Government of **Western Australia**
Department of **Water and Environmental Regulation**

Summary of scientific studies and monitoring programs commissioned and overseen by the Burrup Rock Art Monitoring Management Committee and the Burrup Rock Art Technical Working Group

Department of Water and Environmental Regulation

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1 Introduction

1.1 Background to the scientific studies and monitoring

Under the Burrup and Maitland Industrial Estates Agreement (BMIEA) Additional Deed (January 2003), the Government of Western Australia committed to organise and fund a minimum four-year study (monitoring study) into the effects of industrial emissions on rock art (petroglyphs) within and in the vicinity of that part of the industrial estate that was on the Burrup Peninsula. The monitoring study was established in response to community concerns about the potential effects of industrial air emissions on the rock art.

In 2002, the Burrup Rock Art Monitoring Management Committee (the Committee) was established to independently oversee the monitoring study. The objectives of the Committee were to:

- investigate and report on any impacts of emissions from existing and proposed industrial development to the rock art on and adjacent to the Burrup Peninsula
- ensure the monitoring study was undertaken in an open and transparent manner engaging community input throughout the entire process
- recommend management measures, outlining mitigation and remediation measures for the preservation and conservation of the rock art, whether industrial development on the Burrup Peninsula proceeds or not.

The Committee posed three research questions (CSIRO 2006a):

- Is the natural weathering of the rock art of the Burrup Peninsula being accelerated by industrial emissions?
- Is there a significant and measurable problem?
- If there is a significant issue, what management approaches are recommended?

The Committee commissioned several scientific studies to investigate the possible effects of current and future industrial emissions on the rock art (Burrup Rock Art Monitoring Management Committee 2009; SKM 2009a). These included:

- air dispersion modelling of emissions to air from a range of sources on the Burrup Peninsula to predict emissions, transport and subsequent ground-level concentrations and deposition rates of nitrogen oxides, nitrogen dioxide, sulphur dioxide and ammonia (SKM 2003, 2009b) (Section 2.1)
- air quality monitoring between August 2004 and September 2005, February 2007 and September 2008, and August 2008 to August 2009, to measure concentrations of nitrogen dioxide, sulphur dioxide, ammonia gases and nitric

acid, and benzene, toluene, ethylbenzene and xylene (BTEX) (CSIRO 2006a, 2008a, 2010a) (Section 3.1)

- an assessment of microclimate and its influence on the amount of dust deposited and retained on rock surfaces, and dust deposition processes and the composition of deposited dust (CSIRO 2006a, 2006b, 2007a, 2008a, 2010a) (Section 2.2)
- artificial fumigation (accelerated weathering) studies to investigate physical, chemical and mineralogical changes in rock surfaces at current, future and five to 10-times future pollutant estimates (CSIRO 2007a) (Section 2.3)
- measurement of changes in colour contrast and surface mineralogy of the rock art (CSIRO 2006b, 2007a, 2008b, 2009, 2010b, 2011, 2012, 2013a, 2014a, 2015a, 2017a) (Section 3.2)
- assessment of the gross number and diversity of micro-organisms on rock surfaces over the period 2004–08 to investigate whether microbial activity was stimulated by air pollutants (O'Hara 2006, 2008) (Section 2.5).

Figure 1 outlines the individual components of the monitoring study and the interconnections between the components as "…together they contribute to an overall understanding of Burrup rock surface chemistry and mineralogy, thereby facilitating a detailed knowledge of potential degradation processes for rock art in the region" (CSIRO 2006b, 2007a).

The Department of Industry and Resources, and subsequently the Department of State Development, was responsible for administering and facilitating the monitoring study.

The scientific reports from the monitoring study were independently peer reviewed by international experts. SKM (2009a) prepared a summary of the findings from the monitoring study for the Committee. The peer review reports and the SKM report are available at www.wa.gov.au/government/document-collections/murujuga-rock-art-strategy.

