REANALYSIS OF THE COLOUR CHANGES FROM 2004 TO 2014 ON BURRUP PENINSULA ROCK ART SITES

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(This report supplements the report from 5 April 2016, which included analysis of mineralogy measurements. A different statistical model has been used in this report to determine the direction and significance of changes in colour space variables (L, a*, b*) over time. This report does not change the overall conclusions of the previous report, but strengthens the conclusion that changes over the 11 years of measurement are consistently positive, with no spot showing a significant trend in the opposite direction, across all spots measured and all sites)*

Abstract.

Results from studies of colour changes at rock art sites on Burrup Peninsula from 2004 to 2014 (Markley *et al*. 2015) have been reanalysed using mixed model statistical methods. Contrary to the conclusions by those authors that there is no consistent trend for colour change in an increasing or decreasing direction, the comprehensive statistical analyses showed highly significant ($P<0.01$) colour changes at the rock art sites over the years of measurement from 2004 to 2014. The changes in colour space variables (L*,a*, b*) were consistent in the same direction, with no spot showing a significant trend in the opposite direction, at all rock art sites examined. All slopes for the relationship between colour space variables and time for every point measured (126 relationships; 42 points x 3 colour space variables) on the rocks were either significantly ($P<0.05$) greater than zero or not significantly different from zero. The rocks had become lighter, more red and more yellow over the 11 years of measurement. Changes in colour space variables were significantly different between sites. Change in colour space variables were greatest at Deep Gorge (site 7) and least at the Water Tanks (site 1). At Deep Gorge, there was a several-fold increase in all colour space (L*, a*, b*) variables measured. Lightness of the engravings at this site changed by an average of 24 L* units in a scale of 100 from the darkest black to the brightest white. This change, of approximately 25% of the total range in lightness measurement, in just 11 years suggests substantial changes in the environment over recent years for petroglyphs that have been on Burrup Peninsula for more than 30,000 years.

The colour space variables were used to calculate the change in visual colour assessed using the international CIE ΔE formulae from 1976 and 2000. The mean colour change values from 2004 to 2014 for all spots, background rock and engravings at each site using the CIE ΔE 1976 colour difference formula were, respectively: Dolphin Island (site 1) 12.7; Gidley Island (site 2) 5.6; Woodside (site 4) 8.7; Burrup Road (site 5) 7.8; Water Tanks (site 6) 2.1: Deep Gorge (site 7) 18.3: and King Bay South (site 8) 6.1.

The change in colour across all sites was significantly greater ($P<0.05$) for petroglyph engravings (11.7 ΔE 1976 units) than for background rock (5.8 ΔE 1976 units) adjacent to the engravings. Furthermore, colour contrast between background and engravings, which aids ability to decipher petroglyphs, decreased from 2004 to 2014 at all sites and was significant at sites 1 and 7. The decrease in colour contrast between engraving and background rock over time means petroglyphs have become more difficult to visualise on the rocks in 2014 than they were in 2004. The type of rock on which the engravings were made also significantly ($P<0.05$) affected colour change. Combined colour change for background rock and engravings across all sites was more than twice as great ($P<0.05$) for gabbro (15.5 ΔE 1976 units) than for granophyre rocks (5.9 ΔE 1976 units).

Colour changes on background rock and on engravings between 2004 and 2014 would be perceptible to the eye at all sites examined, except at the Water Tanks (site 6), because colour differences greater than 2 ΔE units can be distinguished by the human eye. There was no significant difference in colour change at the two northern sites compared to the five southern sites closer to industry. However, the number of sites in each category was too small to determine significant

differences with the observed variation within and between sites. Six northern and six southern sites would be needed to show a 15% difference to be significant with the variance in the data collected. Colour change was not closely related to elevation, but may be influenced by air movement and amount of industrial emissions deposited. Unfortunately, other measurements relating to industrial emissions and chemical or biological changes on rocks were not available to evaluate possible causes for the colour changes.

The analyses have implications for government and industry groups who are using the results from Markley et al. (2015) as justification for placing industry on Burrup Peninsula. There have been substantial and significant changes in colour of the background rock and petroglyph engravings over a short time period between 2004 and 2014. These changes vary between sites where measurements were made.

Markley *et al*. (2015) used the two northern sites, on Dolphin and Gidley Islands, as 'control' sites to compare with the southern sites closer to industrial development. The second greatest change for all sites occurred at Dolphin Island, whereas only small changes would be expected at a 'control' site because of the long duration of petroglyphs on Burrup Peninsula. The Dampier port has approximately 19,000 ship movements annually, with the shipping lanes and anchorages within 7-15 km of the northern rock art sites on Gidley and Dolphin Islands. These ships burn high-sulphur bunker-oil. One ship can emit over 5,000 tonnes of sulphur oxides annually. The sulphur oxides are precipitated as sulphuric acid, which is known to be highly corrosive to rocks and to change the mineralogy of rocks on Burrup Peninsula.

Reanalysis of the data stresses the need for continued monitoring of colour changes at rock art sites on Burrup Peninsula. Monitoring of gaseous and particle emissions, anion, cation, pH and nitrate concentration changes as well as microbial activity on the rocks should also be reinstated to identify the causes for the colour changes observed and to allow better assessment of the likely long-term effects of industry on the rock art. Future experiments should measure all variables likely to affect the values recorded for the colour space measurements, so they can be fitted as random effects in statistical models and increase the power of analyses. New control sites, in sufficient numbers and remote from industry, should be established to eliminate the possible effects of shipping on the rock art site on the northern islands of the Peninsula. Colour photographs should be taken regularly under standardised conditions as a visual record of changes over time.

Introduction

Rock art on the Dampier Archipelago is unique in the world. The archipelago includes Murujuga, also called Burrup Peninsula. The peninsula contains more than one million motifs of rock art in the form of petroglyphs. These petroglyphs capture over 30,000 years of change in human culture and activities within a changing environment (Donaldson 2009; Mulvaney 2011). The rock art contains the oldest representation of the human face known in the world. Other petroglyphs include elaborate geometric designs, representations of human activities and beliefs, extinct mammals such as the macro-fauna, the fat-tailed kangaroo and *Thylacines*, as well as existing animals, birds and sea creatures (Bird and Hallam 2006; Mulvaney 2009; Mulvaney 2013). Murujuga inhabitants created this art from before the last ice age glacial period until 1868, when the Yaburara indigenous population was systematically exterminated beginning with the "Flying Foam Massacre" (Bednarik, undated). The petroglyphs on Murujuga are significant to world heritage. The art extends back far longer in origin than the famous paintings in the Lascaux caves in France of 17,000 years (Valladas *et al*. 2001), or the pyramids of Giza or Stone Henge, which were both formed around 4,500 years ago (Spence 2000; Pearson *et al*. 2007).

Burrup Peninsula is also the site of a huge industrial complex. An iron ore export terminal was established at the Port of Dampier near the southern end of Burrup Peninsula in 1963 and a salt production and export facility commenced operation in 1968. These developments were followed in the mid 1980's with natural gas processing facilities on Burrup Peninsula and a liquefied natural gas production plant in 1995. An ammonium fertiliser plant commenced production in 2006 and an ammonium nitrate production facility is nearing completion to commence operation in 2016. The Port of Dampier is one of the busiest bulk-handling ports in the world. During the year 2013-2014, 6027 vessels entered the port with exports approaching 180 million tonnes. The liquefied gas, fertiliser and ammonium nitrate plants are in close proximity to the rock art motifs. Indeed, many rocks containing motifs were removed to allow construction of the liquefied natural gas facility.

Recognising the incongruity of having a huge industrial complex in close proximity to rock art of world heritage significance, the Western Australian government established in 2002 the Burrup Rock Art Monitoring Management Committee (BRAMMC). The committee was established to oversee studies designed to determine whether the rock art was likely to be adversely affected by industrial emissions. Five studies were initiated; an air pollution study (Gillett 2008), atmospheric modelling of air pollutant concentrations and depositions (SKM 2009), artificial fumigation studies (Lau *et al*. 2007), a microbiological diversity study (O'Hara 2008) and an ongoing colour change and a mineralogy study of petroglyphs and background rock from seven sites across Burrup Peninsula (CSIRO 2008). A summary of the reports (SKM 2009) to BRAMMC concludes: "There are no known impact assessment criteria for the impact of air quality to rocks of the type that exist on the Burrup and that contain rock art." The reports do not state that emissions from industry will not adversely affect rock art. However, industry and government submissions (e.g. EPA 2011) make claims such as: "... it is unlikely that the relatively small quantities of NO_2 and NH_3 that would be emitted from the TANPF (Technical Ammonium Nitrate Production Facility) would have a significant impact on rock art in the surrounding areas." Similarly, the Yara Pilbara Nitrates (Carter 2010) and the Shire of Roebourne Environmental Strategy (Essential Environmental 2013:45), citing BRAMMC (2009), state there was: 'no scientific evidence to indicate that there is any measurable impact of emissions on the rate of deterioration of the Aboriginal rock art in the Burrup'.

