual variations in water temperature and salinity these factors, which dominate the amount of dissolved oxygen being made available to the corroding wrecks, are not major site variables.

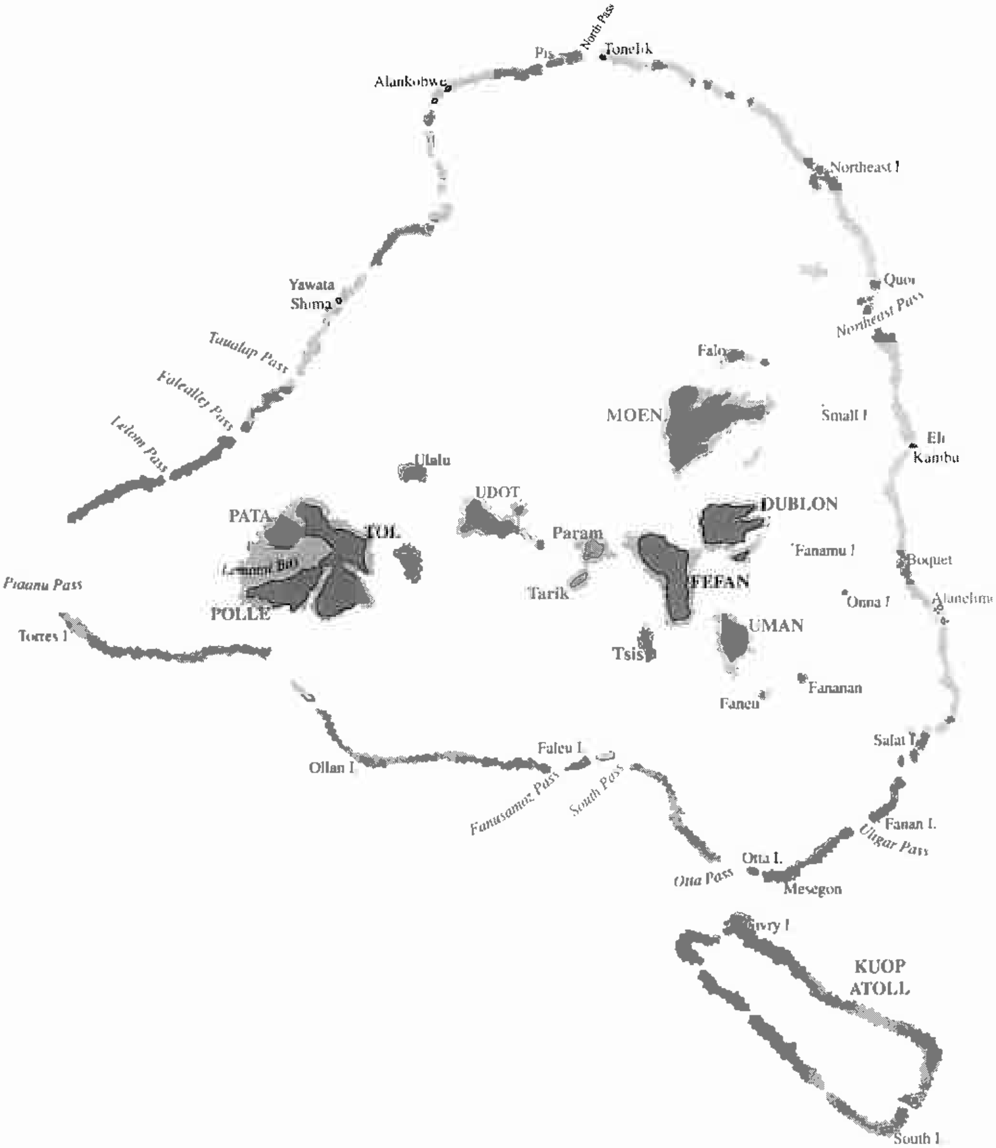

Figure 1. Map of Chuuk Lagoon, Federated States of Micronesia, showing main islands. After Bailey [1].

The rate of deterioration of metals on shipwreck sites is very dependent on the water depth and the flux of oxygenated seawater over the objects lying proud of the seabed. In warm tropical waters, corroding iron and steel in seawater rapidly becomes encapsulated by encrusting organisms such as coralline algae and bryozoans [5]. 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 [6] as seen in Figure 2. 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 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.

**Figure 2.** Extensive encrusting marine growth on the deck of the *Fujikawa Maru* with thicker growth surrounding the broken derrick. Photo Bill Jeffery.

The rates of corrosion are naturally dependent on a range of microenvironmental parameters. For iron materials lying proud of or on the seabed, the primary cathodic reaction is the reduction of dissolved oxygen. 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 [7] since the presence of dehydrogenase enzymes will often control the rate of hydrogen evolution [8, 9].

After nearly sixty years of corrosion in the warm tropical waters of Chuuk lagoon, 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 [10]. 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 [11, 12]. Examples of such damage are readily seen where mooring of visiting dive boats on bollards, davits, kingposts and associated ship structures has caused the concretion to be removed. The telltale signs of recent damage are voluminous red-brown corrosion products on the abraded surfaces.

On an iron wreck, galvanic coupling will protect any non-ferrous materials that are in electrical contact or in close proximity [13]. One result of this interaction is that all the copper, brass and bronze fittings become covered with a thin, adherent white calcareous concretion [14]. Once the concretion has formed, the surface is no longer biologically toxic and is therefore then subject to the normal colonization mechanisms associated with the particular marine ecology of the area. Examples of such galvanic protection can be seen in the way in which brass gun manufacturing plaques on the *Fujikawa Maru* are routinely protected by the corroding mass of the gun and the mounting.

## EXPERIMENTAL METHODS FOR CORROSION POTENTIAL AND pH MEASUREMENTS

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. 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 working electrode such as platinum. Platinum is used because it is electrochemically inert, it does not corrode in seawater and therefore the measured voltages refer to the object itself and are not part of the nature of the experimental apparatus. The acidity of the underlying corrosion interface is measured by gently 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. 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. 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 [15].

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 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. Comparison of the amount of corrosion on two cast iron bollards on the deck of the *Fujikawa Maru* showed that the 6.5 and 6.6mm corrosion profiles demonstrates that reliable measurements can be obtained from objects in the same microenvironment. The error associated with recording a corrosion profile is of the order ± 0.1mm. 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 [10]. 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 $d_g$ (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 wrecks in Chuuk Lagoon was slightly in excess of 58 years.

## CORROSION POTENTIALS AND WATER DEPTH

Since previous studies have shown that there is a linear relationship between $E_{corr}$ and depth, all the data from the $E_{corr}$ and pH measurements were assessed, using linear regression analyses, to determine the response of these corrosion parameters to water depth [6, 16]. Data from the ten wrecks surveyed are summarized in Table 1. The apparent sensitivity of the $E_{corr}$ values to water depth can be grouped into three sets: moderate, low and very low sensitivity to depth. Historic shipwrecks in open-ocean waters, which are characterized by high energy levels of wave action and tidal movement, had $E_{corr}$ values that typically fell by 18mV/m of increased water depth [6]. The apparent sensitivity of the $E_{corr}$ values from the Chuuk wrecks to water depth is much smaller than that previously reported for open-ocean wrecks. Examination of the data in Table 1 shows that the *Fujikawa Maru*, *Susuki*, the *Hino Maru* and the *Sankisan Maru* all have the greatest dependence of $E_{corr}$ on depth, but the *Hino Maru*, being the shallowest of the sites, shows the greatest slope of a fall in $E_{corr}$ of 4.3mV/m compared with the average value of 2.7mV/m. The next group consists of the *Yubae Maru*, *Sapporo Maru*, *Gosei Maru*, *Shinkoku Maru*

Table 1. Mean corrosion potential data for the Chuuk Lagoon shipwrecks

| Wreck | $E_{corr}$ as a function of depth | mean $E_{corr}$ | Std deviation $E_{corr}$ | Mean depth |
|---|---|---|---|---|
| Fujikawa Maru | $-0.512-0.0028\ d_m$ | −0.602 | 0.018 | 18.3 |
| Hino Maru | $-0.594-0.0043\ d_m$ | −0.606 | 0.006 | 4.5 |
| Susuki | $-0.574-0.0028\ d_m$ | −0.594 | 0.006 | 7.6 |
| Sankisan Maru | $-0.598-0.0024\ d_m$ | −0.608 | 0.006 | 16.3 |
| Yubae Maru | $-0.594-0.0013\ d_m$ | −0.613 | 0.015 | 24 |
| Sapporo Maru | $-0.594-0.0010\ d_m$ | −0.609 | 0.007 | 23 |
| Gosei Maru | $-0.599-0.0010\ d_m$ | −0.613 | 0.012 | 14.5 |
| Ei-sen 761 | $-0.594-0.0012\ d_m$ | −0.613 | 0.004 | 14.2 |
| Shinkoku Maru | $-0.606-0.0008\ d_m$ | −0.622 | 0.005 | 24.1 |
| Nippo Maru | $-0.608-0.0002\ d_m$ | −0.613 | 0.001 | 31.3 |