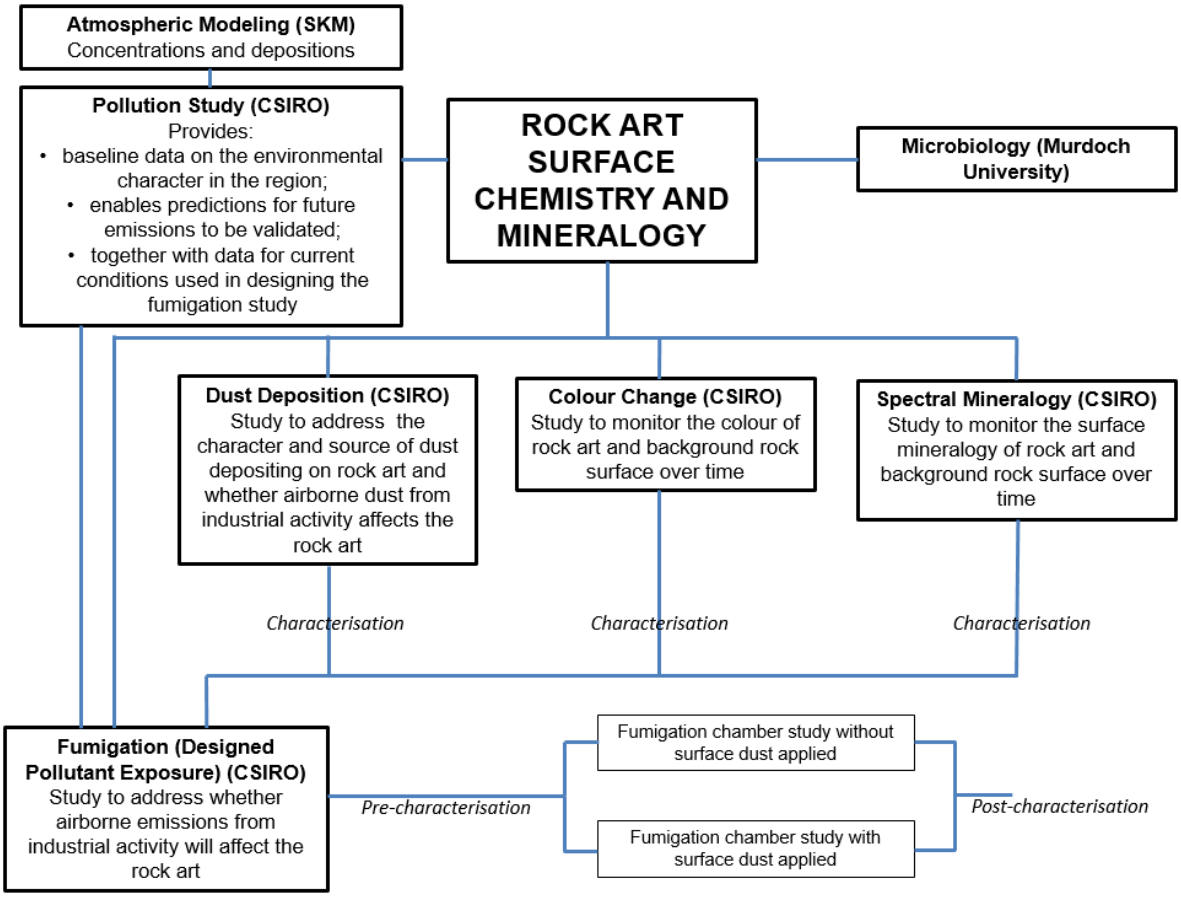

Figure 1 Conceptual framework for the monitoring study components and the interconnections between the components (Source: CSIRO 2006b, 2007a)

Notes:

1. Colour change may be affected by dust deposition and/or spectral mineralogy and together inform the conditions for and interpretation of the fumigation component of the monitoring study (CSIRO 2006b, 2007a).
2. Acknowledged that microbial factors may play a significant role in the surface chemistry, their exact role in the monitoring study was not isolated in order to focus specifically on the individual and combined effects of gaseous airborne emissions and industrially generated dust (CSIRO 2006b, 2007a).

In April 2009, after reviewing the information from the monitoring study and the comments from the international peer reviewers, the Committee released its report and recommendations to the then Minister for State Development on the first four years of the monitoring study (Burrup Rock Art Monitoring Management Committee 2009). The Committee concluded there was no scientific evidence to indicate there was any measurable impact of emissions on the rate of deterioration of the rock art on the Burrup Peninsula. The Committee also concluded that, as the rate of deterioration of rock surfaces was very time-dependent, the results represented a baseline for continued and future monitoring programs.

In its report, the Committee recommended that:

1. colour contrast and spectral mineralogy monitoring be continued on an annual basis for 10 years and be reviewed after five years
2. monitoring of ambient air quality and rock microbiology be suspended and only commenced if warranted by a major increase in emissions or change in emissions characteristics of any existing emission source, a major new emission source, or if evidence became available indicating further monitoring was required (e.g. monitoring of rock surfaces suggested the possibility of changes)
3. a small technical working group be established to replace the Committee and meet annually to consider the results of monitoring of the colour contrast and spectral mineralogy, air quality monitoring, modelling and other studies; and the results be made available to the public on an annual basis
4. no environmental management measures specifically to protect the rock art from air pollution were necessary at that time. If monitoring suggests the possibility of impacts of air pollutants on rock art, the technical working group would report to the government so appropriate action could be initiated.

With the release of the Committee's final report, the objectives of the Committee were met and the Committee was dissolved.