The study monitoring colour and mineralogy changes on selected sites across Burrup Peninsula was continued beyond 2007, adding to the annual measurements taken since 2004. Annual reports on these measurements have been released by the Western Australian government, with the last being for measurements from 2004 to 2014 (Markley *et al*. 2015). A review of these reports including measurements beyond 2007 revealed the following statement (Markley *et al*. 2015): "The comparison of the colour and spectral data collected and processed for both the Northern (control sites) and Southern sites has shown no consistent trend in an increasing or decreasing direction. For the last 11 years no observed accelerated colour contrast change was detected at the Southern test sites, when compared with the Northern control sites." These statements were made without the presentation of statistical analyses until the report including the 2012 results (Lau *et al*. 2013). Limited statistical analyses have been provided in the 2014 and 2015 reports (Markley *et al.* 2014; 2015). The statistical analyses were included in these last two CSIRO reports only after comment and recommendation by one of the authors (JLB) of this report. Even with limited statistical analyses, the accuracy of the statements made in the CSIRO reports could not be verified by outside observers using the information presented in the reports. These latter reports primarily analyse differences between northern and southern sites for colour changes in the current year and for changes in mineralogy. Standard errors for yearly measurements have not been presented and a thorough statistical analysis of all colour measurements does not appear to have been undertaken. A rigorous statistical analysis of the results may lead to different conclusions about colour changes at rock art sites over the years of measurement.

Following an agreement with the Western Australian government, all results from the colour measurements from 2004 to 2014 were made available to the authors for reanalysis. The outcomes from that analysis are presented in this report.

Methods and analyses used in colour and mineralogy studies by Markley *et al*. (2015)

The methods used to measure colour and mineralogy changes on petroglyph engravings and adjacent background spots on selected rocks at seven sites on Burrup Peninsula are described by Markley *et al*. (2015). The location of each site is shown in Figure 1 and information about the sites is given in Table 1. Petroglyphs on sites 2, 4, 5, 6 and 8 were engraved into rock classified as Gidley granophyre, whereas petroglyphs on sites 1 and 7 were engraved into Gidley gabbro.

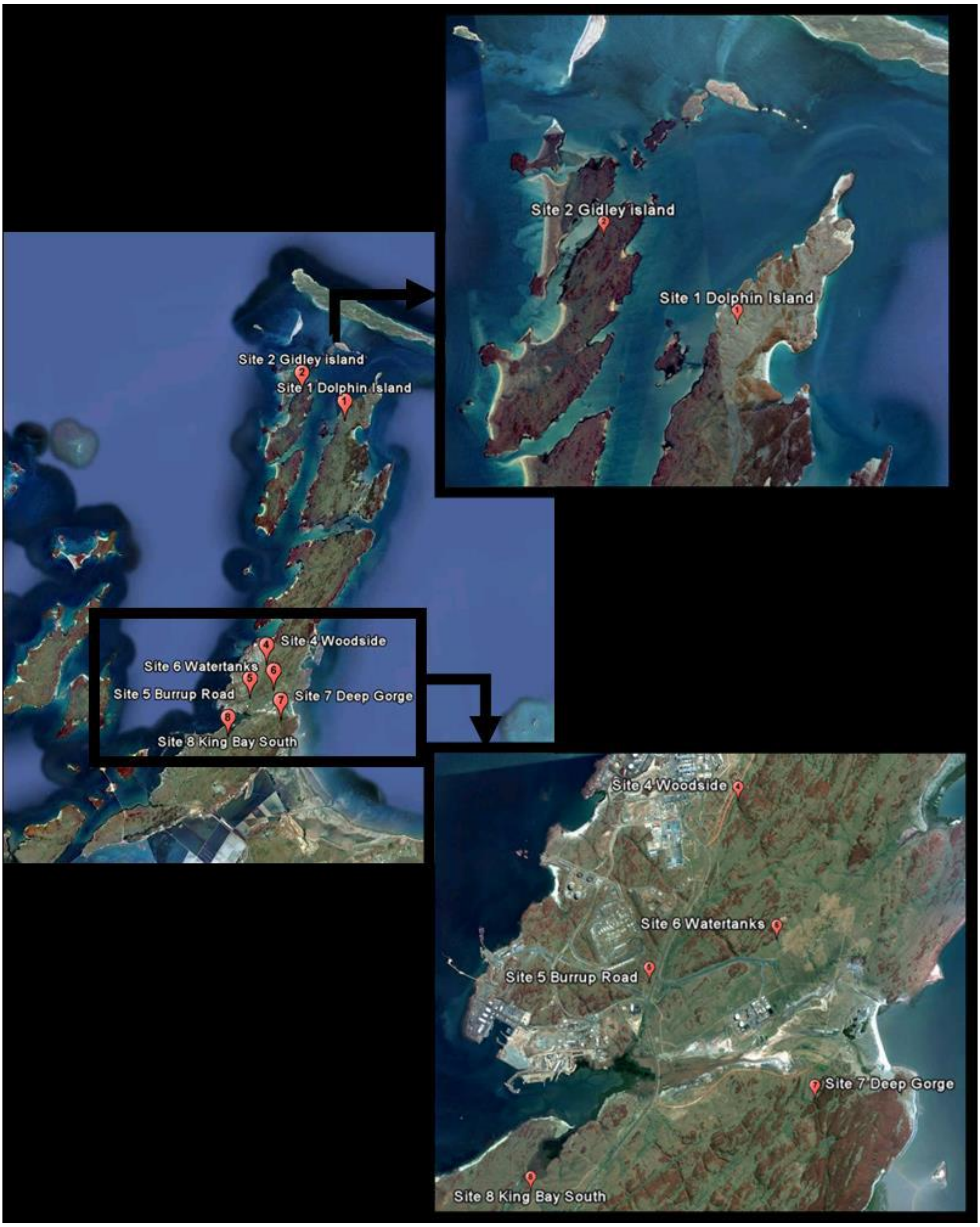

Figure 1. *Map of Burrup Peninsula with location of each site with petroglyphs used in the CSIRO study (Markley et al. 2015).*

Table 1. *Details of the sites used for colour and spectral mineralogy measurement analyses.*

Site	Site name	Coordinates (GDA 94, Zone 50)		Elevation (m)[1]	Petroglyph orientation[2]
1	Dolphin Island	484,975	7,738,503	45	45º, facing Gidley, open site
2	Gidley Island	482,166	7,740,857	30	90º, facing gully, protected[3]
4	Woodside	477,398	7,721,980	40	70º, facing Woodside, open site
5	Burrup Rd	475,959	7,719,771	25	90º, facing road, open site
6	Water Tanks	477,698	7,720,137	35	25º, facing Yara, open site
7	Deep Gorge	477,956	7,717,987	25	50º, facing Yara, gully, open site
8	King Bay South	474,082	7,717,229	10	70º & 35º, facing ore piles, open site

[1]Assessed from Google Earth®; [2]E.Ramanaidou (pers com. 2 February 2016); [3]Protected from weather

There were three sampling 'spots' on each selected petroglyph site. Measurements were made at each spot on: i) an area of 'engraving' defined by graffito lines or pecking marks that constitute an image, and ii) an area classified as 'background' which was rock surface adjacent to, but unmarked by the petroglyph. An additional 'spot' was included for each petroglyph site from 2013, but these additional spots were not included in the current reanalysis of results.

Colour measurements

Colour measurements were made from 2004 to 2014 using a BYK-Gardner portable spectrophotometer (BYK) with inbuilt spectral illuminants. Although the measuring head on the instrument was designed to exclude light on a flat surface, a black fabric collar was used (Markley *et al*. 2015). The measuring aperture for the BYK instrument was 4 mm. From 2009 to 2014 colour measurements, were made also using a Konica Minolta CM-700d spectrophotometer (KM). The measuring aperture for the KM instrument was 10 mm and was assumed to reduce the impact of surface heterogeneity on colour measurements. The operating manual for the KM instrument (Konica Minolta 2013, *http://sensing.konicaminolta.asia/products/cm-700d-spectrophotometer/*) states: "Use the CM-700d/600d at ambient temperature between 5°C and 40°C and relative humidity 80% or less (at 35°C) with no condensation.", which raises some doubt about the suitability of the instrument for the purpose, particularly when temperature and humidity were not recorded.

A comparison between the two instruments on different rock surfaces showed generally lower variance in measurements for the KM than the BYK instrument (Markley *et al*. 2015). Both the BYK and KM instruments were used during the period from 2009 to 2014. Although measurements were made with the BYK instrument in 2013 and 2014, they were not recorded because of failure in the electronic recording system. Measurements were available for this report from the BYK instrument for 2004 to 2012, from both BYK and KM instruments for 2009 to 2012 and for the KM instrument only for 2013 to 2014.

Repeat colour measurements were made at each spot for both the engraving and background. Seven repeat measurements were made in 2004, but this was increased to 21 repeats from 2005. Repeat measurement involved removing the instrument from the spot and replacing it on the rock, but only at one time each year. All repeat measures were made over the same short time period and no replicate measurements were made at a different time either during the same day or on subsequent days over a short period of time within each year. The repeat measures cannot be regarded as replicate measurements for statistical analysis.

Colour was assessed using the International Commission on Illumination (CIE) standard procedures with measurement of the L*, a* and b* colour space. Lightness is represented by L*, with the darkest black at L* = 0 and the brightest white at L* = 100. The red/green opponent colours are represented by a*, with green at negative a* values and red at positive a* values. The yellow/blue opponent colours are represented by b*, with blue at negative b* values and yellow at positive b* values. Neutral gray occurs when both a* and b* = 0. The difference between two colour measurements, ΔE, was evaluated using the 1976 CIE colour difference formula, or ΔE76 (Hunter and Harold 1987):

$$\Delta E^*_{ab} = [(\Delta L^*)^2 + (\Delta a^*)^2 + (\Delta b^*)^2]^{1/2}$$

Data analyses by Markley *et al*. (2015) involved: i) averaging all replicate measurements for each of L*, a* or b* at each spot and surface type (engraving or background); ii) using only BYK instrument results to 2008 and only KM data from 2009; iii) using the ΔE76 formula to make comparisons between years with the same instruments and between engraving and background; and iv) using a regression established between the BYK and KM instruments for colour comparisons between the first and last year. No statistical analyses were conducted to determine differences in trends over years, impact of site or rock type. Only a visual assessment of graphs of results were made.