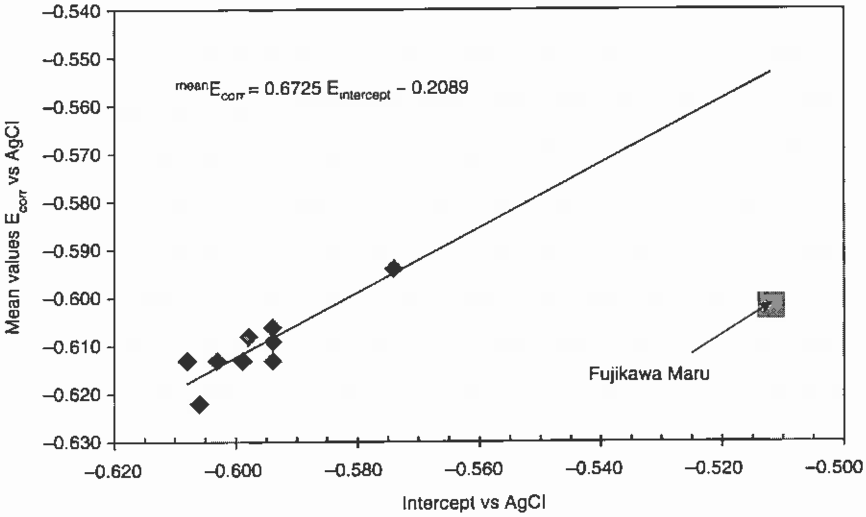

Figure 3. Mean $E_{corr}$ values of hull plates versus the intercept values of the $E_{corr}$ versus depth equations.

and the *Ei-sen 761* tugboat, all of which have about half the sensitivity of the other wrecks, with an average fall of 1.2mV/m of increased water depth. The least affected wreck appears to be the *Nippo Maru*, which is also the one at greatest depth.

Since the extrapolation of the equations listed in Table 1 to zero water depth provides a measure of the relative corrosion rates of the iron wrecks at the seawater–air interface, the intercept values of $E_{corr}$ at zero water depth were plotted as a function of the mean value of the corrosion potential of each of the wrecks. All the wrecks, apart from the *Fujikawa Maru*, illustrated that there was a definite relationship between the intercept values and the mean $E_{corr}$ of each wreck, which is illustrated in Figure 3. The linear regression had a moderate correlation with $R^2$ value of 0.7934, where $R^2$ is the square of the correlation coefficient, and equation (1) defines the relationship

$$^{mean}E_{corr} = 0.673\ E_{intercept} - 0.209 \qquad (1)$$

Since the *Fujikawa Maru* has a different corrosion mechanism to all the other wrecks it is not unexpected that its values for $E_{corr}$ and the intercept are not described by equation (1) [17]. Inspection of the data in Table 1 indicates that the intercept of the $E_{corr}$ versus depth equation for the *Fujikawa Maru* is greater than 80mV more anodic than all the other wrecks. The significance of equation (1) is that the individual equations for each wreck are interconnected and that the average values of the data from all sites are related to each other through a common relationship between water depth and corrosion potentials.

Having established the relationship between the intercept values of the site specific $E_{corr}$ versus depth equations, a more detailed analysis of the apparently different sensitivities of the $E_{corr}$ values to water depth was undertaken. When the slopes of the linear regressions of the $E_{corr}$ values as a function of depth are plotted against the mean depths at which the measurements were recorded, a very clear trend emerges, which is shown in Figure 4. Thus the apparent differences in which the $E_{corr}$ values on the individual wrecks appeared to be responding to the changing water depth are illusory. The slopes of the $E_{corr}$ versus depth plots are systematically linked to each other. For the *Hino Maru, Sankisan Maru, Sapporo Maru, Yubae Maru, Shinkoku Maru, Nippo Maru* and the *Susuki*, the slopes are defined via the relationship

$$\partial^2 E_{corr}/\partial d_m^2 = -0.0045 + 0.0001\, d_m \qquad (2)$$

where $d_m$ is the mean water depth and the units of the slope are in volts per metre. The above relationship had an $R^2$ value of 0.9322, which shows a very high degree of fit for the seven shipwrecks. When equation

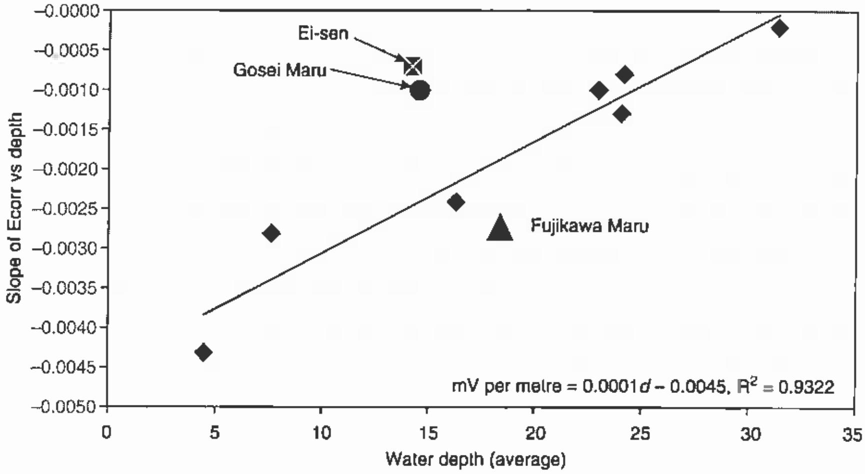

Figure 4. Plot of the slope of the $E_{corr}$ versus depth as a function of mean depth.

(2) is integrated with respect to the mean water depth, the full relationship between $E_{corr}$ and water depth is obtained. Thus the slopes of the $E_{corr}$ versus depth plots for the seven wrecks are all the same and given by the relationship

$$\partial E_{corr}/\partial d_m = -0.0045\, d_m + 0.00005\, d_m^2 \qquad (3)$$

Thus the true dependence of the way in which $E_{corr}$ varies with water depth is shown in Table 2. The data from the *Fujikawa Maru* lie off the general line of best fit and this is due to the different corrosion mechanism operating on this wreck. The two other wrecks that lie outside the relationship are the *Ei-sen 761*, which is in the lee of Dublon Island, and the *Gosei Maru*, which is lying on its side in waters from 4 to 38m. Most of the measurements on the *Gosei Maru* were recorded on the sheltered port side of the vessel, thus it is only natural that these data points should reflect a different sensitivity to water depth than for the other vessels where there was no specific site orientation of the measurement data set. When the $E_{corr}$ versus depth data were compared across the lagoon sites, a re-analysis demonstrated that the *Gosei Maru* showed a similar quadratic dependence on water depth, with the $R^2$ value for the correlation being essentially the same as for the linear regression. The more sheltered nature of the site gave a smaller dependence on depth and the square of the depth, as shown by the equation

$$^{GoseiMaru}E_{corr} = -0.595 - 0.0012\, d_m + 0.000003\, d_m^2 \quad (4)$$

Table 2. Depth dependence of $E_{corr}$ in quadratic and linear forms

| Wreck | $E_{corr}$ vs water depth | $^{mean}E_{corr}$ | Mean depth |
|---|---|---|---|
| Hino Maru | $-0.594–0.0045\ d_m + 0.00005\ d_m^2$ | −0.606 | 4.5 |
| Sankisan Maru | $-0.598–0.0045\ d_m + 0.00005\ d_m^2$ | −0.608 | 16.3 |
| Yubae Maru | $-0.594–0.0045\ d_m + 0.00005\ d_m^2$ | −0.613 | 24 |
| Sapporo Maru | $-0.594–0.0045\ d_m + 0.00005\ d_m^2$ | −0.609 | 23 |
| Shinkoku Maru | $-0.606–0.0045\ d_m + 0.00005\ d_m^2$ | −0.622 | 24.1 |
| Nippo Maru | $-0.608–0.0045\ d_m + 0.00005\ d_m^2$ | −0.613 | 31.3 |
| Susuki | $-0.573–0.0045\ d_m + 0.00005\ d_m^2$ | −0.594 | 7.6 |
| Fujikawa Maru | $-0.512–0.0028\ d_m$ | −0.602 | 18.3 |
| Gosei Maru | $-0.595–0.0012\ d_m + 0.000003\ d_m^2$ | −0.613 | 14.5 |
| Ei-sen 761 | $-0.594–0.0012\ d_m$ | −0.613 | 14.2 |

for which the $R^2$ was 0.9463. The data from the *Ei-sen 761* and the *Fujikawa Maru* showed that their $E_{corr}$ values were not amenable to further analysis. The original apparent sensitivity of $E_{corr}$ to water depth, as presented in Table 1, has been reformatted to present the results of the detailed analysis in Table 2. This confirms that for the majority of the iron wrecks in Chuuk Lagoon there is a common response of corrosion potentials to water depth.