In July 2010, given the Department of Environment and Conservation's (DEC) role in environmental monitoring and management of emissions from industry on the Burrup Peninsula, the coordination responsibilities for the rock art monitoring program and the establishment of the technical working group were transferred from the Department of State Development to DEC.

The Burrup Rock Art Technical Working Group was established in September 2010. The role of the Technical Working Group included:

- managing the rock art monitoring program
- reviewing the annual monitoring reports
- recommending, where appropriate, any management and mitigation strategies based on the findings from the monitoring
- reviewing the need, and make recommendations where required, for further atmospheric monitoring in light of additional emissions or observed changes on rock surfaces
- reviewing the need, and make recommendations where required, for further or amended monitoring of rock surfaces
- liaising, facilitating meetings and actively communicating with indigenous groups, community groups and other stakeholders on the rock art monitoring program.

In September 2010, the rock art monitoring program was extended for a further 10 years, with a review to be undertaken after five years by the Technical Working

Group and a report provided to the Minister for Environment and DEC on the outcomes of the studies to date and recommendations for the continuation of the program.

The tenure of the Technical Working Group expired in June 2016. The Department of Environment Regulation (DER) and, since July 2017, the Department of Water and Environmental Regulation (DWER), have been responsible for managing the monitoring program from the expiry of the Technical Working Group's tenure

CSIRO has undertaken annual monitoring to detect changes in the colour contrast and spectral mineralogy of the rock art since 2004 at seven sites, with three additional sites incorporated since 2014 (CSIRO 2006b, 2007a, 2008b, 2009, 2010b, 2011, 2012, 2013a, 2014a, 2015a, 2017a) (Section 3.2). Monitoring has not been undertaken at the full suite of sites in 2017, 2018 or 2019.

In 2016, the Technical Working Group commissioned an extreme condition weathering study to investigate the effects of different concentrations of nitric acid, sulphuric acid, ammonium nitrate and ammonia on weathered rock surfaces (Section 2.4). The aim of the study was to provide an indication of the level of resilience of rock art substrates to extreme exposures of substances emitted from industry on the Burrup Peninsula and an indicator of the symptoms of physical, mineralogical or colour changes in the weathered rock surfaces in response to the exposures. The study was to repeat the tests previously undertaken by CSIRO (CSIRO 2007a).

1.2 Independent review

There has been criticism of the methodology used and the interpretation of the findings from some of the research studies and monitoring that have been undertaken over the past 15 years (e.g. Bednarik 2004, 2007a, 2007b, 2009; Hallam 2009; Black et al. 2017a). Several inadequacies in the statistical analysis of the annual colour change and spectral mineralogy monitoring data have also been identified (Black and Diffey 2016a; Black et al. 2017a).

DER commissioned Data Analysis Australia (DAA) to undertake two independent reviews relating to the rock art monitoring program:

1. An independent expert review of statistical analyses and underlying data to determine the validity of the approaches taken to monitor potential impacts of industrial emissions (colour change and spectral mineralogy) on rock art at the Burrup Peninsula (Data Analysis Australia 2016).
2. A review of the underlying data and the suitability of the statistical methodology used by CSIRO in the draft report *Burrup Peninsula Aboriginal Petroglyphs: Colour Change & Spectral Mineralogy 2004–2016* and CSIRO's advice in relation to the recommendations in the report *Review of Statistical Aspects of Burrup Peninsula Rock Art Monitoring* (Data Analysis Australia 2017).

The conclusions from these reviews included:

- the colour change and spectral mineralogy monitoring program was less than ideal in experimental design and was not based on firm statistical principles, which has led to a lack of clarity in purpose, inefficient design of data collection and a lack of focus on analysing the results
- given the considerable quantity of monitoring data collected, there was a need for robust data management practices to be implemented (including preparation of appropriate metadata)
- there was a need for improved statistical methods, with the data subject to appropriate statistical analysis, if the meaning and significance of the data was to be understood.

DAA (2017) recommended that consideration should be given to redesigning the monitoring program based upon well-established principles of experimental design, including:

- a clearly stated definition of effects or changes that the monitoring should be able to detect which will enable the design to be optimised for monitoring such possible changes
- identification of the optimal number of sites, spots within sites, replicates within spots and duplicates within replicates, based on an understanding and quantification of the sources of error, including consideration of the variation between sites, between spots on a site, between points within a spot, between times for each point, and between replicate (taking recording head off surface between readings) and repeat measurements (recording head kept in place)
- a clear role for the control sites, with an appropriate balance between the number of control sites and treatment sites, noting that for simple designs with a constraint on total effort it is optimal to have equal numbers of control and treatment sites
- the required level of statistical power to detect a change of a certain size, with consideration of the size of changes that are meaningful or of practical importance.