Reanalysis of experimental results

The statistical analyses were to determine: a) whether there were significant consistent trends over time in colour space (L*, a*, b*) variables, at any site, in an increasing or decreasing direction; and b) whether there were significant differences in colour change from 2004 to 2014 as determined by ΔE calculations using the CIE 1976 and 2000 formulae (Habekost 2013) between: i) sites; ii) background rock and engravings; iii) northern and southern sites; and iv) gabbro and granophyre rocks.

Change in colour space variables over time

Repeat measurements for each colour space variable (L*, a*, b*) at every spot, background rock or engraving were averaged before including in the statistical analyses. The repeats were averaged because measurements were taken within a narrow time frame on a single occasion each year and not as designed replicate measurements within each year. In addition, averaging greatly reduced the computation requirements for fitting the complex statistical model with the number of data records being reduced from 15560 to 551. A preliminary evaluation using all repeat measurements or averaged values did not change the significance of trends, but using all repeat measurements reduced the standard errors of estimates.

Mixed model methods were used to fit a statistical model to the data for each colour space variable. The mixed model was formulated in a way that is analogous with ANOVA (analysis of variance). The mixed model included terms that were fitted as fixed effects, similar to representing experimental treatments, which included site, Julian days (linear component) and type of rock measurement (background or engraving). Spot was considered within Site because spots were coded 1, 2 and 3 for all seven sites and measured at the same time for any site. The model also included random effects such as the type of spectrophotometer (BYK and/or KM) used for colour measurements and the curvilinear component of the effects of time expressed as Julian days. Random terms had an associated variance component and these were estimated using residual maximum likelihood (REML; Patterson and Thompson 1971). The R package *asreml* (Butler 2009) was used to fit all models.

The models were used to: i) determine the statistical significance of fixed effects and the form and significance of the trend over years of measurement for each colour space variable (L*, a*, b*); and ii) predict values for each colour space variable for every site, engraving and background by accounting statistically for the effects of the instrument used. The values predicted from the statistical model were used for the numerical analyses of ΔE colour change.

The model used to calculate significance of effects for colour trait, L*, a*, b*, using the notation described by Wilkinson and Rogers (1973), was:

colour trait ~ 1 + Site + lin(jday) + Type + Site:Spot + lin(jday):Site + Site:Type + lin(jday):Type + lin(jday):Site:Type + lin(jday):Site:Spot + Site:Spot:Type + lin(jday):Site:Spot:Type + **spl(jday)** + **spl(jday):Site** + **spl(jday):Type** + **spl(jday):Site:Type** + **spl(jday):Site:Spot:Type** + **dev(jday)** + **dev(jday):Site** + **dev(jday):Type** + **dev(jday):Site:Type** + **dev(jday):Site:Spot:Type** + **Machine** + **Machine:Site** + **Machine: dev(jday)** + **Machine:Type** + **Machine:Site:Spot** + **Machine:Site: dev(jday)** + **Machine:Site:Type** + **Machine: dev(jday):Type** + **Machine:Site: dev(jday):Type** + **Machine:Site: dev(jday):Spot** + **Machine:Site:Spot:Type**

where terms in bold are fitted as random effects and have an associated variance component. The term 1 is the overall mean; the term Site is sites 1, 2, 4, 5, 6, 7 or 8 (Figure 1 and Table 1); the term Type is background or engraving; Spot is spots 1, 2 or 3 for background and engraving at each site; Machine is BYK or KM. A large number of interactions between factors were examined. The cubic smoothing spline formulation described by Verbyla et al. (1999) was implemented to model curvature over Julian days (with origin at 01-01-1970). In this formulation the trend over Julian days is decomposed into an underlying linear trend, referred to as lin(jday), curvature about the linear trend, referred to as spl(jday), and random deviations not captured by the two preceding terms, referred to as dev(jday). Terms comprising spl(jday) and dev(jday) are fitted as random effects, whereas terms comprising lin(jday) are fitted as fixed effects (Verbyla et al. 1999). There was evidence of variance heterogeneity at the site level, therefore a separate variance component was fitted for each site.

The model was used to predict colour space values, L*, a* and b*, for background and engraving at each spot on every rock at each site for every year. Least significant difference (LSD) values at the 5% level of statistical significance were calculated and used to identify significant differences between individual measurements.

The direction and magnitude of slope in the linear trend line over time and whether it was significantly different from zero was determined using a statistical test of the difference between the predicted colour measurements at the end-point of the linear trend line. Values for the predicted slopes were multiplied by 3655 days to represent magnitude of predicted changes due to the linear component of the model over the range of the data collection from 27th July 2004 to 29th July 2014, for each of the colour space variables.

Careful consideration was given to deciding whether time [lin(jday)], Site, Type and Spot should be included in the model as fixed or random terms. An important consideration for whether a term is designated as fixed or random, is that of inference (Searle 1971). If time, Site, Type and Spot were measured only to make inferences about the wider population of years and rock art sites, they would be included in the model as random. However, a major objective of the analysis was to predict the changes in colour space variables over time for each point on the rocks measured and to determine the direction and significance of changes at each point over time. Consequently, lin(jday), Site, Type and Spot were included in the statistical model as fixed terms. This formulation provides F-statistics and associated P-values for main effects of, and relevant interactions between, lin(jday), Site, Type and Spot. An additional reason for including these terms as fixed is that the predicted values are not subject to "shrinkage" (Verbeke and Molenberghs 2009), which would be the case if they were fitted as random. Shrinkage is the result of the assumption that random terms have zero mean. Shrinkage results in a rescaling of calculated values. A different variance component was fitted for each site, so there will be different rates of shrinkage at each site. Since the colour space variables predicted from the model are used in the calculation of ΔE (colour differences, between 2004 and 2014, background and engraving, and rock type), differences in ΔE must not be due to different rates of shrinkage at different sites.

Changes in colour between 2004 and 2014

The model predicted values for L*, a* and b* were used to calculate CIE ΔE 1976 and 2000 values for changes in colour between background and engravings and over time from 2004 to 2014. Two statistical models were fitted. The first examined the effect of Site, Type, Spot within Site and Type within Site:

$$\Delta E \sim 1 + \text{Site} + \text{Type} + \text{Site:Spot} + \text{Site:Type}$$

The second statistical model included site groupings (SiteGrp). Two site groupings were examined. The first site grouping was to determine whether colour change at the two northern sites (1 and 2) used by Markley et al. (2015) as 'control' sites were different from the sites closer to industry (4, 5, 6, 7, and 8). The second site grouping was to determine whether colour change was affected by rock type where gabbro (sites 1 and 7) was compared with granophyre (sites 2, 4, 5, 6 and 8).

$$\Delta E \sim 1 + \text{SiteGrp} + \text{Site} + \text{Type} + \text{Site:Spot} + \text{SiteGrp:Type} + \text{Site:Type}$$

Results from the statistical analysis

Change in colour space variables over time

Results from the statistical analysis, with probability estimates (P-values), for the colour space variables, L*, a* and b*, are shown in Table 2. The raw data, the fitted cubic smoothing spline and the underlying linear trend over the years 2004 to 2014 for each Site, Spot, Type combination are presented in Figures 2, 3 and 4, respectively, for L*, a* and b* colour space variables. There were significant differences in all colour variables across sites, which was visually noticeable from inspection of rocks at the sites. Most important, there were significant changes in all colour variables over time and across spots and sites.

The direction and significance of the linear slope per Julian day multiplied by 3655 for L*, a* and b* for every site, spot and background rock or engraving are presented in Table 3. The values in Table 3 represent the linear component of the cubic smoothing splines curve only and are, therefore, slightly different to values predicted using all components of the curve.

Changes in L* over the time of measurement were positive for every one of the 42 points measured, showing that the direction of change was consistent across sites. The slope was significantly greater than zero ($P<0.05$) for 29 of the 42 points measured, representing 70% of the measurements. The analysis shows that rocks at all sites became consistently lighter over the period from 2004 to 2014. The change in lightness was large for some measured points. The greatest change in lightness predicted from the full cubic smoothing spline model was 29.1 L* units for the engraving spot 3 at site 7. The average change in lightness for the three engravings spots at site 7 was 24.1 L* units. This change in L* represents almost a 25% change in 11 years across the full lightness scale of L*, which ranges from 0 to 100 units.

Analysis of the slope for changes in a* over time shows a general trend for the rocks, particularly the engravings, to become redder in colour. The slope for a* was significantly greater ($P<0.05$) than zero for 14 of the 42 points measured. Although the slope for 12 of the 42 points measured was negative, suggesting an increase in green colour, none of these were significantly different from zero. Engravings for all spots at sites 1 and 4, and for two of the three spots at sites 7 and 8 had become significantly redder in colour over the time of measurement.

Table 2 Results from the statistical analysis with probability estimates (P-values) for colour space variables L*, a* and b*.