The value of such relationships is that they allow site managers to have a more general tool to use, rather than having to collect data for each individual wreck site across the waters of the lagoon. In simple terms this means that it can be reasonably assumed that the way in which $E_{corr}$ values change with depth for wrecks that are not in a sheltered site or have unusual orientation is straightforward in that there is a simple relationship between $E_{corr}$ and water depth (see equation (3)). The reason why the Chuuk data showed a quadratic rather than a linear dependence on water depth may simply be a reflection of the better quality of the data that were obtained in a very short time frame where the conditions of water temperature, salinity and water movement were essentially constant. Given that the data from open-ocean sites were collected over many years with measurable differences in salinity and temperature, with their concomitant effects on the amount of dissolved oxygen in the surrounding waters, the experimental variables associated with the different sites may have prevented such relationships being discerned.

## EFFECTS OF DEPTH AND CONCRETION FORMATION ON SURFACE pH

When it comes to the interpretation of data from *in situ* corrosion studies, there are inherent challenges with the interpretation of $E_{corr}$ data on intact iron wrecks, since the voltage tends to be reflective of the average local environment of the hull plates and structural elements that are in electrical connection with each other. This means that although the voltage may be measured at a depth of 20m, the electrochemical cell of which that hull plate is a part may extend over a depth range of several metres. pH data have been shown to be 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 [18, 19]. Comparison of how the pH changes with depth on the wrecks is much clearer, as the pH represents the local equilibrium between the corrosion rate and the hydrolysis of the corrosion products with water. The pH is very sensitive to the impact of site disturbances, such as dynamite fishing, and provides a useful indicator of local degradation processes. Since the local corrosion rate is also dependent on the orientation of the vessel and the work history of being exploded, rammed or otherwise scuttled, it is likely that the pH measurements can provide an insight into the significance of such events. The mean pH data for the sites are summarized in Table 3.

In reviewing the data in Table 3 it is noted that the slopes of the pH versus depth plots for the older concretion for the *Hino Maru*, which had the shallowest mean depth of 7.5m, showed the greatest sensitivity of pH to water depth with an increase of 0.39 pH/m. The *Yubae Maru*, *Sapporo Maru* and the *Ei-sen* 761 had similar sensitivity of 0.23 pH/m at 24, 23 and 14.2m, respectively. These large rates of decrease in acidity with increasing water depth indicate that the corrosion rate is very sensitive to water depth. The *Susuki Maru* and *Sankisan Maru* had the same slope of +0.17 pH/m, the *Gosei Maru*

Table 3. Mean pH values for the wrecks of Chuuk Lagoon and effects of water depth

| Wreck | Mean pH | Std deviation pH | pH vs depth *old cover* | pH vs. depth *new cover* |
|---|---|---|---|---|
| Fujikawa Maru | 6.79 | 0.64 | $4.52 + 0.09\ d_m$ | $5.35 + 0.09\ d_m$ |
| Gosei Maru | 6.82 | 0.79 | $3.93 + 0.11\ d_m$ | $5.66 + 0.09\ d_m$ |
| Shinkoku Maru | 6.50 | 0.43 | $6.09 + 0.05\ d_m$ | $5.12 + 0.05\ d_m$ |
| Sankisan Maru | 6.55 | 0.80 | $1.78 + 0.17\ d_m$ | $5.03 + 0.11\ d_m$ |
| Yubae Maru | 7.00 | 0.73 | $0.80 + 0.23\ d_m$ | |
| Sapporo Maru | 7.10 | 0.59 | $1.89 + 0.23\ d_m$ | |
| Hino Maru | 7.22 | 0.45 | $5.48 + 0.39\ d_m$ | |
| Susuki | 7.11 | 0.67 | $5.16 + 0.17\ d_m$ | $5.93 + 0.17\ d_m$ |
| Ei-sen *761* | 7.24 | 0.45 | $3.91 + 0.23\ d_m$ | |

was +0.11 and the *Fujikawa Maru*, at 0.09 pH/m, was the least sensitive wreck.

During the analysis of the pH and depth data from the ten wrecks it was apparent in many instances that there were at least two sub-sets of data that had the same or similar slopes of pH versus depth, but which had clearly different intercept values. The intercepts associated with the lower values, i.e. the more acidic ones, were assigned to the old, thicker concretion, which covered parts of the wrecks. On many of the vessels there were clearly widely differing thicknesses of concretion on the corroding iron surfaces. The thinner concreted surfaces have more alkaline or less acidic intercepts and may be regarded as being most recently formed after traumatic events such as typhoon activity or damage due to dynamite fishing has caused the disbondment of the old concretion. Analysis of the pH and depth data shows that many of the 'old' and 'new' slopes are the same, which indicates that the underlying corrosion mechanism is also the same.

Generally the 'secondary' responses of pH to water depth, which appear to be associated with the thinner layers of concreted metal, show either the same or a lower dependence of pH on water depth. This difference is simply a reflection of the ability of the concretion to act as a semi-permeable membrane that facilitates separation of the anodic and cathodic sites in the corrosion cells and the length of time that the processes have been taking place. The ability of the concretion to act as a diffusion barrier is demonstrated by the systematic difference in the pH of the cast iron and steel, wrought iron on both the *Fujikawa Maru* and the *Gosei Maru*. The higher phosphorus content in the cast iron, through the interaction of anaerobic bacteria, provides a direct stimulant for marine growth [20]. The higher phosphorus levels are reflected in the mean cast iron pH for the *Fujikawa Maru* being 0.46 lower than the surrounding thinner concreted steel. In the same vein the mean pH for cast iron on the *Gosei Maru* is 0.39 pH units more acidic than the mean values of the steel elements. The differences in the pH of the cast iron and steel components on the same wreck are therefore not necessarily indicative of differences in corrosion rate.

The merchant vessels were constructed in Japanese yards between 1919 and 1940 and are likely to have been made from common structural steel alloys associated with contemporary naval architecture codes. Cast iron fittings such as bollards, windlasses and gun mounts will naturally corrode in a different fashion to steel, owing to the dissimilar nature of the phases present in the cast iron, which is much more heterogeneous. The presence of graphite as one of the phases in cast iron is the principal reason why the decayed microstructure retains the original archaeological profile of the objects. Corrosion profiles are recorded only on cast iron objects since these are the only reliable source of information about the accumulated corrosion index of the objects. The more uniform microstructure of the steel generally results in a more uniform corrosion rate across the surface but the low carbon content of the steel means that there is normally no retention of the original profile.

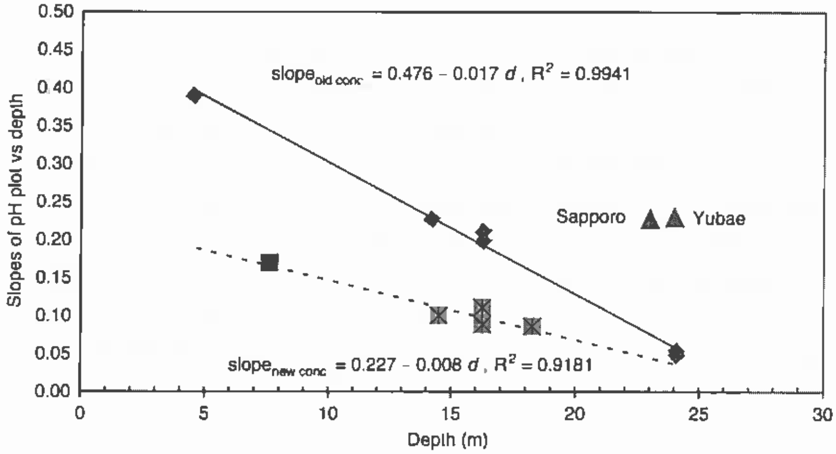

Figure 5. Plot of slope of pH on wreck sites versus water depth.

At the time of sinking, all the vessels would have had protective layers of paint on the steel structural plates that were exposed to seawater. Modelling of the corrosion behaviour of former Royal Australian Navy vessels *Swan*, *Perth* and *Hobart* has shown that, even with military specifications, the seawater penetrates all paint films within a few years [21] so the overall impact of different thicknesses of paint on the long-term corrosion processes of the hull structures is considered to be of minor significance.

