Dynamic interaction of marine ecosystems with wrecks in Chuuk Lagoon, Federated States of Micronesia

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Abstract

Based on measurements of biotic factors and electrochemistry of submerged wrecks, it has been shown that surface roughness (rugosity) created by encrusting marine biota affect localised turbulence and corrosion processes. Data showing the relationship between rugosity and changes in the E_{rr} and the pH of the metal-concretion interface are reported as preliminary observations of the first direct evidence that biological processes materially affect the decay of historic shipwrecks and aluminium aircraft.

Keywords: marine growth, corrosion, shipwrecks, aircraft, World War II

Introduction

This work reports the preliminary observations of the relationship between biological colonisation data of wrecked ships and aircraft and the in situ corrosion potentials (E_{corr}) and pH of Japanese wrecks in Chuuk (Truk) Lagoon, approximately 7°N and 152°E, in the Federated States of Micronesia. Descriptions of the wreck sites and their cultural significance have been recently reported (Jeffery 2004a and 2004b; MacLeod 2005, MacLeod 2006a). In-situ data was collected during July and December 2006. The survey in 2002 showed evidence of the impact of dynamite fishing, wreck orientation, depth and the sheltering effects of nearby islands (MacLeod 2006b). Deterioration of encrusted iron shipwrecks is logarithmically dependent on the water depth and the flux of oxygenated seawater (MacLeod 2006b) which is partially regulated by the surface roughness of the substrate. All the wrecks were created in February 1944 during bombing raids by aircraft from the US Navy carrier supported strike force (Bailey 2002) and the iron wrecks are protected by layers of marine concretion. Damage to the concretion creates a differential corrosion microenvironment which accelerates corrosion of the underlying metal (MacLeod 2002). The colonisation of aluminium aircraft is generally patchy, as seen on the Emily flying bomber, because aluminium corrosion products are biologically inert (Kamimura and Araki 1984). This paper presents the first preliminary study of relationships between living marine concretions and corrosion mechanisms. The corrosion potentials were measured with a platinum electrode to make contact with the metal and a silver chloride reference electrode. The total depth of drill bit penetration (mm) into the concretion and corroded metal zone t_d is obtained from a vernier micrometer placed in the hole (MacLeod 2005). Each set of pH and digital multimeters in the waterproof housings were calibrated using standard buffer solutions and the voltages of the $Ag/AgCl_{sea}$ electrodes were calibrated against the voltage of a platinum electrode in a pH 4 solution that is saturated quinhydrone. Water depths were noted from the diver's computer.

Effect of concretion thickness on the pH of corroding metal interface

Although the increased corrosion of iron wrecks caused by massive loss of concretion associated with dynamite "fishing" has been reported (MacLeod 2006b) this paper presents the first data on how thick the new concretion needs to be to re-establish a steady state corrosion environment. Without sufficient thickness of concretion the pH of the solution formed during hydrolysis of the metal ions will not be truly reflective of the corrosion rate. The pH and the t_d data from the *Fujikawa Maru*, the *Yamamoto* (Jeffery 2oo6) and the *Susuki* showed that the acidity increased in a linear fashion with increasing concretion thickness until a plateau was formed. This plateau level indicated the minimum concretion thickness that is needed to get a representative pH value. The iron wrecks all followed relationships such as that shown in equation 1, which for the *Yamamoto* gun boat had an R^2 (square of the correlation coefficient of the linear regression) value of o.9914 and gave equation 1,

$$^{Yamamoto}\mathrm{pH}_{\mathrm{steel}} = 8.31 - 0.44\, t_d \qquad \text{.........................(1)}$$

The response of the other wrecks to the concretion thickness is shown in table 1. A minimum thickness of 8 mm of concretion on cast iron on the *Yamamoto* gun boat was needed before a steady

Table 1: Effect of concretion thickness on the pH of the corroding metal interface

Wreck	Average measurement depth, metres	$\partial pH / \partial t_d$	Intercept	R^2
^{old} *Fujikawa Maru* July o6	20.2	-0.15	8.43	0.9550
^{new} *Fujikawa Maru* Nov o6	3.2	-0.41	8.20	0.9481
$^{stbd.}$ *Susuki* July o6	8.9	-0.66	10.49	0.8760
^{port} *Susuki* July o6	9.0	0.49	12.28	0.8185
^{steel} *Yamamoto* July o6	5.5	-0.44	8.31	0.9914
^{cast} *Yamamoto* July o6	4.8	-0.72	12.48	0.9180