Variable	Degrees of freedom	Probability value		
		L*	a*	b*
Intercept	1	5.418e-02^{NS}	2.885e-02	2.196e-02
Site	6	1.056e-02	5.417e-03	1.275e-02
lin(jday)	1	2.804e-07	1.401e-02	1.679e-01^{NS}
Type	1	3.055e-01^{NS}	3.565e-01^{NS}	9.600e-02^{NS}
Site:Spot	14	3.507e-08	8.456e-08	1.860e-09
lin(jday):Site	6	3.273e-04	3.781e-03	1.213e-02
Site:Type	6	3.323e-03	8.806e-03	5.774e-03
lin(jday):Type	1	1.943e-04	2.799e-03	5.009e-03
lin(jday):Site:Type	26	2.582e-04	3.709e-02	1.294e-02
lin(jday):Site:Spot	14	9.448e-03	5.135e-02^{NS}	2.331e-01^{NS}
Site:Spot:Type	14	2.938e-05	1.487e-04	5.711e-06
lin(jday):Site:Spot:Type	14	4.641e-04	1.335e-02	4.380e-03

^{NS}Not significant at $P>0.05$

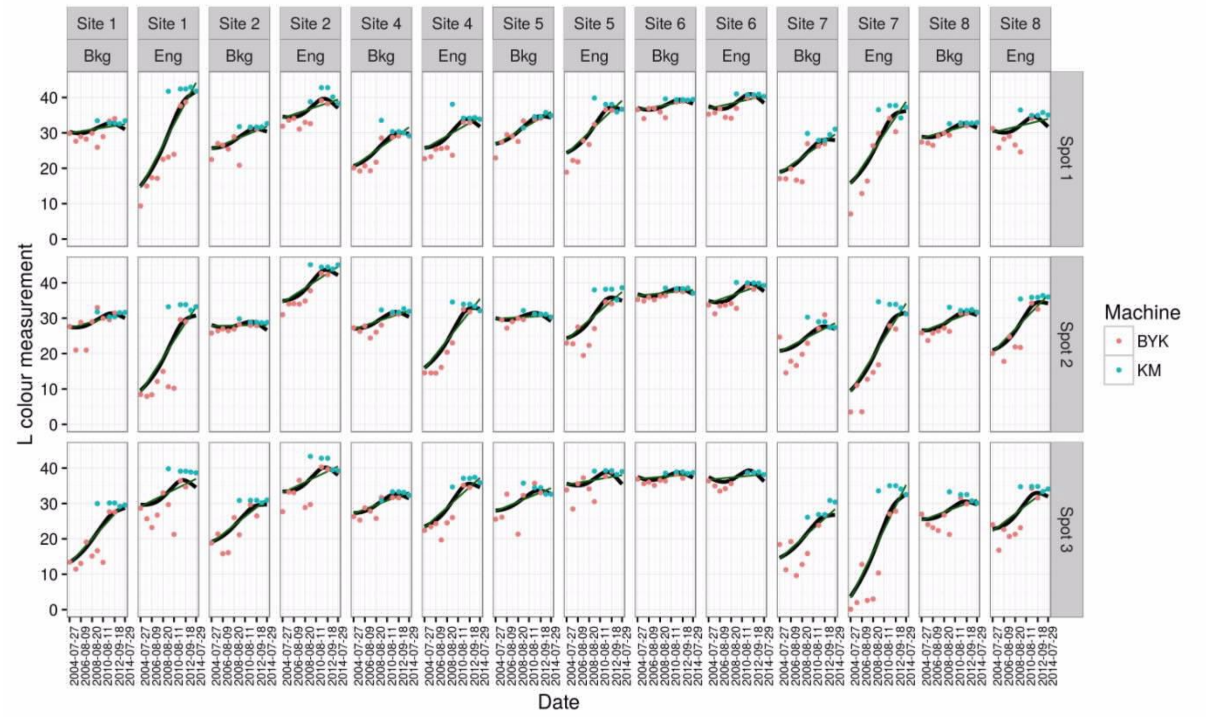

Figure 2 Cubic smoothing spline model fit (heavy line) and linear component (light line) to the measured colour space variable, L*, for all spots, background (Bkg) and engraving (Eng) at each site from 2004 to 2014.

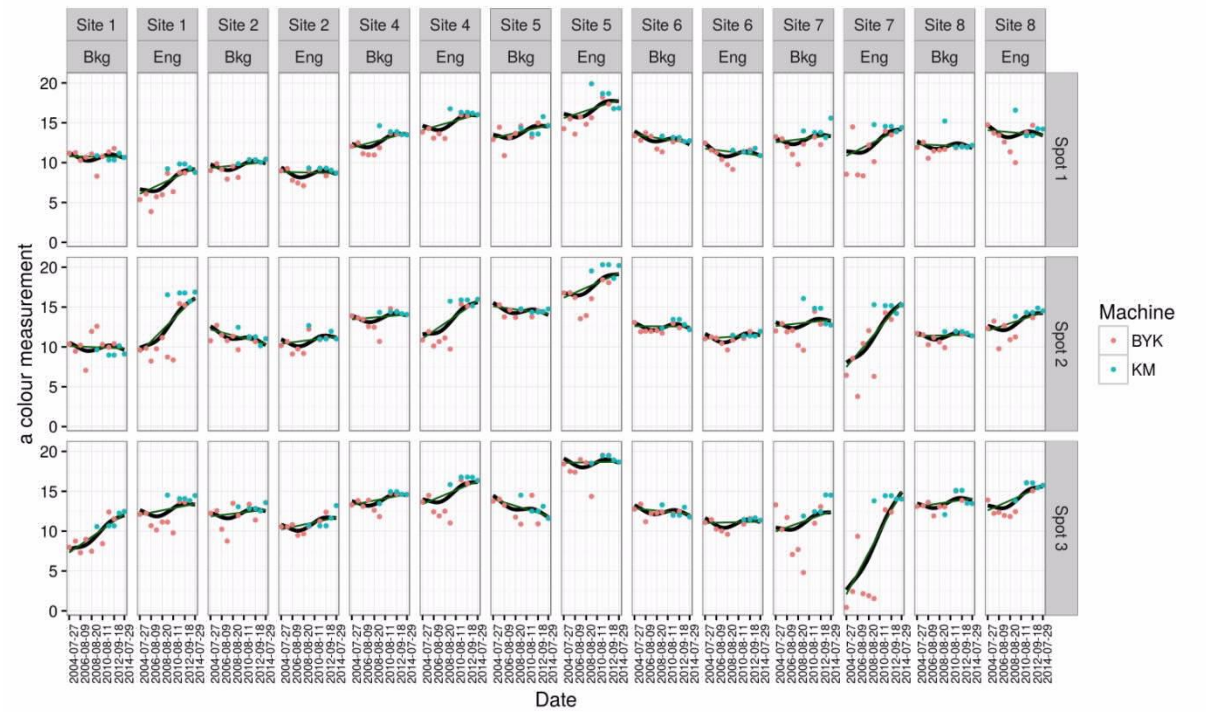

Figure 3 Cubic smoothing spline model fit (heavy line) and linear component (light line) to the measured colour space variable, a*, for all spots, background (Bkg) and engraving (Eng) at each site from 2004 to 2014.

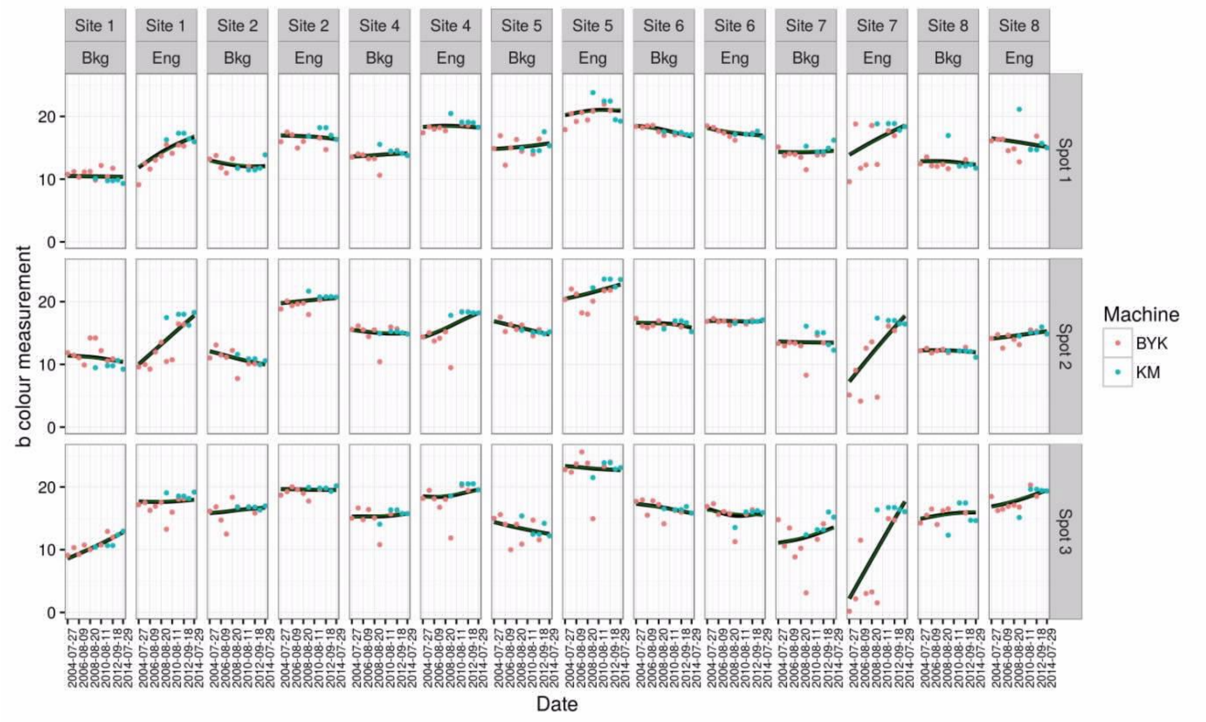

Figure 4 Cubic smoothing spline model fit (heavy line) and linear component (light line) to the measured colour space variable, b*, for all spots, background (Bkg) and engraving (Eng) at each site from 2004 to 2014.