A more detailed analysis of the way in which the pH varied with depth was warranted, since the data in Table 3 indicated that there were three different sets of responses of the wrecks, which seemed inherently unsupportable as the sites are so similar. When the slopes of the 'old' and 'new' concreted surfaces of the wrecks are plotted as a function of the mean depth of the sites some marked differences emerge, as seen in Figure 5. The depth sensitivity of pH for the seven wrecks *Shinkoku Maru, Sankisan Maru, Hino Maru* and *Ei-sen* for the older concretion showed that the individual slopes of the pH versus depth plots were indeed dependent on the mean depth of the sites. The regression analysis on the 'old' concretion zones had an $R^2$ value of 0.9856, with an intercept of 0.476 ± 0.018 and a slope of −0.017 ± 0.001, with the general relationship being given by equation (5) in which $d_m$ is the mean depth of the site in metres

$$\partial^2 \mathrm{pH}^{\mathrm{old}} / \partial d_m{}^2 = 0.476 - 0.017\, d_m \qquad (5)$$

Thus the apparent variable sensitivity of the pH on water depth for the *Shinkoku Maru, Sankisan Maru, Hino Maru* and *Ei-sen* can be reformatted in the integrated form of equation (5) to show that for these wrecks the pH has a quadratic dependence on water depth of the form

$$\partial \mathrm{pH}^{\mathrm{old}} / \partial d_m = +0.476\, d_m - 0.0085\, d_m{}^2 \qquad (6)$$

It is noteworthy that the sensitivity of pH on depth is roughly one hundred times greater than the sensitivity of the $E_{corr}$ values, which indicates the value of conducting such measurements on the wreck sites since the pH value is very sensitive to changes in apparent corrosion rate.

Inspection of the data in Figure 5 shows that the *Yubae Maru* and the *Sapporo Maru* have a much greater sensitivity of pH to depth than would be predicted by equation (6). The lower sensitivity shown by the *Fujikawa Maru, Gosei Maru, Susuki Maru* and the newer concretions on the *Sankisan Maru* are indicators that the three sites for which the apparent 'old' concretion sensitivities do not conform to equation (5) have been strongly affected by episodes of dynamite fishing or by the impact of natural deconcreting forces associated with typhoons. Given that the *Sapporo Maru* had been found only a few weeks before the *in situ* corrosion measurements were carried out it is most unlikely to have been subjected to the illegal activity of dynamite fishing. The greater depth of this vessel and the *Yubae Maru* may have also been of assistance in saving the sites from such disturbances. Thus the apparently much higher sensitivity of the more heavily concreted *Sapporo Maru* and the *Yubae Maru* may turn out to be a true reflection of the undisturbed state of the iron wrecks.

The way in which the pH versus depth slopes varied for the *Fujikawa Maru, Gosei Maru, Susuki Maru* and the newer concretions on the *Sankisan Maru* is given by equation (7), for which the $R^2$ value was 0.9181 with an intercept of 0.227 ± 0.021 and a slope of −0.0079 ± 0.0014, as shown below

$$\partial^2 \mathrm{pH}^{\mathrm{new}} / \partial d_m{}^2 = 0.227 - 0.0079\, d_m \qquad (7)$$

The equations for the 'old' and 'new' concretions have the same value at a depth of 27.7m, which indicates that at this depth, the amount of water movement has diminished to such a point that there is no net effect of increased water depth on the local corrosion rate. The observation that the slopes for the 'old' and 'new' concreted surfaces on the *Fujikawa Maru* and the *Gosei Maru* are the same and that the data on pH sensitivity of the *Susuki Maru* are described by the same equation as the 'new' concretion on the *Sankisan Maru* indicates that these wrecks have been subjected to extensive dynamite fishing or other related activities.

It is useful to compare the corrosion behaviour of wrecks that have similar average depths but have differing aspects with regard to wreck orientation or physical location on the slopes of underwater cliffs or in the lee of islands. The *Gosei Maru* and the *Ei-sen 761* have similar mean depths and the *Gosei Maru* mean pH is 6.82 while the *Ei-sen 761* is 7.24. The lower acidity of the *Ei-sen 761* is consistent with the sheltered nature of

Table 4. Surface pH on Chuuk wrecks and their dependence on depth

| Wreck | Mean pH | pH vs. depth old | pH vs. depth new |
|---|---|---|---|
| Fujikawa | 6.79 | $4.52 + 0.227\ d_m - 0.0040\ d_m^2$ | $5.35 + 0.227\ d_m - 0.0040\ d_m^2$ |
| Gosei | 6.82 | $3.93 + 0.227\ d_m - 0.0040\ d_m^2$ | $5.66 + 0.227\ d_m - 0.0040\ d_m^2$ |
| Shinkoku | 6.50 | $6.09 + 0.476\ d_m - 0.0085\ d_m^2$ | $5.12 + 0.476\ d_m - 0.0085\ d_m^2$ |
| Sankisan | 6.55 | $1.78 + 0.476\ d_m - 0.0085\ d_m^2$ | $5.03 + 0.227\ d_m - 0.0040\ d_m^2$ |
| Yubae | 7.00 | | $0.80 + 0.23\ d$ |
| Sapporo | 7.10 | | $1.89 + 0.23\ d$ |
| Hino | 7.22 | $5.48 + 0.476\ d_m - 0.0085\ d_m^2$ | |
| Susuki | 7.11 | $5.67 + 0.227\ d_m - 0.0040\ d_m^2$ | |
| Ei-sen 761 | 7.24 | $3.91 + 0.476\ d_m - 0.0085\ d_m^2$ | |

the site in the lee of the island whereas the *Gosei Maru* is more exposed. Another pair of wrecks is the *Shinkoku Maru* at 24.1m and the *Yubae Maru* at 24m, where the respective mean pH values are 6.50 and 7.00. The higher acidity of the *Shinkoku Maru* may be a reflection of the fact that it was blown up by torpedoes three times, whereas the *Yubae Maru* was subjected to attack on one principal occasion. The accumulated stress will lead to greater localized corrosion rates on the *Shinkoku Maru*, which is reflected in the more acidic values.

In the light of the data obtained from equations (6) and (7), which determine the true relationship between pH and water depth for most of the 'old concreted' and 'newly concreted', the original data in Table 3 can be reformatted to give the integrated values of how the local pH, and hence the corrosion rate, varies with depth. Thus the pH data can now be viewed as showing a quadratic dependence on water depth, rather than the apparent linear dependence that was indicated when only individual sites were initially assessed. The standardized table for the shipwrecks is shown in Table 4.

The analysis of the way in which the slope of the pH versus depth plots changed with depth showed that the initial classification of the slope of the *Yubae Maru* and the *Sapporo Maru* as being for old concretion was correct and that these two vessels may represent the most intact sites that were measured, in terms of them not having been subjected to some form of major site disturbance that saw massive amounts of old concretion being removed from the surface. The observation that the *Fujikawa Maru*, *Susuki Maru*, *Gosei Maru* and the newer concretion from the *Sankisan Maru* all responded in the same way to mean water depth is a sure sign that the first three sites can be generally viewed as having been subjected to major site disturbance. The sensitivity of the 'old concretion' pH values to water depth is similar to that found on the *City of Launceston* (1865) in Port Phillip Bay, Victoria, which is of a similar size to Chuuk Lagoon at 1915 km² [22, 23].

## USING pH TO CALCULATE AVERAGE CORROSION RATES

Analysis of the way in which the depth of graphitization (corrosion) varied with the pH of cast iron objects showed that for the *Fujikawa Maru* there was a linear relationship between the log of the annualized depth of graphitization $d_g$ in mm/year and the pH of the corroding matrix

$$^{Fujikawa\ Maru}\log d_g = 0.758 - 0.260\,pH \qquad (8)$$

Equation (8) was used to calculate an average corrosion rate for the wreck using the range of pH values at various depths across the site. The mean corrosion rate was 0.124 ± 0.045mm/year. Part of the reason why there is a large scatter in the average results is due to the major site disturbances, which have resulted in the observed *in situ* pH values not being truly reflective of the long-term corrosion microenvironment. In the absence of a large number of data points that provide reliable $d_g$ and pH, it is possible to use relationships such as shown in equation (8) to provide an estimate of the corrosion rate across a site. Owing to the disturbed nature of the *Fujikawa Maru* site, the regression analysis for equation (8) has relatively large errors. This is because the $R^2$ value of 0.8948 was relatively low, which was manifested in the standard deviations of the intercept 0.758 ± 0.573 and the slope of –0.260 ± 0.089. Despite the limitations of the data it is nevertheless useful to have this type of relationship to provide a guide to the apparent corrosion rates.

## EFFECTS OF WATER DEPTH ON CORROSION RATES

Since the corrosion of concreted iron objects in seawater is controlled by the flux of dissolved oxygen to the surface of the encapsulated iron, it is not unexpected to find that the depth of the site has a major impact on the rate of decay of the wrecks and their associated fastenings. Data from the ten wrecks have shown that the water depth has a most pronounced effect on the overall corrosion rate. Wreck locations associated with poorly cast fittings, zones that are galvanically connected to bronze propellers or are associated with gun mountings have high corrosion rates, as noted in Table 5 and shown in Figure 6.