DAA (2017) suggested considering in the redesign of the monitoring program:

- the inclusion of additional control sites to bring the number close to the number of treatment sites
- the inclusion of additional monitoring sites to balance the monitoring program design across factors such as distance from the sea, rock types, age and orientation, and enable formal analysis of site specific effects
- the number of replicate measurements made at each sampling point. DAA suggested it was likely that fewer replicate measurements could be made at each spot since at that level the results were more repeatable.

DAA (2017) acknowledged that redesign of the monitoring program would not be without cost and would take time.

DAA (2017) also recommended that:

- a formal monitoring program design document should be produced, including explanations for any departures from the established principles of experimental design
- to maintain scientific rigour, data collection should follow a fully documented and detailed protocol, with any changes in measurement practices documented
- data analysis should be based on a formal analysis plan produced in parallel with the design document and certified by a competent statistician.

1.3 The Murujuga Rock Art Strategy

In September 2017, the draft Burrup Rock Art Strategy was released for public comment. The Murujuga Rock Art Strategy was released in February 2019. The strategy builds on the scientific studies and monitoring undertaken previously, to establish a scientifically rigorous approach to monitoring and management that will provide an appropriate level of protection for the rock art on Murujuga.

1.4 Purpose of this report

The purpose of this report is to address the request from the Murujuga Rock Art Stakeholder Reference Group for “a summary of information from the monitoring and scientific studies undertaken to date, including any limitations”.

This report presents a summary of the studies and monitoring programs commissioned under the BMIEA and overseen by the Burrup Rock Art Monitoring Management Committee and, subsequently, the Burrup Rock Art Technical Working Group. Each study and monitoring program, where relevant, provides:

- objective(s)
- sites
- timing and frequency of sampling
- overall approach
- methodology
- summary of key findings
- overview of limitations identified by third parties
- data availability.

For further information on the studies or monitoring programs, the relevant source material should be referred to.

No further analysis or interpretation of the results and findings, assessment of the limitations of the studies and monitoring programs, or commentary on the limitations identified by third parties, is presented in this report.

2 Summary of scientific studies

2.1 Air dispersion modelling

Study objectives

Dispersion modelling of the atmospheric pollutants from a range of sources that were considered to be of most concern and have a possible impact on the rock art was undertaken (SKM 2003, 2009a). The modelling updated that originally undertaken in 2002 with revised emission parameters for the Woodside facilities and improved estimates of ship emissions. The objectives were to provide updated:

- estimates of annual concentrations and deposition of nitrogen dioxide (primarily emitted from industry) and sulphur dioxide (primarily emitted from ships) for existing and future industry and shipping
- estimates of annual concentrations and deposition of ammonia from existing industry and future industry
- estimates of nitrogen dioxide for one-hour and ozone for one-hour and four-hour averages to assess the levels at Hearson Cove, Conzinc Bay, Dampier and Karratha (SKM 2003, 2009a).

The modelling was used as a basis for deciding on control and industry-affected rock art monitoring sites (SKM 2009a). The modelling would also be used to provide information on concentrations of air pollutants experienced by the rock art if any changes were noted during the monitoring program.

In 2009, the 2003 modelling study was updated and refined in light of results from the air quality monitoring (Section 3.1). The objectives were to:

- revise the previous modelling study to cover the periods for which air quality monitoring was undertaken (2004-05 and 2007-08)
- revise estimates of industrial emissions using available public documentation of industrial developments, to represent actual industrial operations during the monitoring period
- analyse modelling results of concentrations and deposition of nitrogen dioxide and sulphur dioxide and compare with the results of the monitoring program (SKM 2009a, b).

2003 modelling methodology

Two models were used to predict annual concentrations and the deposition of nitrogen dioxide, sulphur dioxide and ammonia (SKM 2003):

1. The Air Pollution Model (TAPM) — a prognostic meteorological and air pollution dispersion model developed by CSIRO (CSIRO 2008a, 2010a). The meteorological component predicts the local-scale flow, such as sea breezes and terrain-induced circulations, given the larger-scale synoptic meteorology.

The air pollution component uses the model-predicted, three-dimensional meteorology and turbulence, and consists of a set of species conservation equations and an optional particle trajectory module.

2. The Californian Puff Model (CALPUFF) — an air pollution dispersion model developed by Earth Tech Inc. (USA) that simulates the transport and diffusion of a plume via the puff approach in which a plume is described as consisting of a series of puffs (CSIRO 2008a, 2010a). The model uses meteorological data generated by the processor CALMET.

The 1999 meteorology was used in the modelling, as it was the only year with good-quality emission, meteorological and monitoring data to enable model validation (SKM 2003).