Table 3 Model predicted linear slope in L*, a* and b* per day multiplied to show change from 27th July 2004 to 29th July 2014 (3655 days) for background and engraving at every spot and every site.

Site	Type	Spot 1			Spot 2			Spot 3		
		L*	a*	b*	L*	a*	b*	L*	a*	b*
1	Bkg[1]	2.49^{NS}	-0.07^{NS}	-0.14^{NS}	4.31^{NS}	-0.31^{NS}	-1.00^{NS}	17.26^{S}	4.84^{S}	4.17^{S}
	Eng[2]	29.65^{S}	3.22^{S}	4.95^{S}	24.12^{S}	6.90^{S}	7.78^{S}	7.76^{S}	1.37^{S}	0.26^{NS}
2	Bkg	6.39^{S}	0.74^{NS}	-0.98^{NS}	0.26^{NS}	-1.79^{NS}	-2.17^{NS}	12.36^{S}	0.82^{NS}	0.92^{NS}
	Eng	5.24^{S}	-0.17^{NS}	-0.55^{NS}	10.14^{S}	0.91^{NS}	0.85^{NS}	7.49^{S}	1.48^{NS}	-0.16^{NS}
4	Bkg	11.03^{S}	1.83^{S}	0.54^{NS}	5.18^{NS}	0.60^{NS}	-0.60^{NS}	6.02^{S}	1.34^{S}	0.38^{NS}
	Eng	8.94^{S}	1.95^{S}	-0.09^{NS}	19.70^{S}	4.72^{S}	3.98^{S}	14.02^{S}	2.87^{S}	1.10^{NS}
5	Bkg	9.20^{S}	1.62^{NS}	0.87^{NS}	0.89^{NS}	-0.94^{NS}	-2.12^{NS}	6.49^{S}	-2.14^{NS}	-1.90^{NS}
	Eng	15.02^{S}	2.28^{NS}	0.77^{NS}	13.44^{S}	3.06^{S}	2.29^{NS}	2.69^{NS}	0.13^{NS}	-0.68^{NS}
6	Bkg	2.74^{NS}	-1.07^{NS}	-1.74^{NS}	1.61^{NS}	-0.05^{NS}	0.67^{NS}	1.38^{NS}	-0.71^{NS}	-1.52^{NS}
	Eng	3.56^{NS}	-0.86^{NS}	-1.21^{NS}	5.40^{S}	0.46^{NS}	-0.07^{NS}	1.51^{NS}	0.16^{NS}	-0.83^{NS}
7	Bkg	10.90^{S}	0.87^{NS}	0.16^{NS}	8.07^{S}	0.77^{NS}	-0.18^{NS}	14.00^{S}	2.52^{NS}	2.44^{NS}
	Eng	23.29^{S}	3.45^{NS}	4.70^{NS}	25.00^{S}	8.11^{S}	10.48^{S}	31.90^{S}	12.93^{S}	15.50^{S}
8	Bkg	4.26^{NS}	-0.24^{NS}	-0.53^{NS}	6.08^{S}	0.15^{NS}	-0.30^{NS}	5.89^{S}	1.04^{NS}	1.07^{NS}
	Eng	3.84^{NS}	-0.61^{NS}	-1.38^{NS}	16.17^{S}	2.26^{S}	1.19^{NS}	12.09^{S}	3.06^{S}	2.60^{NS}

[1]Background rock; [2]Engraving; ^{S}Significant at $P<0.05$; ^{NS}Not significant at $P<0.05$

Analysis of the slope for changes in b* over time shows fewer of the points measured to be significantly different from zero than for either L* or a*. Six of the 42 measured points had slopes significantly different ($P<0.05$) than zero. All of these significant slopes were positive, indicating that the rocks had become more yellow in colour. Background for one spot at site 1, engravings for two spots at site 1, one spot at site 4 and two spots at site 7 had become significantly more yellow in colour over the time of measurement.

Statistical evaluation of the slopes of the linear component of the cubic smoothing spline model for the change in all measured colour space variables over time show a consistent positive direction of trend across all sites, spots, background and engraving. No measured point showed a statistically significant trend in the opposite direction.

Impact of spectrophotomete and non-linear component of Julian day on variance

Including instrument (Machine) as a random term in the statistical model substantially improved the statistical power of the analyses by reducing the residual variance for the colour space measurements (Table 4). Instrument and its interactions with site and measurement type accounted for approximately 49% of the variance in measurement for L*, 24% for a* and 17% for b*.

The deviation component [dev(jday)] of the statistical model was included as a random term to capture variation in measured colour contrast values associated with the day on which measurements were made. The spline component and the deviation component and their interaction with instrument, Site, Spot and Type of measurement (background or engraving) accounted for approximately 24% of the variance in measurement for L*, 29% for a* and 35% for b*.

Including these instrument and Julian day random terms reduced the residual variance for the measurement of L*, a* and b* to 27%, 47% and 48%, respectively. The reduced residual variation in measured values increased substantially the capacity of the statistical model to identify significant differences between site, background and engravings, and the slope of changes over years.

Table 4. Contribution of the BYK and KM instruments (Machine), the spline and random deviation component of the cubic smoothing spline and their interaction with other terms to the variance of the colour space measurements L*, a* and b*.

Term	Contribution to measurement variance (%)		
	L*	**a***	**b***
Machine	35.3	12.5	2.3
Machine:Type	7.9	4.4	6.9
Machine:Site	4.7	0	0
spl(jday)	8.3	7.0	0
dev(jday)	0	0	0
Machine:Site:Type	1.4	6.4	8.2
Machine:Site:Spot	0	0	0
spl(jday):Type	1.4	0.2	0
dev(jday):Type	0	0	0
Machine:dev(jday)	9.9	9.9	11
Machine:Site:Spot:Type	0	1.0	0
Machine:dev(jday):Type	1.1	2.8	1.8
spl(jday):Site	0.2	0	0
dev(jday):Site	0.6	0	0
spl(jday):Site:Type	0	0.1	0.1
dev(jday):Site:Type	0	0	0
Machine:Site:dev(jday)	2.3	2.4	6.9
Machine:Site:dev(jday):Type	0	0.1	1.8
spl(jday):Site:Spot:Type	0	0.1	0.4
dev(jday):Site:Spot:Type	0	4.1	5.2
Machine:Site:dev(jday):Spot	0	2.5	7.6
Residual variance	26.9	46.5	47.8

Changes in CIE ΔE colour between 2004 and 2014

Results from the statistical analyses, with probability estimates (P-values), for changes in colour at all sites from 2004 to 2014 as assessed by the CIE ΔE 1976 and 2000 formulae are shown in Table 5. There were significant differences in the change in colour from 2004 to 2014 between sites and between background and engraving using both CIE ΔE 1976 and 2000 formulae. There was no effect of spot within a site. However, there was an effect of background or engraving within site for the CIE ΔE 1976 formula predicted values. Model predicted colour change between 2004 and 2014, averaged across spots, is shown in Figure 5 for background rock and engravings at each site. The greatest colour change occurred at site 7 followed by site 1 and the smallest colour change occurred at site 6 followed by sites 2, 8, 5 and 4. Mean colour change for background rock and engraving from 2004 to 2014 at site 7 was significantly greater ($P<0.05$) than for all other sites except site 1. Colour change at site 6 was significantly ($P<0.05$) less than at sites 1, 4, 5 and 7. The mean colour change values for all spots, background rock and engravings at each site using the CIE ΔE 1976 and 2000 formulae were, respectively: site 1, 12.7 and 9.1; site 2, 5.6 and 4.3; site 4, 8.7 and 6.5; site 5, 7.8 and 5.9; site 6, 2.1 and 1.4; site 7, 18.3 and 12.7; site 8, 6.1 and 4.5.

Table 5 Results from the statistical analysis with probability estimates (P-values) for colour change from 2004 to 2014 using both the CIE ΔE 1976 and CIE ΔE 2000 colour contrast formulae.