The extent of corrosion of the fittings associated with ordnance (square data points in Figure 6) on the *Fujikawa Maru*, *Hino Maru* and the *Nippo Maru* do not follow the same trends as other ship fittings and hull plates and represent a separate category of objects. The gun mounts are clearly much more extensively corroded than would be expected based solely on the water depth. One of the reasons why the ordnance supports have a much higher corrosion rate than other cast iron objects is due to their very high profile on the wreck site that will cause significant eddying and localized water turbulence around them. Given that the gun barrels and the upper workings of the weapons are subject to the greatest amount of water movement over their surfaces, compared with the bases supporting them, it is also likely that the barrels act as sites for the cathodic reduction of oxygen. In such circumstances this would result in a concomitant increase in the anodic activity of the base supporting structures, hence the higher than anticipated corrosion rates. The different metallurgical structure of the gun barrels and their different chemical composition will naturally make

Table 5. Corrosion rates on Chuuk Lagoon shipwrecks in mm/year

| Vessel | Depth | Corrosion rate (mm/year) | Object | Observation |
|---|---|---|---|---|
| Ei-sen 761 | 10.9 | 0.041 | Base plate at foot of smoke stack | Very sheltered location |
| | 11.6 | 0.093 | Stern bollard | Normal exposure |
| | 14.6 | 0.048 | Windlass | Possibly chill cast iron |
| Sankisan Maru | 2.1 | 0.170 | Top knee of mast | Subjected to wave action |
| | 17.1 | 0.095 | Bollard near kingpost | |
| | 16.4 | 0.550 | Windlass near kingpost, casting defects | Very extensively corroded |
| | 16.5 | 0.107 | Starboard bollard 10m from bow | |
| | 19.7 | 0.065 | Cast iron fitting, unknown function | |
| Fujikawa Maru | 12.2 | 0.112 | Forward bollard port bow | |
| | 12.2 | 0.113 | Rear bollard port bow | |
| | 12.5 | 0.199 | Gun mount | |
| Nippo Maru | 37.7 | 0.111 | Gun turret on the Japanese light tank | Very heavily concreted |
| Yubae Maru | 21.7 | 0.101 | Bollard | |
| | 27.8 | 0.088 | Deck winch | Marked gas evolution |
| | 28.4 | 0.095 | Iron frame near stern | |
| Shinkoku Maru | 23.3 | 0.086 | Cast iron bollard | |
| Gosei Maru | 5.4 | 0.151 | Bollard near stern | Casting porosity issues |
| | 5.4 | 0.095 | Bollard near stern | |
| | 18.8 | 0.089 | Deck winch | |
| | 36.6 | 0.084 | Bollard at bow | |
| Hino Maru | 2.8 | 0.161 | Base of forward gun mount | |
| | 2.8 | 0.327 | Steel brace under gun mount | Extremely corroded |
| Susuki Maru | 3.4 | 0.209 | Frame near bow | Base of spotlight assembly |
| | 7.4 | 0.132 | Windlass winder | High profile of object noted |
| | 8.1 | 0.303 | Stern bollard with copious gas | Suspect galvanic coupling |

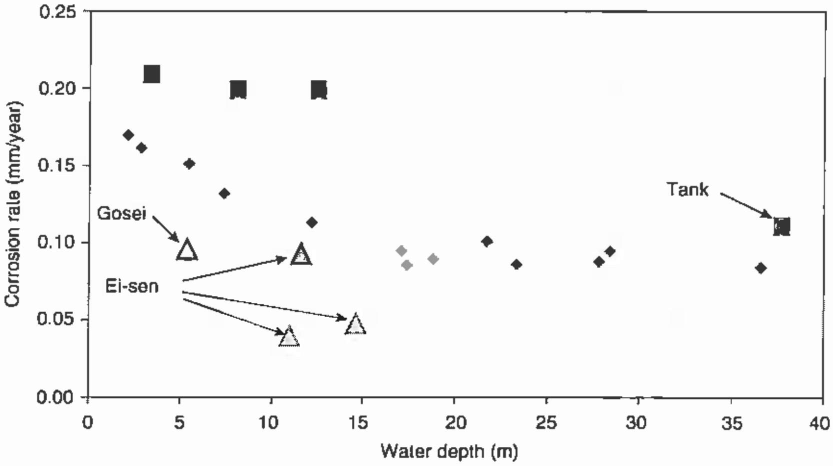

Figure 6. Plot of average corrosion rates as a function of water depth.

them less reactive than the lower quality steel and cast iron used in their support structures and this will also lead to a localized form of preferential iron corrosion. The corrosion rate of the gun base on the *Hino Maru* is very similar to that of the stern bollard on the *Susuki Maru*, which is believed to have been preferentially corroded by its proximity to the large bronze propellers on the vessel [5] (see Figure 7).

It has been previously noted that the location of the data points from the *Ei-sen* and the *Gosei Maru* reflect a lower corrosion activity (triangular points in Figure 6) because of the sheltered nature of the measurement sites. These differences are reflected in their corrosion rates lying below the general data as a function of water depth (diamond points) as shown in Figure 6. The square data points with the cross inside them in Figure 6 are from corroded support systems for guns on the decks of the vessels, or on the turret of a light armoured tank in the case of the *Nippo Maru*.

Figure 7. Gun from the *Hino Maru* showing exposed condition on the wreck site. Diver is Bill Jeffery, photo Jeremy Green.

The corrosion rate for the Chuuk lagoon wrecks has a logarithmic decrease with increasing water depth, as illustrated with the *Sankisan Maru* in equation (9)

$$^{Sankisan\ Maru}\log d_g = -0.7056 - 0.0203\,d \qquad (9)$$

This equation can be used to estimate the corrosion rate on other cast iron fittings and for other iron alloys, after a small correction for the ennobling effect of the carbon content. When equation (9) is used across the *Sankisan Maru* site, which ranged in depth from 2.1 to 19.7m, the mean corrosion rate was 0.090 ± 0.032 mm/year; that is the same as the calculated rates of all the iron fittings and steel plates. Owing to the logarithmic nature of the corrosion rate on water depth, as shown in equation (9), the corrosion rate falls quite quickly with increasing depth. When the data in Table 5 are plotted as a logarithmic function, i.e. log $d_g$ against the depth, where $d_g$ is the corrosion rate measured in mm of graphitization per year of immersion in mm/year, two distinct sub-sets of the general corrosion data become apparent, as shown in Figure 8.

When data from all the wrecks are considered, a general corrosion equation can be developed for the depth range of 0–20m, as shown in equation (10)

$$^{0-20\text{metres}}\log d_g = -0.7314 - 0.0181\,d \qquad (10)$$

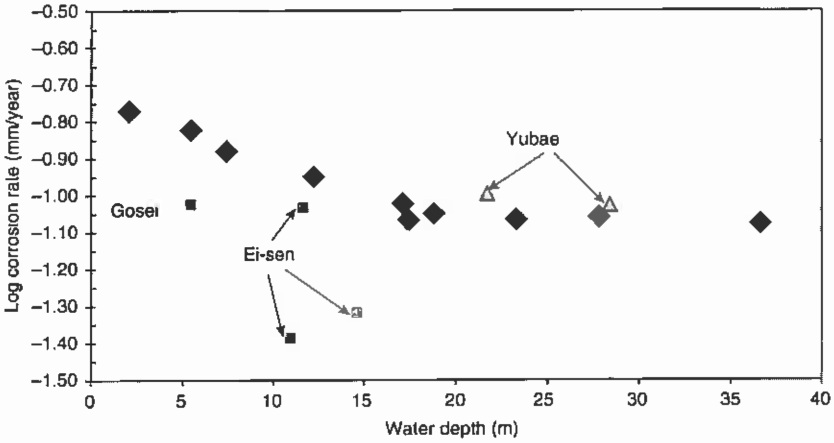

Figure 8. Plot of the log of the annualized corrosion rate for iron shipwrecks

in which $d$ is the depth at which the depth of graphitization was measured. The $R^2$ value for this relationship is 0.9849, which is a remarkably good fit given the very different nature of the sites and the errors associated with determining average long-term corrosion rates. The slope of −0.0181 (0.0010) for the logarithmic corrosion plot means that the corrosion rate falls by approximately 4.2% per metre. The intercept, i.e. the corrosion rate at the seawater–air interface, had a value of −0.731 ± 0.012, which equates to an annual corrosion rate of 0.186 ± 0.005mm/year. The data from equation (9) for the *Sankisan Maru* gave a surface corrosion rate of 0.197mm/year, which is very close to the average value determined by equation (10). The averaged slope for this line of best fit (equation (10)) is statistically indistinguishable from the slope of −0.020 ± 0.006 per metre for the *Sankisan Maru.*

Having established a general corrosion equation for the shallower wrecks in Chuuk lagoon it is possible to then use it to compare the observed depths of corrosion with those predicted and use the differences to obtain an estimate of the impact of the local microenvironment. For a sheltered bollard on the *Gosei Maru,* the observed corrosion rate is 36% lower than that calculated on depth alone. The object was sheltered from the prevailing wind-driven water movement, but a bollard at a similar depth that was not sheltered had the 'normal' corrosion rate. In the case of the *Ei-sen 761* tugboat, the corrosion rates were lowered because the site lies in the lee of Dublon Island. The reduced rates varied from 19% lower for a bollard at 11.6m to 52% lower for the windlass at a depth of 14.6m. The presence of a large amount of finely dispersed silty sediment may have lowered the conductivity of the concretion on the *Ei-sen 761* and thereby lowered the corrosion rate.