To assess the capability of the two models, comparison of predicted and observed concentrations of nitrogen oxides and nitrogen dioxide at Dampier were undertaken (SKM 2003). SKM (2003, 2009a) concluded:

- as configured in this study, the TAPM model generally reproduced the nitrogen oxides statistics as measured at Dampier and significantly over-predicted the nitrogen dioxide concentrations (by up to 100 per cent for short-term concentrations). Annual predictions of nitrogen dioxide concentrations, and as a result the nitrogen dioxide deposition, were therefore likely to be over-predicted
- the CALPUFF model under-predicted the nitrogen oxides and nitrogen dioxide concentrations at Dampier. Predictions of pollutants, except for near-field over land (within several kilometres [km] of the source) were likely to be underestimated. CALPUFF modelling could potentially be improved with the incorporation of more data, principally over water winds, sea temperatures and air temperatures from the Burrup Peninsula.

Two scenarios were assessed, involving:

- existing sources of emissions to air at the time of the assessment, including the Woodside Onshore Treatment Plant, Hamersley Iron Power Station and shipping
- a future scenario[1] including emissions to air from the Woodside Onshore Treatment Plant with additional processing trains 4 and 5, Hamersley Iron Power Station, seven new industries (Methanex, GTL, Burrup Fertilisers, Dampier Nitrogen, Japan Dimethyl Ether (DME) and two other industries equivalent to Japan DME and Dampier Nitrogen), and current and potential shipping (SKM 2003).

[1] Date unspecified but for a point in time when the proposed additional emissions would likely be operating (SKM 2009a).

Predicted health impacts because of industry expansion and new industry were assessed for nitrogen dioxide and ozone, the pollutants of most concern, and for shorter averaging periods less than one day.

For further information on model set-up and validation refer to SKM (2003).

2009 modelling methodology

The TAPM model was used to predict nitrogen dioxide and sulphur dioxide concentrations and deposition (SKM 2009a, b). Model configuration was as for SKM (2003), with the exception that shipping sources were set explicitly as volume sources.

The scope of the study was restricted to using the model domain and non-industrial emissions data from the 2003 modelling (SKM 2009b). Consequently, the monitoring sites Dolphin Island and Mardie Station were outside the innermost TAPM modelling domain and were not addressed in this study. Resource constraints precluded the development of a new model domain.

Air emissions were modelled for:

- the current scenario including emissions from industrial sources that were operating during the monitoring program.
- a future scenario including emissions from industrial developments that had received regulatory approval and were expected to proceed in the foreseeable future (SKM 2009b).

Emission characteristics were taken from SKM (2003) and revised in light of publically available emissions data (SKM 2009b). Relevant emissions sources included contributions from industry as point sources, shipping represented as small volume sources and area emissions from biogenic and anthropogenic sources.

Both the current and future emissions scenarios were modelled for the periods of the monitoring program.

For further information on model set-up and validation refer to SKM (2009b).

2003 key study findings

The model results for nitrogen dioxide showed (SKM 2003, 2009a):

- the maximum annual nitrogen dioxide concentration as a result of emissions from existing sources was 2.7 parts per billion (ppb) and increased to 5.2 ppb with future sources
- the maximum predicted deposition rates were up to 0.26 kilograms (kg) of nitrogen per hectare per year from existing sources of nitrogen dioxide and 0.64 kg of nitrogen per hectare per year from future sources of nitrogen dioxide. The maximum predicted deposition rates were up to 3.3 kg per hectare of nitrogen as a result of future emissions of ammonia

- highest modelled concentrations and deposition occurred near the Woodside Onshore Treatment Plant, extending in a general westward and eastward direction in line with the prevailing easterly and westerly winds. The concentrations and deposition decreased most rapidly in roughly a north/south direction
- the CALPUFF model predicted a more rapid decrease in concentrations with distance than the TAPM model
- both models showed West Lewis Island had relatively high concentrations and deposition compared with other locations
- the CALPUFF model indicated Karratha should have the lowest concentrations and deposition followed by West Intercourse Island. The TAPM model indicated that the lowest concentrations and deposition were on West Intercourse Island, Dolphin Island and Enderby Island, with little difference between the three locations.

The model results for sulphur dioxide showed (SKM 2003, 2009a):

- the maximum annual sulphur dioxide concentrations increased from 0.5 ppb as a result of emissions from existing sources to 1.6 ppb for future sources
- the maximum predicted deposition rates were up to 1.7 kg of sulphur dioxide per hectare per year for existing sources and 2.6 kg of sulphur dioxide per hectare per year from future sources
- highest modelled concentrations and deposition occurred over water near the shipping berths. Given the poor dispersion of shipping emissions due to the relatively low temperature and low heights of ship funnels, maximum concentrations of sulphur dioxide were recorded close to the shipping berths. This contrasted with emissions of nitrogen oxides from the Woodside Onshore Treatment Plant and the Hamersley Iron Power Station, which were much hotter emissions from higher release points (high chimneys/stacks), which aided the dispersion of nitrogen oxides and resulted in maximum concentrations being further from these sources
- both models indicated that West Lewis Island would have the highest relative concentrations and deposition.
- both models showed that the lowest concentrations and deposition occurred at Karratha followed by West Intercourse Island and Dolphin Island.