Variable	Degrees of freedom	Probability value	
		CIE ΔE 1976	**CIE ΔE 2000**
Site	6	3.938e-03	5.363e-03
Type	1	4.159e-03	4.014e-03
Site:Spot	14	5.673e-01^{NS}	5.605e-01^{NS}
Site:Type	6	4.399e-02	6.453e-02^{NS}

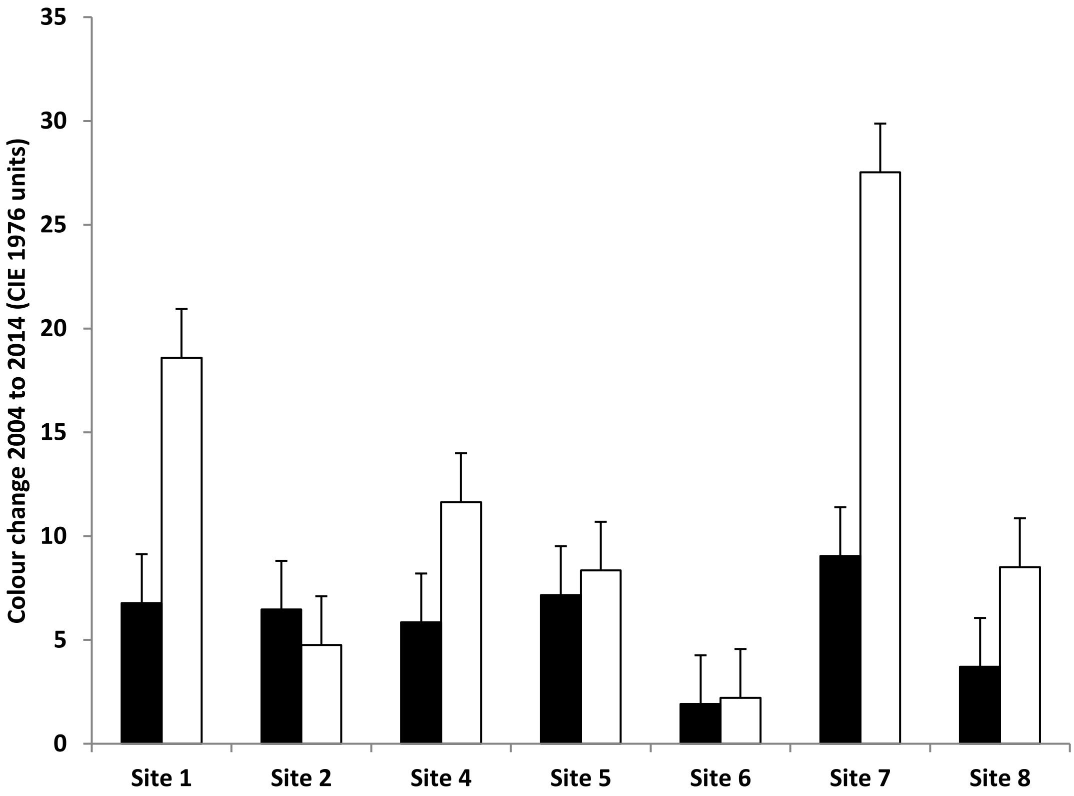

Figure 5 Mean change in colour (CIE ΔE 1976 units) between 2004 and 2014 for each site background rock (solid bar) and engraving (open bar).

Mean colour change across all sites and spots was twice as great ($P<0.05$) for engravings (11.7±2.35 ΔE 1976 units) than for the background rock (5.8±2.47 ΔE 1976 units). The greatest colour change between 2004 and 2014 was 27.5 CIE ΔE 1976 units for engravings at site 7, whereas the smallest colour change was for background at site 6 (1.9 ΔE 1976 units). All colour changes over time for both background rock and engravings at all sites, except perhaps at site 2, should be perceptible to the average human eye, which can generally discern differences from around 2 ΔE units (Habekost 2013).

Colour change from 2004 to 2014 at the northern sites (1 and 2) was not significantly different ($P =$ 0.19 ΔE 1976; = 0.28 ΔE 2000) from the southern sites (4, 5, 6 ,7 and 8). However, there were highly significant ($P<0.01$) differences in colour change from 2004 to 2014 between rock types and for the interaction between rock type and measurement type (Table 5). The mean colour change for background rock and engraving across all measured points was approximately 2.5-fold greater for gabbro rock (30.9 ΔE 1976 units) than for granophyre rock (11.9 ΔE 1976 units). The colour change for engravings on gabbro rock was three times greater than for background rock on gabbro rock (Table 6). In contrast, the colour change for engravings was only approximately 50% greater than for background rock on granophyre rock.

Changes in colour contrast between engravings and background rock

Differentiation in colour of engravings from background rock aids the ability to decipher petroglyphs. Figure 6 shows the mean colour contrast for all spots at each site between engraving and background rock at the beginning of measurements in 2004 and for the last year of measurement in 2014. In 2004, the greatest difference in colour between engravings and background rock was at site 1 followed by sites 7, 2, 5, 4, 8 and 6. The contrast in colour was 17.8 ΔE 1976 units at site 1 and only 2.0 ΔE 1976 units at site 6.

The contrast in colour between engravings and background rock has decreased at all sites from the date of initial measurement in 2004 to the last available measurement in 2014. The greatest decrease in colour differentiation between engravings and background rock occurred at sites 1 and 7 on gabbro rock. The next greatest decline in colour differentiation between engravings and background rock occurred at site 4. The decline in colour differentiation over the time from 2004 to 2014 was statistically significant ($P<0.05$) for sites 1 and 7.

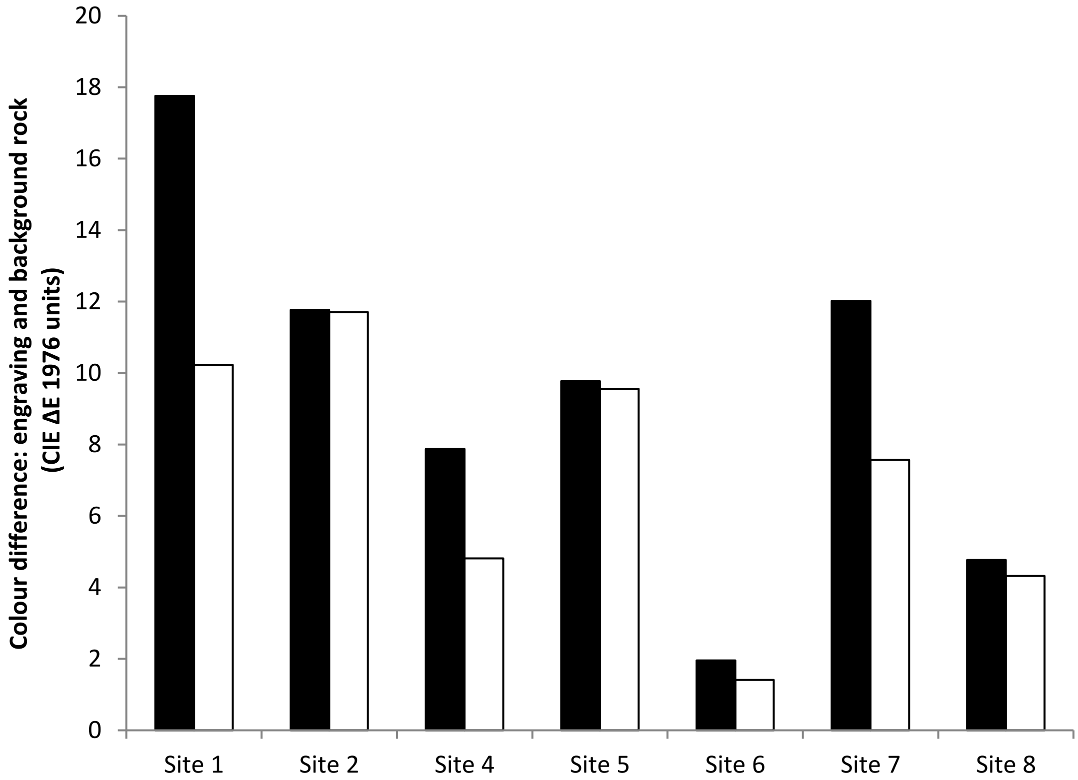

Figure 6 Colour difference CIE ΔE 1976 units between engravings and background rock for the mean of spots at each site for the initial year of measurement in 2004 (solid bar) and the last year of published measurement in 2014 (open bar).

Discussion

Contrary to the conclusion by Markley et al. (2015), "The comparison of the colour and spectral data collected and processed for both the Northern (control sites) and Southern sites has shown no consistent trend in an increasing or decreasing direction", the comprehensive statistical analyses shows highly significant and consistent changes in the same direction for all colour variables at all measured spots, background rock and engravings at all sites over time from year 2004 to year 2014. There were no significant changes in the opposite direction. The slope of the relationship for L* over time was positive for all measured points and significant in 70% of cases. The slope of the relationships for a* and b* over time were significantly positive for 33% and 17%, respectively, of all cases measured. Slopes for all other measured points were not significantly different from zero. These results mean there was a general increase in lightness, redness and yellow colour for all rock sites measured on Burrup Peninsula over the period from 2004 to 2014. Changes in colour at some sites were large. There was up to a 10-fold change in L*, a* and b* on engravings at site 7. The change in L* for engraving at spot 3 at site 7 was 29.1 units, and the average across the three spots at site 7 was 24.1 units over the 11 years of measurement. The range in L* values from the darkest black to the brightest white is 100 units. A change of approximately 25% of the full range in brightness in 11 years at site 7 for rock art that has been in existence for over 30,000 years, suggest a recent change in conditions must be affecting colour of the rock art.

The changes in L*, a* and b* were reflected as changes in colour contrast measures using the CIE ΔE 1976 and 2000 formulae (Table 5). There was a change in colour at all sites over the time of measurement, with this change being greatest at site 7 and least at site 6 (Figure 5). The average change in colour across all measurements was twice as great for engravings than for background rock. Site 2 was the only site where the colour change over time was greater for background than for engravings, although the difference was not statistically significant. Colour change was more than twice as great on gabbro rock than on granophyre rock (Table 6). The changes in colour between 2004 and 2014 ranged from 1.9 ΔE 1976 units for background rock at site 6 to 27.5 ΔE 1976 units for engravings at site 7 (Figure 6). All colour changes, except those at site 6, were sufficient to be perceived by the human eye, which can distinguish a difference of approximately two ΔE units (Habekost 2013).