Analysis of the data from the deeper wreck sites shows that the *Yubae Maru* has a higher corrosion rate than other vessels and this may be a reflection of the increased physical stresses associated with the upside down orientation of the ship. Data from the remaining wrecks are very limited and more studies are needed to confirm the applicability of the corrosion equation. For the deeper water sites, the apparent rate of corrosion is given by

$$^{20-38\,\text{metres}}\log d_g = -0.889 - 0.0052\,d \qquad (11)$$

For equation (11) the $R^2$ value for the four data points was 0.7928, the intercept value was calculated to be −0.889 ± 0.055 and the slope of the log of corrosion rate versus depth was 0.0052 ±0.0018. The intercept value predicts a corrosion rate of 0.129 ± 0.023mm/year for objects at the seawater interface. This is significantly lower than the value of 0.186 ± 0.005mm/year based on the vessels in the shallower waters that are much more strongly agitated by wave action and by the eddying effects of local currents. Since the data used to estimate the variables in equation (10) do not reflect any shallow water sites, the value of the intercept has relevance only for determining the corrosion rates in the 20–38m range of water depths.

This lowered dependence of corrosion rate on depth for the deeper sites is equivalent to a drop of

1.1% per metre, compared with 4.2% for the shallower sites. If we use equation (11) to calculate the expected corrosion rates on the *Yubae Maru* fittings at 21.7m, the observed value is 1.4% higher than anticipated and the fitting at 28.4m is some 3.3% higher than would otherwise be surmised on the basis of the above relationship. Given that the *Yubae Maru* is upside down, with physical pressures on fittings that were not meant to be load-bearing etc., it is reasonable to expect the vessel to be corroding at a faster rate than would be predicted on the basis of only the water depth. In order to improve the precision of the corrosion equation (11), more data need to be collected in the range of 20–38m of water. The slope of the log corrosion rate versus depth equation for the deeper water sites is 1.9 times less than the shallower sites. This is largely a reflection of diminished water movement from wave action than in the shallower sites. The nature of the flux of dissolved oxygen in Chuuk lagoon is further complicated by the fact that the floor of the lagoon appears to be subjected to influx of fresh water from underground springs. This would cause lower salinity at the bottom, which could reduce the impact of chloride ions but would increase the concentration of dissolved oxygen [24, 25]. Data from corrosion simulation experiments indicate that the corrosion rate of cast iron falls off in a linear fashion with the logarithm of decreasing concentration of chloride [26]. The plots of equations (10) and (11) for the shallow water and the deep water sites intersect at a depth of approximately 18m.

The author has previously reported how the corrosion rate of iron wrecks in open ocean environments varied as a function of water depth [27]. Using the criteria of the best $R^2$ value, the data fitted best to a quadratic equation, which gave a minimum corrosion rate at a depth of 27m. The mathematical implications of this relationship were that the corrosion rate would increase beyond that depth, which clearly has no physical reality. It is of interest that the calculated depth for the minimum corrosion rate for open-ocean sites is essentially the same depth as that predicted for the shallower Chuuk sites at which the pH of the corroding iron would be independent of depth. When the corrosion rates of the open-ocean sites were plotted on a logarithmic scale, see equation (12)

$$^{\text{open-ocean}}\log d_g = -0.630 - 0.0156d \qquad (12)$$

the $R^2$ value was only marginally lower than that for the published quadratic equation, where $d_g$ and $d$ have their normal definitions. The slopes of the log corrosion rate versus depth plots for the *Sankisan Maru* and the shallow-water Chuuk equation (equations (9) and (10)) are the same within experimental error, but are 16% steeper than that for the open-ocean sites. The *Sankisan Maru* is characterized by good marine growth and a wreck deposition trail that provides access to a number of measurement points that cover a good range of water depth. The greater sensitivity of the Chuuk sites to water depth is simply a reflection of the different amounts of water mixing in the two marine environments.

The differences between the Chuuk slope and the open-ocean slope is greater than 1.3 times the sum of

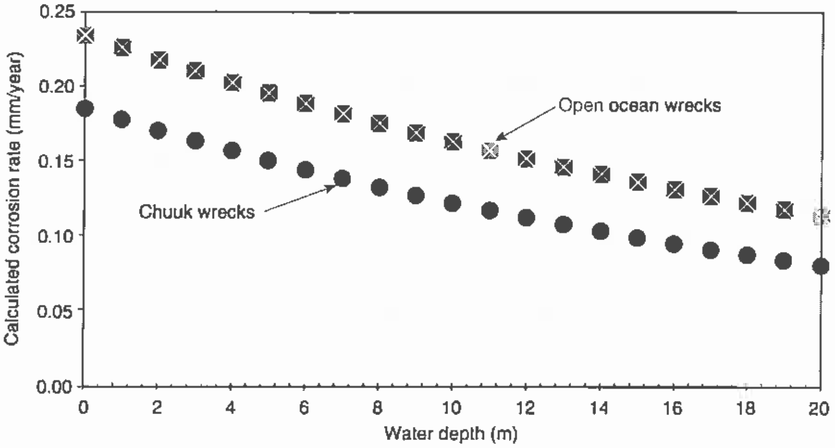

Figure 9. Comparative plot of predicted iron corrosion rates in open-ocean versus Chuuk lagoon.

the errors associated with the plots, so the slopes are statistically significantly different. The different slopes mean that the corrosion rate for shipwrecks in Chuuk Lagoon decreases 16% more than for open-ocean wrecks per metre of increased water depth. A summary of the equations used in calculating corrosion rates for shipwrecks in open-ocean environments and in the sheltered waters of Chuuk Lagoon is shown in Table 6. The impact of the lagoon environment on the overall corrosion rates of the vessels is readily apparent when the intercept values of the corrosion equations are compared, as seen in Figure 9 at the depth of 0m, where the annual corrosion rate for the Chuuk sites is 0.186mm/year or 21% lower than the open-ocean value of 0.235mm/year.

The lower corrosion rate of the Chuuk sites is essentially due to the more sheltered nature of the lagoon waters. The differences in corrosion rates increase with depth so that by 20m the Chuuk sites are predicted to be corroding 29% slower than the open-ocean analogues. The previous history of the vessels is also seen to have an impact on the way in which they are corroding. Those vessels that had been previously torpedoed and repaired (the *Shinkoku Maru* and the *Yubae Maru*) appear to be corroding faster than vessels that had no previous history of physical damage. It is likely that stresses in the steel, either from the accumulation of stress from having been blown up and repaired or the stresses associated with the catastrophic shipwrecking processes, are being reflected in elevated corrosion rates. An example of such processes may be the way in which hull plates are falling off the *Yubae Maru*, which is also stressed by lying upside down on the seabed [28]. Physical observations from divers and the historical record are of assistance in determining the nature of the deterioration processes and how to develop appropriate management strategies that address these issues.