Table 2: Physical and chemical characterisation of four wrecks, December 2006

Wreck site	Site depth metres	Turning point depth	% site depth of turn over	Temp °C	Dissolved oxygen ppm	Salinity ‰
Yamamoto	7	47	67	29.7±0.1	5.0±0.2	35.1±0.1
Susuki	14	7.8	56	29.8±0.1	4.7±0.3	35.1±0.1
Emily	17	8.9	52	30.0±0.1	4.8±0.1	35.1±0.1
Fujikawa	32	30.3	95	30.0±0.2	4.8±0.3	35.1±0.2

Table3: Effects of rugosity R_u an the pH of Chuuk wrecks

Wreck	Average depth, metres	Intercept	Slope of $E_{,o}$ vs. rugosity (volts)	R^2
^{pH} *Fujikawa Maru* July 06	20.2	0.26	+7.62	0.9499
^{pH} *Fujikawa Maru* Nov o6	16.4	3.51	+4.50	0.9148
$^{pH\ thick}$ *Susuki* July o6	8.9	-2.70	+11.0	0.8588
$^{pH\ thin}$ *Susuki* July o6	8.9	-1.90	+11.5	0.9946
^{pH} *Susuki* Nov o6	6.2	0.21	+8.83	0.8365
^{pH} *Yamamoto* July o6	5.0	-0.90	+8.63	0.8367
^{pH} *Emily* July o6	13.7	6.86	+1.04	0.7765

Thick and thin relate to more mature and more recent concretion layers

pH value of 6.0 was attained. There was insufficient data on the steel and wrought iron objects to determine the plateau value.

In table 1, old and new relate to the relative age and thickness of the concretion, stbd. refers to the starboard side and port refers to the port side of the vessel, steel relates to the mild steel structural elements and cast to cast iron fittings. When the slopes of all the pH vs. t_d relationships listed in table 1 are plotted as a function of average water depth, there is a reasonable correlation with the average water depth, the regression analysis had an R^2 of 0.7532, and the relationship between the slopes and depth is given in equation 2,

$$\partial pH / \partial t_d = -0.80 + 0.032\ d_m \quad \text{(2)}$$

For well established sites with good concretion cover it has been shown that the pH of corroding marine iron is quite sensitive to water depth (MacLeod 2006b) as shown in equation 3 for the *Susuki* patrol boat and the *Fujikawa Maru*,

$$\partial pH / \partial d_m = 0.227\ d_m - 0.0035\ d_m^2 \quad \text{(3)}$$

Since the sensitivity of pH on concretion thickness is roughly $^1/_7$ its sensitivity to water depth, it can be seen that the effect of concretion thickness on the pH is of secondary importance compared with depth. In order to obtain representative in-situ corrosion measurements it is important to study well concreted older areas of the vessels.

During measurements on the Yamamoto gun boat it was noted that a large amount of magnetite, Fe_3O_4 was released. When the E_{corr} was plotted against pH, the slope of the equation was consistent with the corrosion process producing magnetite since the slope of -0.011±0.004 volt/pH is equivalent to four protons per electron according to the equation,

$$3\ Fe^{2+} + 4\ H_2O \rightarrow Fe_3O_4 + 8\ H^+ + 2e^- \quad \text{(4)}$$

In 2002 the *Fujikawa Maru* had a different corrosion mechanism compared to those of the other vessels in Chuuk Lagoon (MacLeod 2006b) but measurements in July 2006 showed that the original slope of 59 mV/pH had reverted to the 29 mV/ pH value found on the other iron shipwrecks in the lagoon. The oceanographic environment of the wrecks is remarkably coherent (table 2). In Chuuk Lagoon the salinity of 35.1‰ was constant, the mean site temperatures were 29.9±0.15°C and the average dissolved oxygen was 4.8±0.1 ppm. Despite apparently similar dissolved oxygen levels each site had a measurable profile of oxygen with water depth. The oxygen values gradually fall with increasing depth until they rapidly drop and follow a sigmoidal curve before reaching their minimum at the atoll lagoon floor. The turning point of the oxygen-depth plots is determined by plotting the value of $\log\{DO_{bottom} / (DO_{depth\ x} - DO_{bottom})\}$ against depth which produced a horizontal line intersecting with a rapidly ascending straight line. This data is reported in Table 2 and is also expressed as a percentage of the site maximum site depth.

The *Yamamoto* gunboat is fairly close to the shore off Tonoas, the *Susuki* patrol boat is close to Tonoas near Fefan Island and the Emily lies in sheltered waters between Tonoas and Eten and had been previously been reported as being inherently sheltered. All these sites have their oxygen turning point in the range <67%-52%> of maximum water depth while the *Fujikawa Maru*, lying in the main shipping channel, had a turning point at 95% maximum water depth.