The TAPM model results for ozone showed (SKM 2003):

- the maximum one-hour and four-hour concentrations were predicted to decrease from 82 per cent and 73 per cent respectively of the National Environment Protection Measure (NEPM) standard to 74 per cent and 65 per cent respectively of the standard with the addition of new sources.
- this decrease occurred as the new sources were estimated to emit principally nitrogen oxides and negligible amounts of reactive organic compounds, such

that the additional nitrogen oxides would suppress ozone formation. This result was very dependent on the amount of reactive organics emitted.

Modelling of one-hour average nitrogen dioxide concentrations using the TAPM model indicated (SKM 2003):

- concentrations were predicted to increase at all locations with the addition of new sources, with the maximum anywhere increasing from 58 per cent to 62 per cent of the NEPM standard
- the maximum concentrations at residential sites or where people may congregate increased from 46 per cent to 58 per cent of the NEPM standard

It was noted these predictions were considered to be overly conservative because of the higher than expected conversion of nitric oxide to nitrogen dioxide within the TAPM model.

Modelling of nitrogen dioxide concentrations using the CALPUFF model indicated (SKM 2003):

- maximum predicted concentrations at all locations were similar to those from the TAPM model, with the maximum increasing from 51 per cent to 73 per cent of the NEPM standard with the addition of new sources. The CALPUFF model predicted that the maximums occurred within several kilometres to the west of the Woodside Onshore Treatment Plant and the TAPM model predicted the highest concentrations could occur up to 15 km from the Woodside Onshore Treatment Plant
- the maximum concentrations at residential sites or where people may congregate were about half that predicted from the TAPM model, increasing from 21 per cent to 30 per cent of the NEPM standard for the future scenario.

2009 key study findings

Key findings included (SKM 2009a, b):

- modelling results suggested that future development proposals may lead to an increase in nitrogen dioxide deposition of between 50 per cent and 80 per cent. In absolute terms, predicted concentrations remained small (tens of milligrams per square metre per year [mg/m^2/year]) compared to air quality standards commonly applied in cities and residential areas in Australia
- comparison of current and future scenarios showed that commissioning of the planned industrial plant was expected to increase longerterm average concentrations of nitrogen dioxide by about 30 per cent. In absolute terms the concentrations remained small (in the order of 3 ppb) and below the NEPM standard
- modelled longer-term average concentrations of nitrogen dioxide and sulphur dioxide were similar to measured concentrations at the monitoring sites and the spatial distribution of modelled and measured results were broadly consistent between sites across the Burrup Peninsula. Modelled

concentrations were much lower than the measured concentrations at the site in Karratha

- the ratio of modelled to measured concentrations of sulphur dioxide was greater and more variable than for nitrogen dioxide. This may have been attributable to an error in the zero reading of the monitored data, or from higher emissions in the modelling input data files (SKM 2009b)
- the ratio of predicted to measured ground-level concentrations varied significantly with wind direction and speed. With respect to wind direction, the TAPM model over-predicted when the wind blew from the west, which may be attributable to an overestimation of shipping emissions or an underestimation of dispersion of emissions from ships at berth (SKM 2009b). In contrast, the ratio was strongly correlated with the inverse of wind speed: low wind speeds were associated with an overestimation of concentrations
- comparison between the predicted isopleths and the gridded measurements indicated good agreement for nitrogen dioxide of between 1.5 ppb and 2 ppb. Sulphur dioxide isopleths matched the gridded measurements better in shape but the predicted values were higher than the measured data. Ambient concentrations of sulphur dioxide were likely to be over-predicted by the model because the representation of ships as volume sources did not incorporate the effect of buoyant plume rise from the ship exhaust (SKM 2009b).

There are no known impact assessment criteria for air quality and deposition impacts to rock art (SKM 2009a). Modelled concentrations from existing and future scenarios were small relative to assessment criteria for human health and vegetation, as well as concentrations in urban areas, and the increases because of future emissions were modest. In the context of the likely impacts to rock art, there were no changes to the conclusions of the 2003 study from the 2009 study.

Summary of results (Burrup Rock Art Monitoring Management Committee 2009)

- Ground-level concentrations and deposition rates were predicted to increase for the future modelled scenario, consistent with the predicted increase in industrial activity on the Burrup Peninsula.
- Modelled concentrations from both existing and future predicted scenarios of emissions to air were small relative to assessment criteria for human health and vegetation. The increases because of future emissions were modest, with maximum annual nitrogen dioxide concentrations from the total of existing and future sources predicted to be 5.2 ppb and 1.6 ppb for sulphur dioxide.
- The conclusions from the 2009 study were unchanged from the 2003 study and the predicted ground-level concentrations of air pollutants were generally similar.