Ability to perceive petroglyphs on rocks is enhanced when the contrast in colour between the background rock and engraving is greater. The contrast in colour between engraving and background declined from 2004 to 2014 for all sites, with the contrast being significantly less at sites 1 and 7 (Figure 6). This decrease in colour contrast between background rock and engravings suggests, contrary to the conclusion of Markley et al. (2015), that petroglyphs at the measured sites have become more difficult to distinguish from the background rock over the 11 years of measurement.

The statistical analyses conducted on the results obtained by Markley et al. (2015) have major implications for those government and industry groups using the Markley et al. (2015) report and previous reports in the series as justification for placing more industry on Burrup Peninsula. Clearly, there have been substantial and statistically significant changes in colour of the background rock and petroglyph engravings over the years of measurement from 2004 to 2014. There is evidence the petroglyphs are becoming more difficult to discern from background rock. Unfortunately, other measurements of airborne industrial emissions or changes to anions, cations and pH on rocks were not made and a cause for the colour changes cannot be properly determined.

The statistical analyses confirm one observation by Markley et al. (2015) that there were no differences in colour change between the two northern sites (1 and 2) and the southern sites closer to industry. However, the variation in measurements within and between sites showed that there were too few sites in the northern and southern regions for differences to be significant. Using traditional power analyses (Hill and Lewicki 2007) and the variation in colour change measurements between and within sites, it is possible to estimate the number of 'control' and 'industry' sites needed to show significant differences. This number will vary depending on the percentage change in colour considered to be important. If a 5% change in colour was considered important, 44 replicate control and industry sites would be needed to show significance ($P=0.05$). Eleven sites in each category would be required to show a 10% difference in colour to be significant, whereas six sites would be required to show a 15% difference to be significant. These numbers for replicates needed, depending on percentage difference to be significant, suggest that two northern and five southern sites are not adequate to determine significant differences in colour change.

Reasons for the changes in colour need to be considered on a site-by-site basis. There does not appear to be a close association between elevation and the change in colour of engravings between year 2004 and year 2014 (Figure 7). The greatest colour change occurred at site 7, which is in the gully of Deep Gorge. This rock art site is an open site on the side of the gully. The colour changes at the southern sites are not readily explained by the concentrations of NO_x and SO_x compounds in the air measured by Gillett (2008) over two periods from July 2004 to August 2008. The concentrations of these compounds were not higher at site 7 than other sites on Burrup Peninsula. However, site 7 had the highest concentration of total suspended particles followed by site 8 (Gillett 2008).

Close examination of the colour space variables over time shows that the major changes at site 7 occurred from 2007 to 2011, with a decline in the rate of change from 2011 to 2014. The ammonium fertiliser plant, which is in close proximity to site 7, commenced operations in 2006. The plant emits gaseous NO_x compounds from the primary reformer stack at a higher elevation, 36 m (EPA 2001), than site 7, which is approximately 25 m above sea level. Unfortunately, air quality measurements were not taken at the sites from 2008, so there is no way to examine scientifically whether the concentrations of emissions increased at site 7 in association with ongoing operation of the fertiliser plant. Although, ammonium gas is lighter than air, it is not when combined with atmospheric water. Gillett (2008) found that maximum daily humidity for all months examined at site 7 ranged from 91-100%. NO_x compounds are also heavier than air and it is possible the emissions could 'flow' from higher emission points at the fertiliser plant and accumulate in Deep Gorge, particularly during periods with high humidity and low inversion layers in the atmosphere.

Site 6, which has the second highest elevation of the southern sites and is an open site on a hillside, showed the smallest changes in colour over time. This result may suggest that higher air movement reduced the deposition of polluting emissions. Rock at Site 6 was initially lighter in colour than rocks at most other sites at the beginning of the measurements. The rock at site 6 also has a shallower weathering rind than rocks at other sites. The time from rock fracture is likely to be less than for other sites and may explain the small changes in colour observed.

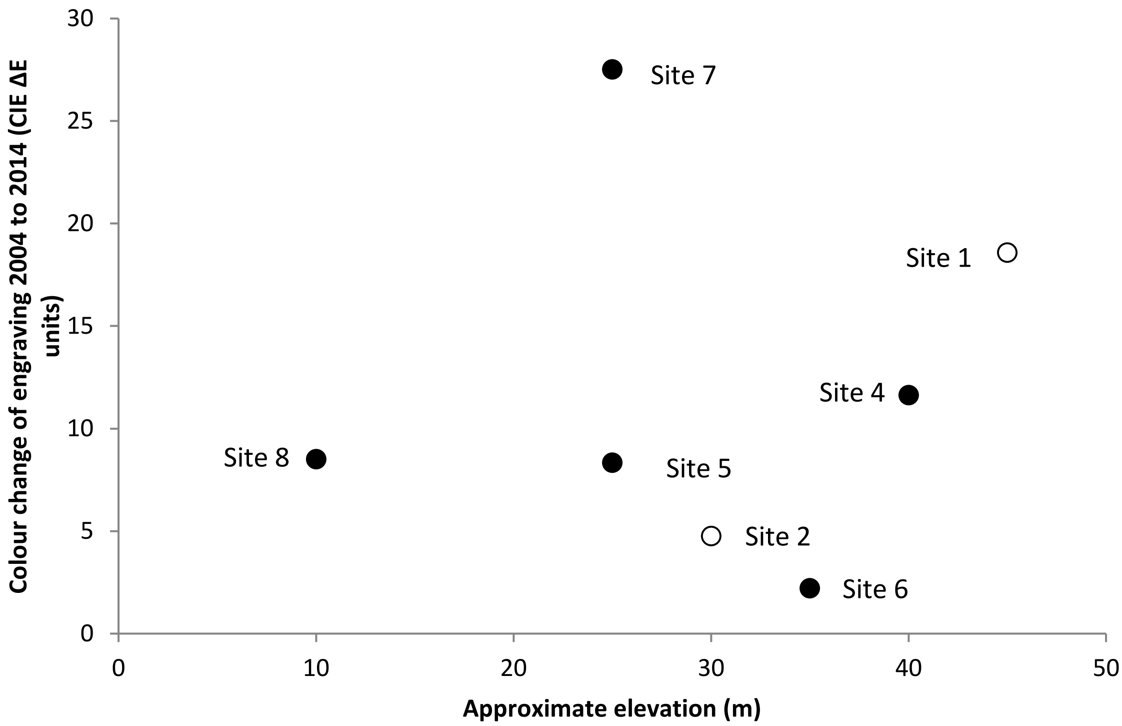

Figure 7 Association between changes in colour of engravings between 2004 and 2014 and elevation of each site. Solid circles represent southern sites, open circles represent northern sites.

The greatest changes over time occurred at site 7, which is close to industry, and site 1, which is on Dolphin Island. The base rock at these two sites is gabbro, whereas the rock at other sites is granophyre. Both rock types are fine grained, intrusive igneous rock, formed under high pressure (Donaldson 2011). Gabbro is composed of felspar and pyroxene crystals, while granophyre is composed of quartz and alkali felspar (Donaldson 2011). Petroglyphs have been carved into the weathering rind of the rocks, which varies from around 2 mm to 20 mm, depending on the time from fracture of the rock and other conditions (Bednarik 2007). The weathering rind consists of an outer, dark-coloured, patina layer, often called rock varnish, formed mainly from accretion of mineral deposits extracted from dust during mist and light rain (Lau *et al*. 2007; Bednarik 2009). The outer layer is 1 mm to 2 mm thick and consists primarily of iron and manganese oxides. The inner layer is composed primarily of kaolinite clays formed from decomposition of felspars and is lighter in colour than the outer surface. Pyroxenes decompose into red and brown haematite and geothite oxides and manganese rich clays with darker colour. Emissions on Burrup Peninsula may be having a greater effect on the pryoxene formed clays than the felspar formed clays. Watchman et al. (2014) conclude that engravings on Burrup Peninsula "are more vulnerable to weathering than the surrounding natural red brown iron-stained surfaces". This statement supports the conclusion from this analysis showing colour changes to be greater for engravings than for background rock.

Markley et al. (2015) have assumed that the two northern sites would be unaffected by industry and can be used as 'control' sites. A control site would be expected to change little over the 11 year period of measurements because of the slow rate of formation of the rock patina (Lau et al. 2007; Bednarik 2009) and rock erosion (Pillans and Fifield 2013). However, the changes over time in colour from the year 2004 to the year 2014 at both Dolphin Island (site 1) and Gidley Island (site 2) were statistically significant. An argument can be made that industry is also having an effect on the rock art at the two island sites through the effects of shipping. Dampier port is one of the busiest bulk-ports in the world with 5,170 ships entering the port in the year 2014-2015 (Pilbara Ports Authority, 2015). The shipping lane and numerous anchorages are within 7 km from Gidley Island and 14 km from Dolphin Island (Figure 8).