## CORROSION OF ORDNANCE FIXTURES

The very high corrosion rates of the gun support structures has been previously noted in terms of preferential corrosion associated with the widely dissimilar nature of the metallurgical and chemical composition of the gun barrels and their bases. Differences in chemical and microstructural composition may be further exacerbated by the high profile of the ordnance, which leads to the gun barrels being sites for cathodic reduction of oxygen and the supports acting as corrosion sites. Despite the limited amount of data, the four supports indicate a familiar logarithmic trend with water depth, as shown in equation (13)

$$^{\text{ordnance}}\log d_g = -0.488 - 0.0097\,d \qquad (13)$$

for which the $R^2$ value is 0.8482, $d_g$ and $d$ have their normal meanings. The intercept value of −0.488 ± 0.006 equates to a surface corrosion rate of 0.325 ± 0.044mm/year and slope was −0.0097 ± 0.0029. The errors associated with the slope and intercept are a reflection of the relatively low value of $R^2$, the square of the correlation coefficient. The differential corrosion rate of the gun support compared with the actual gun barrel is exemplified by the measurements carried out on the *Hino Maru*. The observed corrosion rate of 0.162mm/year for the *Hino Maru* gun barrel is the same as 0.165mm/year from the general Chuuk corrosion equation (equation (10)), however the gun base has suffered a 24% increase in corrosion over what would have been expected from the general corrosion equation. The slope of the logarithmic plot for the gun supports is roughly half that of the normal wreck materials and the surface corrosion rate is 74% higher than that predicted for general iron fittings, as shown

**Figure 10.** Conservators drilling into the turret of the Japanese light tank on the deck of the *Nippo Maru*. Note the extensive marine growth on the cast steel structure. Photo Bill Jeffery.

from the intercept of the Chuuk shallow-water corrosion rate equation. Further studies on this type of object are needed to fill in the data gaps between the *Fujikawa Maru* at 12.3m and the *Nippo Maru* tank at 37.7m, as seen in Figure 10.

## CALCULATED RATES FOR LOSS OF SHIPWRECKS

Open-ocean studies have used the relationship between the depth of graphitization and the $E_{corr}$ values to estimate corrosion rates across a wreck site, since the $E_{corr}$ values have been found to relate to a series of essentially isolated structural elements of the wrecked vessel [29]. Owing to the relatively small number of years since the wrecking events in Chuuk, the wrecks are largely intact, with major elements of the vessels being in direct electrical contact with each other. Under these conditions it was found that the $E_{corr}$ values often reflected the corrosion microenvironment of local areas rather than specific objects. The review of corrosion data from the Chuuk wreck sites has shown that the most reliable method of assessment of corrosion across the sites can be obtained from corrosion and depth relationships, as exemplified by equation (9) from the *Sankisan Maru* and the general Chuuk lagoon corrosion equation (10). For comparative purposes it is useful to contrast the calculated corrosion rates with the data collected at different water depths from specific parts of the wreck where cast iron objects could be measured. The $E_{corr}$ and pH data on the *Sankisan Maru* were collected at depths ranging from 2.1 to 29.5m, and these depths were used to gain a number of calculated corrosion rates via equation (9)

$$^{Sankisan}\log d_g = -0.7056 - 0.0203\text{m} \qquad (9)$$

Results from the calculations are shown in Figure 11 and the mean of the calculated values was 0.093 ± 0.032mm/year, which is the same as the average value of 0.090 ± 0.032mm/year that was based on the observed depths of graphitization. The anomalously high corrosion observed on the windlass at 32mm in 60 years is probably due to a combination of galvanic action and very poor casting techniques and was not included in the calculation of the mean corrosion rate.

The Chuuk government had requested advice as to the length of time that could reasonably be expected for their wrecks to survive in their current configuration. Rather than being primarily a matter of heritage resource management the issue is of vital significance to the local economy, which depends heavily on diving cultural tourism. In previous studies measurements of residual metal thickness, combined with data on the long-term corrosion rates, have been combined to provide an estimate of how long before collapse can be expected in a vessel [19, 29]. Since budget constraints prevented measurements of existing metal thickness being conducted during the *in situ* studies, estimates of the length of time before loss of

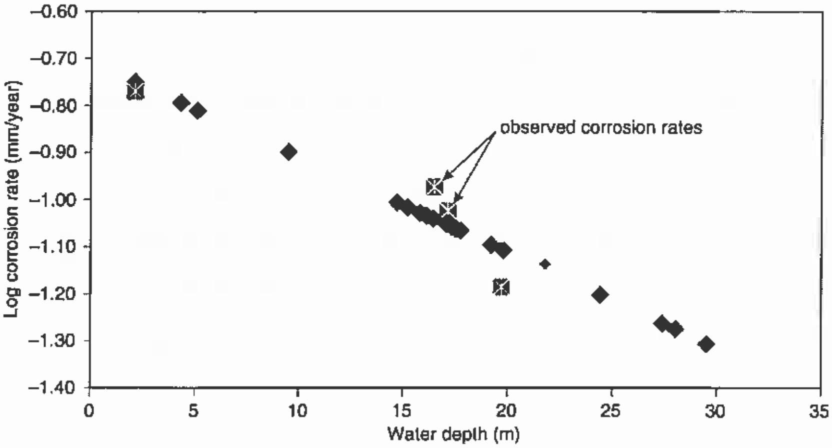

Figure 11. Logarithmic values of the calculated corrosion rate on the *Sankisan Maru*.

Table 6. Comparative corrosion equations for Chuuk wrecks and open-ocean sites

| Equation values | *Sankisan Maru* | Chuuk shallow sites | Open-ocean shallow | Chuuk deep sites |
|---|---|---|---|---|
| Slope | −0.0203 ± 0.0056 | −0.0181 ± 0.0010 | −0.0156 ± 0.0009 | −0.0097 ± 0.0029 |
| Intercept | −0.706 ± 0.087 | −0.731 ± 0.012 | −0.630 ± 0.010 | −0.488 ± 0.059 |
| $R^2$ values | 0.8665 | 0.9849 | 0.9818 | 0.8482 |

metal thickness have to be made on the basis of existing literature on Japanese merchant vessels. The primary source of data is that associated with the rules from the Lloyds Registers for scantlings. The thickness of the steel used in construction of merchant vessels is controlled by a set of ratios of length, breadth and width, which may have been used in the specifications for the construction of the vessels. Estimates of the overall corrosion rates on various sites have been made using both the mean of the observed depths of graphitization and the general equation for the wrecks in shallow waters. The results of these calculations are summarized in Table 7 and there is good agreement between the rates calculated by the general equation (11) and the average rates calculated from specific depths of graphitization. Given that the internal faces of the ribs, frames and hull plates will also be corroding, though not necessarily as fast as on the seaward face because of less water movement, the calculations of the 'life expectancy' of the fixtures has been adjusted downwards on the assumption that the internal corrosion rate is 30% of the external corrosion rate.

The calculations are based on mean corrosion rates observed at the individual site locations on the actual wrecks: naturally different parts of a ship will perforate at different rates owing to the differences in original thickness of steel used in the construction. Since the author did not have the original specification of the wrecks, the dimensions of the scantlings have to be estimated. The Lloyds Rules [29] provide guidance as to the range of metal thickness used in the construction of the vessels. For example, a vessel of 6938 tons, such as the *Fujikawa Maru*, would have deck plates that ranged from 9.1 to 11.2mm, garboard strakes 13.7–15.2mm, plates from the upper turn of the bilge (UTB) to the sheer strakes 11.7–16.3mm. Estimates of how long the average corrosion rate would take to penetrate the plates or frames are listed in Table 7 and the typical error associated with the calculations is of the order ±15%. The range of values for the anticipated times for total metal loss reflect the listed variations in the thickness of steel in the Lloyds Rules.

The anticipated time for total metal loss has been corrected for the 61 years since the vessels were sunk in Operation Hailstone, using the assumption that the average corrosion rate has been applied for all that time. Since the calculated and observed corrosion rates are fundamentally based on the drilled cast iron objects, the data do reflect the net accumulated impact of human and naturally destructive events in the lagoon. The negative numbers in parentheses indicate that there should be no solid metal left in 2005 and the years relate to the time elapsed since total metal loss occurred. Inspection of the *Fujikawa Maru* deck showed several areas of total metal loss, as seen in Figure 12, also seen on some of the bridge plating, which is consistent with the calculated data of there being no residual metal thickness expected for these structural elements. Similarly the *Gosei Maru* has some holes in the deck plating and most of the area appears to be

Table 7. Number of years for perforation post 2005

| Mean corrosion (mm/year) | Fujikawa Maru | Gosei Maru | Sankisan Maru | Yubae Maru |
|---|---|---|---|---|
| Observed (mm/year) | 0.123 ± 0.018 | 0.105 ± 0.031 | 0.110 ± 0.045 | 0.095 ± 0.070 |
| Calculated (mm/year) | 0.119 ± 0.013 | 0.086 ± 0.010 | 0.092 ± 0.032 | 0.109 ± 0.007 |
| Garboard | 16–9 | 31–17 | 62–46 | 39–30 |
| Garboard to Upper Turn Bilge (UTB) | 19–16 | 17–15 | 54–30 | 32–28 |
| UTB to Sheer Strake | 19–14 | 17–15 | 50–25 | 32–27 |
| Frames | 11–5 | 24–(−5) | 41–25 | 28–7 |
| Deck | (−2)–(−12) | 32–(−5) | 25–3 | 28–7 |

Figure 12. Deck of the *Fujikawa Maru* showing loss of deck plating from corrosion and spalled metal surfaces exposed after recent 'dynamite fishing'.

structurally intact. One important safety issue is that a wreck may well collapse when metal thicknesses are reduced to a few millimetres. This was observed in Port Phillip Bay in Victoria, Australia, with significant collapse of the structure some five years after frame and plate thickness had been reduced to a measured value of only 3mm [30]. The heavier *Yubae Maru* and the *Sankisan Maru* would have had similar thickness of the garboard strake plates and so the ranges of 39–30 years for the *Yubae Maru* and 62–46 years for the *Sankisan Maru* indicate that these parts of the vessel have a good life expectancy and that conservation management issues will not become a major issue for several decades.