Comparison of air quality monitoring data with modelling studies

The concentrations and deposition of nitrogen dioxide and sulphur dioxide measured during the 2004/05 air quality monitoring were compared with the results of modelled concentrations predicted using the TAPM and CALPUFF models (CSIRO 2010a).

Key findings included (CSIRO 2010a):

- the measured nitrogen dioxide concentrations at Dolphin Island, North Burrup and Woodside East compared favourably with the TAPM model predictions but were higher at other sites, in particular the site in Karratha where the measured concentration was about double that predicted by the model
- the measured nitrogen dioxide concentrations compared closely with the TAPM model results and were higher than those predicted by the CALPUFF model
- the CALPUFF model predicted higher sulphur dioxide concentrations than the TAPM model and were more consistent with the measured concentrations
- both models predicted lower deposition fluxes of nitrogen and sulphur than the measured fluxes, meaning:
    - the average annual nitrogen dioxide deposition fluxes predicted by the TAPM model were lower than the measured values by a factor of between two and five
    - the predicted deposition fluxes of sulphur dioxide from both models were similar to each other, with measured deposition fluxes higher than the models by a factor of about two and five.

Limitations

Hallam (2009) expressed concern that statements that the scientific reports from the monitoring study showed that the rock art on the Burrup Peninsula was not being affected by industrial emissions were unjustified based on the available scientific information. Hallam (2009) considered the main issue with the conclusions from these reports was summarised in SKM (2009b): “Current ambient levels [of pollutants] are well within NEPM standards for ambient air quality…although the NEPM standards are *related to human health and amenity and do not necessarily reflect concentrations that may degrade the petroglyphs*.” Hallam (2009) noted the investigators cited no literature on the effects of air quality on rock engravings or on the rock crusts.

Data availability

Information on existing and future-scenario emission characteristics and a summary of the modelling results are provided in SKM (2003, 2009b).

2.2 Dust deposition

Study objectives

Dust deposition processes and the composition of deposited dust were measured to determine whether dust deposition plays a role in rock surface weathering mechanisms (CSIRO 2006b, 2007a; SKM 2009a). The objectives were to:

- characterise (by chemical and mineralogical analysis) the dust that settled on the rock surface
- identify the source of dust settling on rock surfaces
- monitor dust deposition processes and composition of deposited dust on the rock surfaces (CSIRO 2006b, 2007a; SKM 2009a).

Field measurements of rock washings were undertaken on one occasion to investigate the deposition of acidic gaseous species (nitrate and sulphate) directly on the surface of rocks (CSIRO 2007a).

Sampling sites

Dust collection was undertaken at three sites: Dolphin Island, Burrup Road and King Bay South (CSIRO 2006b, 2007a).

Field measurements of rock washings were undertaken at four sites: Dolphin Island, Gidley Island, Water Tanks and King Bay South (CSIRO 2007a).

Timing and frequency of sampling

The first tile collector exposure period was for three months from August 2004 (CSIRO 2006b, 2007a; SKM 2009a). To increase the amount of dust collected, tile collectors were exposed for a period of 12 months for the second collection period, with dust collected at six-month intervals.

Field measurements of rock washings were undertaken in August 2006 (CSIRO 2007a).

Approaches to the study

The deposition processes and composition of deposited dust were assessed through the use of tile collectors designed to emulate the surface micro-topography of typical engraved rocks (CSIRO 2006b, 2007a; SKM 2009a). The simulated rock surfaces were then exposed in order to collect dust representative of that actually settling on rock surfaces and the rock art, rather than all airborne dust available for settling.

Methods that involved brushing or vacuuming the rock surfaces in situ were not used because the rock surface contains hematite and the mineralogical composition resembles iron ore dust and local soil (CSIRO 2006b, 2007a).

Methodology

The tile collectors were made of a polyurethane polymer with silica filler selected for its weatherability (CSIRO 2006b, 2007a). A silicon moulding resin that could reproduce detail to one micron (µm) was applied to the selected representative rock surfaces over an area of about 100 millimetres (mm) x 150 mm. Polyurethane resin was cast into the moulds to a depth of 5–8 mm and a 100 mm x 150 mm x 3 mm aluminium support backing applied. Cured tiles were removed from the moulds, trimmed, washed with soapy water, rinsed with deionised water and stored with the surface protected until exposure. Four collector tiles were erected onto an exposure rack deployed at each site (Figure 2).

Figure 2 Exposure rack with collector tiles at Dolphin Island (Source: CSIRO 2007a)

At the end of each sampling period, the dust collected on the tiles was measured (CSIRO 2006b, 2007a; SKM 2009a). Insufficient quantities of dust were collected on the collector tiles to enable a comparative diagnosis to be undertaken. In order to collect sufficient material for characterisation, a modified approach was adopted whereby dust was collected from the protected interleaved horizontal surfaces of the data logger housing at each of the sites.