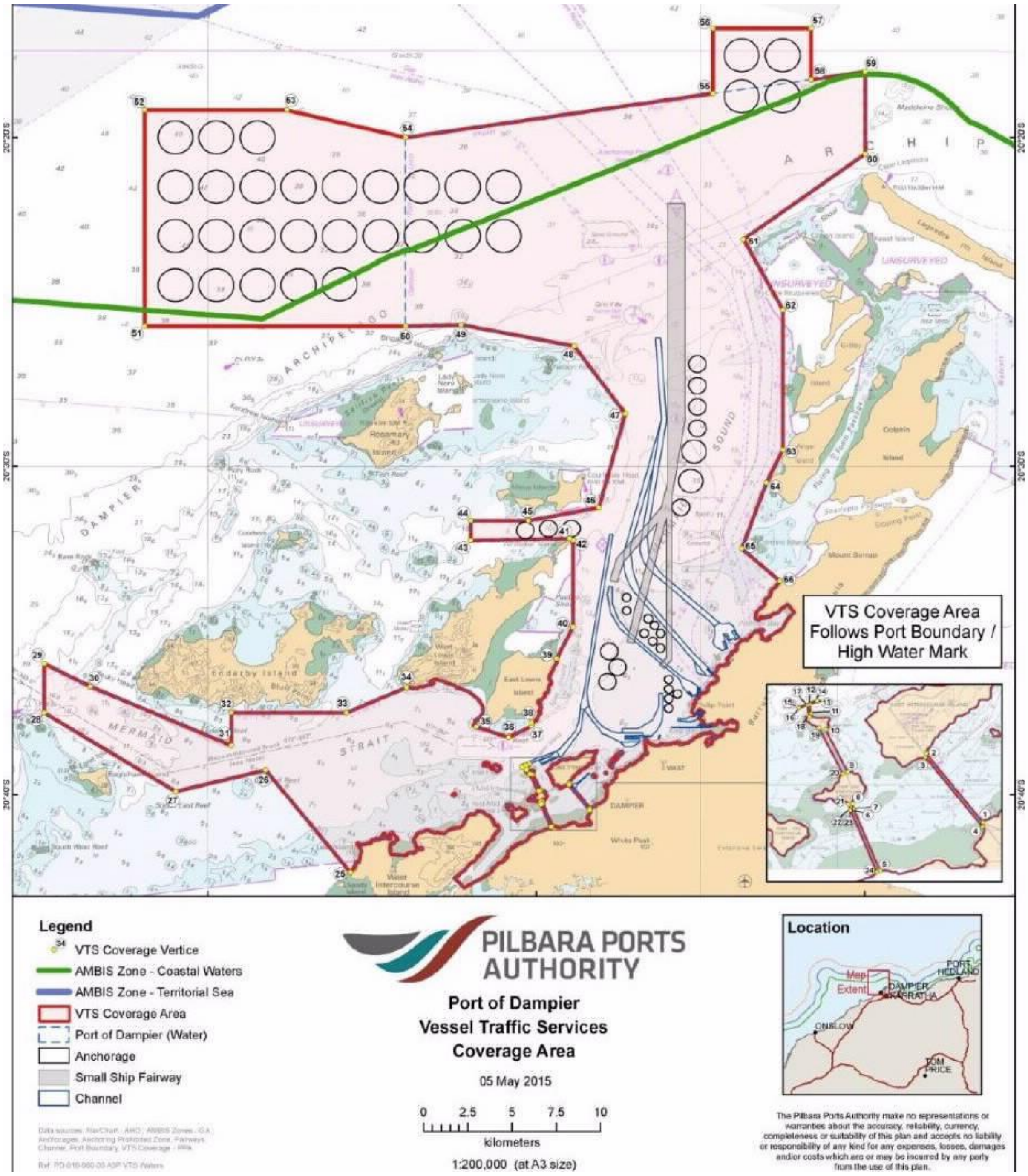

Figure 8. *Map of the Dampier Archipelago showing the port of Dampier, shipping lanes and anchorages in relation to Gidley and Dolphin islands. From Pilbara Ports Authority handbook (2015).*

There were 19,000 ship movements near the islands in 2014-2015 (Pilbara Ports Authority, 2015). There is no restriction on the use of bunker oil for ships entering Dampier port. Consequently, the majority of ships will be burning high-sulphur content fuel. A single bulk cargo ship burning high-sulphur fuels has been estimated to release 5,200 tonnes of sulphur oxides into the atmosphere per year (Vidal 2009). The emissions are highest during start-up and shut-down (USEPA 2010), which occurs when arriving at and departing from an anchorage. Sulphur oxides form sulphuric acid and precipitates as acid rain, with severe effects on stone buildings, rocks and rock art (Doehne and Clifford 2010). Lau et al. (2007) found that one molar concentration of sulphuric acid significantly changed the mineralogy of rocks from Burrup Peninsula. Gillett (2008) reported that the prevailing wind for the period from May to late August would blow the pollution from ships towards the islands. These facts about pollution from shipping suggest that sites 1 and 2 are not suitable as true 'control' sites for assessing the impacts of industry on rock art colour.

Possible suitable control sites control sites maybe rocks with petroglyphs in the Roebourne area (Reynolds 1987) or sites identified in the 'West Pilbara site documentation project' (Reynolds 1989). These sites are distant from shipping activity, land-based industry and transport, and have petroglyphs on gabbro and granophyre rock type. However, these sites are distant from the sea. Another possibility for 'controls' maybe to relocate to an area distant from industry and shipping, but close to the sea, Burrup Peninsula rocks that have already been removed from their original place. Approval from traditional owners would be needed for this latter option.

Overall, the reanalysis of results has shown that there have been significant changes in colour and colour contrast between background and petroglyph engravings at the sites observed over the 11 years of measurement. The changes are in a consistent direction across sites, with no negative slope being significantly different from zero, but vary in magnitude. The differences between sites do not appear to be influenced by elevation, but may be influenced by air movement, amount of deposition and inversion layers containing industrial emissions. The changes were greater for petroglyphs engraved into gabbro than granophyre rocks. The changes in colour space variables at some sites were many-fold. The colour changes were greater for the engravings than for the background rock, perhaps suggesting a lower effect of emissions on the rock patina and desert varnish than on the lower layers of the rock patina (Pillans and Fifield 2013).

Adequate experimental design, standard operating procedures and reporting of results by Markley *et al*. (2015) impacts on the reproducibility of experiments and the accuracy of experimental results. The reports on colour change (e.g. Lau et al. 2007; 2013, Markley et al. 2014; 2015) do not provide details of the experiment design, explicit notes of measurement difficulties, or refer to standard operating procedures. The change from seven measurements in 2004 to 21 from 2005 onward is justified "to reduce sample variance introduced by surface heterogeneity or roughness, and by systematic error" (Markley et al. 2015). The degree of roughness or the nature of the systematic error is not described. The reason for choosing 21 replicates at each measuring site is not clear. Other reports related to spectrophotometer measurements (Butts 2004; Prieto *et al*. 2010) have provided protocols for the determining the number of replicates needed to provide valid and reliable results. These authors report that the spectrophotometer is randomly placed (Prieto *et al*. 2010) or rotated and repositioned (Butts 2004) for each reading. A standardised protocol, or standard operating procedures, exemplified by EPA (2004) and Pfitzner *et al*. (2011), would increase confidence in the results and reduce variation between measurements made in future.

The new ammonium nitrate plant, as proposed, is to release into the atmosphere 25.2 t/year from 2016, with greater than 600 tonnes released over the lifespan of the facility, of PM_{10} sized particles that will be dispersed across the environment (EPA 2011). This will be in addition to NO_x compounds and ammonia being released from the LNG facility and the ammonia fertiliser plant. Atmospheric nitrate and NO_x compounds are another cause of acid rain, which is known to be associated with deterioration of rock art around the world (Giesen *et al.* 2014). Nitrate is also a stimulant to plant and microbial growth. Growth of bacteria, fungi and lichen are a major cause of the deterioration of rock surfaces.

Burrup Peninsula is a relatively dry place with an average rainfall of only 250-300 mm annually and extreme summer rock surface temperatures up to 54ºC (MacLeod 2005). Consequently, O'Hara (2008) reported relatively low numbers of viable organisms, with 20-50% of all samples taken from rock surfaces near the rock art monitoring sites showing viable bacteria and other organisms. O'Hara (2008) also reported that "Lichens were not uncommon on rock surfaces at two of the southern sites (site five (Burrup Road) and Site seven (Deep Gorge)...". However, MacLeod (2005) found that rocks on Burrup Peninsula, which had previously been classed as 'sterile' without measurable microbiological activity, showed marked bacterial, yeast and mould activity following an overnight thunderstorm. MacLeod (2005) measured nitrate concentrations and pH of the rock surfaces in association with the microbes and found a logarithmic increase in bacterial population with increased rock nitrate concentration. Rock surface pH declined linearly with the increase in nitrate and microbial concentrations. MacLeod (2005) assumed the increase in acidity was associated with microbial production of metabolites and organic acids such as acetic and oxalic. MacLeod (2005) also found that mobilisation of metallic cations on the rock surface increased as the acidity increased, which may suggest a decline in the integrity of the rock patina, essential for maintenance of the petroglyphs.

The results presented stress the need for continued monitoring of colour changes at rock art sites on Burrup Peninsula. In addition, monitoring of gaseous and particle emissions, anion, cation, pH and nitrate concentration changes as well as microbial activity on the rocks, especially after rain, should be reinstated to identify the causes for the colour changes observed and to allow better assessment of the likely long-term effect of industry on the rock art. Future experiments should measure all variables likely to affect the values recorded for the primary variables of interest, so they can be fitted as random effects in statistical models and increase the power of analyses. New control sites remote from industry and out of the path of prevailing winds carrying polluted air masses should also be established to eliminate the possible effects of shipping on the rock art site on the northern islands of the peninsula. In addition, the feasibility should be investigated of taking at least annual colour photographs of the petroglyphs under 'standardised' conditions, so the extent of colour changes on the rocks over time is observable and recorded. In addition to maintaining a longitudinal photographic record of colour at the sites, the digital camera may be useful as a non-contact colorimeter (Sanmartín *et al*. 2014). The images can be compared across time using image-change detection algorithms (Coppin *et al*. 2004; Radke *et al*. 2005).

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