Effects of rugosity on the corrosion processes

The biological survey involved randomly placing four replicate 25cm x 25cm quadrates around the hole drilled to measure corrosion parameters, which was tagged with a numbered plastic tape held in position with underwater epoxy. Rugosity, R_u, ranges from 0 to 1, where 1 relates to a perfectly smooth surface while smaller fractions equate to greater surface roughness. The rugosity and depth of these quadrates were recorded and marine biota within each quadrate was identified. Branching life forms of some of the benthic organisms increase the flow of nutrients to the growing surfaces and this increased turbulence increases the corrosion rate.

For each wreck site the pH and E_{corr}, values were plotted as a function of the rugosity and a series of linear relationships revealed that the corrosion rate, as reflected by less cathodic potentials and more acidic pH values for iron wrecks, was directly proportional to the surface roughness. Because aluminium alloys corrode under a passive film (MacLeod 2006a) compared with the iron wrecks in a film free environment, the sign of the slope of the E_{corr} vs. R_u is opposite to that of the iron wrecks. The E_{corr} and R_u data are shown in figure 1. The slopes of all the pH vs. R plots are all positive which indicated that the acidity increased with increasing roughness (see table 3).

Apart from the July data for the *Fujikawa Maru*, all the slopes of E_{corr} vs. R_u increased with depth as shown in equation 5, for which the R^2 was 0.9387,

$$\partial E_{corr} / \partial R_u = -0.0116 - 0.0043\, d_m \qquad \ldots\ldots(5)$$

where d_m is the mean depth of the combined biological and electrochemical measurement points.

Water movement from wind chop dominates shallower sites and the impact of surface roughness on corrosion becomes more significant with depth. The slopes of the pH vs. R_u plots were also found to be dependent on the mean depth and the *Susuki* and *Yamamoto* data followed equation 6, with an R^2 of 0.9437

$$\partial pH / \partial R_u = 4.72 + 0.73 d_m \qquad \ldots\ldots(6)$$

The *Fujikawa Maru* and *Emily* plots showed a similar slope but with a different intercepts.

Conclusion

The increased turbulence created by the surface roughness (rugosity) due to the marine biological colonisation of iron and

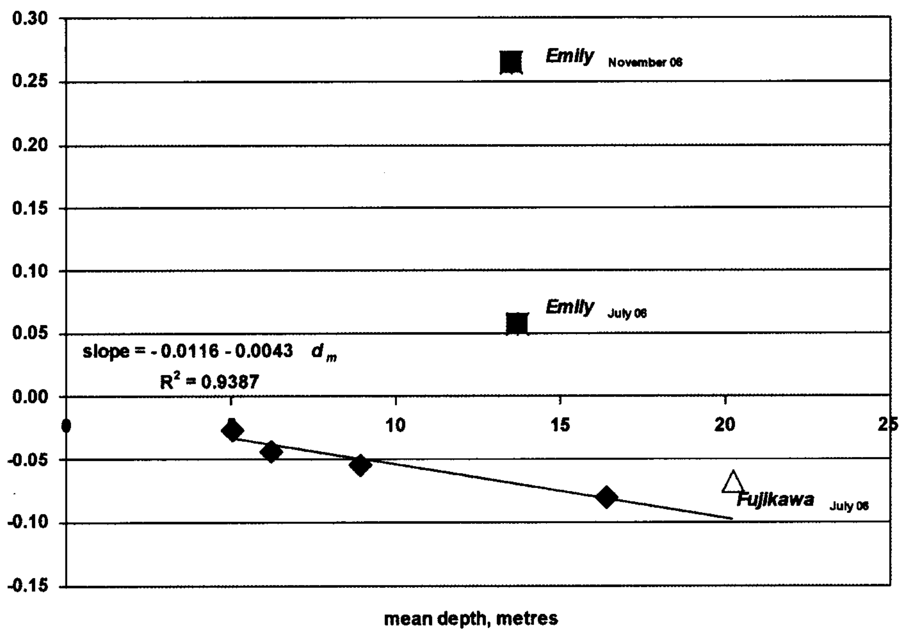

Figure 1: Plot of slopes of E_{corr} vs R_u data for iron and aluminium wrecks

aluminium wrecks in Chuuk Lagoon had a direct affect on the underlying metal corrosion rate that is reflected in the E_{corr} and pH values. This finding highlights the fact that the conservation of historic heritage values goes hand in hand with environmental conservation needs. The wrecks at Chuuk were found to harbour rare coral species which increases their value even further (Beger and Richards 2007), in a world where natural reef habitats are in decline (Pandolfi et. al. 2005). Dynamite fishing severely damages the marine ecosystem developed on these "artificial reefs", but at the same time it damages the underlying wreck by accelerating decay processes of the metal matrix. The increased corrosion caused by the rugosity is much less significant than the overall protection provided by the encrusting marine organisms. The water depth is the main factor determining corrosion rates.

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