In order to be sure of the extent to which the internal corrosion rate of the vessels is contributing to the overall rate of decay, it is essential to obtain a series of measurements of actual residual metal thickness on a number of wrecks. The choice of wrecks would be predicated by the physical differences at the site, i.e. sheltered, exposed, vessel upside down, on the side, etc. The case of the *Yubae Maru* is unusual since the data in Table 7 indicate that the hull plates and frames require roughly 30 years before perforation occurs. It is important to note that the supporting frames have only seven years left in them, which may account for the fact that whole plates are spalling off the frames, as distinct from hull plates developing lacunae. This phenomenon may be a reflection of the stress associated with the nature of the upside down wreck. The estimates for the length of life of the *Sankisan Maru* vary from 62 to 25 years for loss of the main structural elements, however the deck would be the first area to be lost. Before any detailed management plans can be drawn up, further work on the residual metal thickness of the structures on the wrecks has to be conducted to allow testing of the corrosion models. Despite the limitations of the calculations it is apparent that some form of physical intervention to halt or slow down the rate of corrosion is needed to ensure that penetration diving remains a safe cultural experience.

## RECOMMENDATIONS REGARDING SITE MANAGEMENT STRATEGIES

Examination of the way in which the pH varies with depth has also shown clear evidence of episodic changes to the microenvironment of the wrecks. Such changes are consistent with major microenvironmental damage that fits in with physical impact of either shockwaves from dynamite fishing or from massive tropical storms. Such periodic shedding of the protective layers of marine concretion cannot be allowed to continue, since this will inevitably result in an increased rate of decay of the shipwrecks. At this stage it is not possible to determine from our data whether such periodic stripping is a result of typhoons or from dynamite fishing, but anecdotal community evidence strongly indicates that explosions play a major role. It is essential that all dynamite fishing on the wreck sites be outlawed through the passage and enactment of appropriate legislation.

Further studies on sheltered wrecks such as the *Ei-sen 761* tug boat and the *Gosei Maru* are needed to quantify the nature of the protection and to determine how much is due to the influence of site conditions such as turbidity and how much to sheltering from the normal agitation associated with wind-borne wave action. The apparently good state of preservation of the *Fujikawa Maru* was indicated by the different corrosion mechanism that was operating on the site and by the fact that most of the $E_{corr}$ measurements showed that the steel plates, deck beams and knees were electrically interconnected. This is in marked contrast to many of the other wrecks that were examined. Apart from a more detailed examination of the vessel, its engine and the contents of the cargo holds, new data on the residual metal thickness are needed. Through a combination of archival data on the original dimensions of the scantlings and the residual metal thickness, it will be possible to determine the net corrosive microenvironment of the wreck and develop appropriate conservation management plans.

In order to obtain reliable data on residual metal thickness, it is necessary to deconcrete areas of 5–8cm in diameter, since practice has shown that the sensing head of the ultrasonic metal thickness gauge needs to be moved across the surface until a good echo is found. Once a semi-uniform substrate is located, reproducible readings are obtained. Damage to the underlying metal caused by removal of the protective concretion zone will be avoided through the use of underwater putty that will 'patch' the area. This approach was used to good effect in the pre-disturbance studies on the *H.L. Hunley* submarine in Charleston Harbour prior to its recovery and conservation treatment [31]. An environmentally sustainable cathodic protection system could involve power being generated by an array of photovoltaic cells located on support racks on a diving platform anchored near the site. Cathodic current would be carried through insulated cables to the wreck to perform *in situ* electrolysis while anodes, consisting of mixed metal oxides, would produce oxygen. The diving platform could also be used for interpretative information about the nature of the wreck and have items such as a diving and photographic checklist of highlighted and numbered areas that provide the best image record of the experience of visiting the wreck.

A detailed examination of the wreck of the *Susuki* Patrol Boat is needed to clarify the effects of the collision damage to the vessel and the corrosion performance of the new bow compared with the original structure. Characterization of the apparent impact relating to galvanic and proximity corrosion phenomena is also needed. A metallurgical and physical examination of material from one of the shed hull plates on the wreck of the *Yubae Maru* is needed to determine the corrosion mechanism that is operating on this upside down shipwreck and to determine if the shedding is due to preferential corrosion of the weld zones. More data should be collected from cast iron fittings at depths between 20 and 40m in order to gain a better understanding of the mixing processes that are controlling the microenvironment of the lagoon. The acquisition of detailed physical chemical data on the dissolved oxygen concentration, salinity and temperature profiles on typical sites would improve the reliability of interpretation of the corrosion data.

## CONCLUSION

Analysis of the corrosion processes occurring at ten shipwreck sites in Chuuk Lagoon has shown that the routine measurement of depths of graphitization of the cast iron objects, measurement of the *in situ* pH and corrosion potentials can provide a wealth of information about the nature of the wreck processes. The data collected in two weeks of field studies have revealed the effects of distribution of the vessels in the underwater environment and have established quantitative differences in the corrosion performance of the ships as a result of being upside down, exploded, lying on their side or being in the lee of a nearby island. From the observed corrosion data it has been possible to develop models for predicting the time of collapse of structural elements of the vessels, which has important diving tourism implications as well as major occupational health and safety site management implications.

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## ● Corrosion et gestion pour la conservation de naufrages en fer dans la Lagune Chuuk, Etats Fédérés de la Micronésie

**Ian Donald MacLeod**

### RÉSUMÉ

En 2002, au sein d'une étude sur les valeurs culturelles de sites de naufrages, une série de mesures de la corrosion in situ a été menée sur des embarcations mercantiles et militaires japonaises de la Seconde Guerre Mondiale, qui ont été coulées en 1944 dans la Lagune Chuuk (Truk). Les données proviennent de la perte épisodique de la couche de protection de concrétion marine, qui augmente directement la corrosion du métal sous-jacent et élimine l'information sur l'évolution du microenvironnement. Il est vraisemblable que la peche à la dynamite soit la cause plus probable de ces pertes. Toutes les embarcations, sauf le *Fujikawa Maru*, ont montré un mécanisme de corrosion qui est commun aux naufrages historiques en fer. La sensibilité apparente des potentiels de corrosion et le pH des interfaces de corrosion face à la profondité dans l'eau a été interprété en fonction de la quantité globale d'eau en mouvement et de l'aspect ou de l'orientation des naufrages, c'est-à dire si celle-ci se trouvait en position horizontale, inversée ou inclinée. Les équations du degré de corrosion servent à prévoir que la plupart des naufrages de la Lagune Chuuk maintiendront leur intégrité pour une période de dix à quinze ans, avant de souffrir des collapses importants. Les degrés de corrosion de la Lagune Chuuk sont de 26% à 30% inférieurs à ceux des embarcations en fer qui se trouvent à la même profondeur à mer ouverte.

## ● Corrosión y manejo para la conservación de naufragios de hierro en la Laguna Chuuk, Estado Federados de Micronesia

**Ian Donald MacLeod**

### RESUMEN

En 2002, dentro de un estudio sobre los valores culturales de sitios de naufragios, se realizó una serie de mediciones de corrosión in situ en embarcaciones mercantiles y militares japonesas de la Segunda Guerra Mundial que fueron hundidos en 1944 en la Laguna Chuuk (Truk). Los datos provienen de la pérdida episódica de la capa de protección de concreción marina, que aumenta directamente la corrosión del metal subyacente y elimina información acerca de la evolución del microambiente. Es posible que la pesca con dinamita sea la causa más probable de tales pérdidas. Todas las embarcaciones, excepto el *Fujikawa Maru*, mostraron un mecanismo de corrosión que es común en los naufragios de barcos históricos de hierro. La aparente sensibilidad de los potenciales de corrosión y el pH de las interfaces de corrosión ante la profundidad en el agua se interpretó en función de la cantidad global de movimiento del agua y del aspecto u orientación de los naufragios, es decir si se encontraban de manera horizontal, volteados o inclinados. Las ecuaciones del grado de corrosión predicen que muchos de los naufragios en la Laguna Chuuk mantendrán su integridad por diez o quince años más, antes de sufrir colapsos importantes. Los grados de corrosión en la Laguna Chuuk son de 26% a 30% inferiores en comparación con los barcos en hierro hundidos a la misma profundidad en mar abierto.