Dust samples were analysed using X-ray diffraction to determine the crystalline components of the dust and inductively coupled plasma atomic emission spectroscopy (ICP-AES) to characterise the elemental composition (CSIRO 2006b, 2007a; SKM 2009a). Samples of local soil, iron ore and iron ore dust were also characterised using X-ray diffraction and ICP-AES.

Sampling for rock washings was undertaken using a purpose-built sampler comprising a silicone rubber washer at the base of an open-based plastic container (internal diameter 50 mm) that was pressed against the rock surface (CSIRO 2007a). Fourteen millilitres (mL) of deionised water was placed in the sampler for 20 seconds and then withdrawn and collected. A blank for each site was performed on a clean ceramic tile. Concentrations of nitrate and sulphate were analysed by ion-chromatography, with no pre-treatment.

For further information on the methodology and analysis refer to CSIRO (2006b, 2007a).

Key study findings

Key findings from the study included (CSIRO 2007a):

- Dust deposition rates and retention of dust on rock surfaces were very low. In the long-term (e.g. over a year), natural environmental factors such as wind and washing by rain act to remove deposited material, resulting in levels of dust on unsheltered rock surfaces that were at the limits of detection. The maximum build-up of dust observed on the rough rock type used in this study was in the order of 1–2 µm in thickness at the bottom of depressions measuring 4 mm in depth.
- There was a correlation between the location of the sampling site and the composition of dust collected from protected surfaces. Quartz, sea salt, hematite and goethite predominated in the dust deposited at Burrup Road and King Bay South, indicating that the deposited dust was principally from iron ore. There was less hematite evident in dust deposited at Dolphin Island, with quartz and sea salt predominant, indicating the dust originated from natural sources (windblown soil and sea salt).
- Nitrate and sulphate were not recorded in any of the rock washings.

Data availability

The following data are provided in CSIRO (2007a):

- Concentrations (milligrams per litre [mg/L]) of nitrate and sulphate in rock washings (Table 17).
- Elemental composition (% or parts per million [ppm]) of iron ore, iron ore dust and local soil (Table 19 [not numbered]).

2.3 Accelerated weathering (fumigation) tests

Study objectives

Accelerated erosion tests using laboratory fumigation chambers were undertaken on typical rock samples from the Burrup Peninsula to assess the impact of different pollutant scenarios and to evaluate the role that dust might have in rock surface modification (CSIRO 2006b, 2007a; SKM 2009a). The objectives were to:

- determine whether airborne emissions from industrial activities could affect the rock art
- investigate changes, if any, in the weathered rock and engraved surface
- assess the physical, chemical and mineralogical changes to determine early indicators of damage (CSIRO 2006b, 2007a; SKM 2009a).

Sampling sites

Rock samples were collected from the west side of Gidley Island (about 200 metres (m) from the colour measurement site; refer to Section 3.2) to ensure samples were unlikely to have been contaminated by industrial activities or other sources (CSIRO 2006b, 2007a). Samples with surfaces representative of the engraved and background areas were collected.

To avoid the potential for contamination, rock samples were mechanically broken into pieces with surface areas of about 10–15 square millimetres (mm^2) for use in characterisation before and after fumigation (CSIRO 2006b, 2007a).

Timing of study

The fumigation chamber studies were undertaken in 2006 (CSIRO 2006b, 2007a).

Approach to the study

The key elements of the study included (CSIRO 2006b, 2007a):

1. definition of the test conditions to ensure test cycles reflected the appropriate combination of microclimate cycles and pollutant levels that occurred on the Burrup Peninsula
2. fumigation exposures of rock samples to the climatic cycles (defined in 1.) and different pollutant levels. Tests were also undertaken with adjusted pollutant levels to induce the most extreme pH possible
3. extreme exposures to understand how early indicators of damage may progress to more profound damage
4. analysis (characterisation) of rock surfaces pre- and post-exposure and dust to define early damage indicators and (through 3.) to assess the relevance of early indicators to possible progression of damage under predicted air quality scenarios
5. addition of dust to establish the effect of the presence of dust on rock surfaces.

The studies assessed changes in the weathered surface (covered with desert varnish) and the engraved surface that defines the rock art image, with particular focus on the change in properties observed on the exposed surface (desert varnish) compared with the unweathered zone at depth (CSIRO 2006b, 2007a). The response of iron ore dust to extreme pollutant exposure was used to represent end points in the degradation process because of individual pollutants.

Methodology

Laboratory fumigation chamber studies on typical rock samples involved the exposure of rocks at current, future and at five to 10-times future estimates of air pollutants likely to be experienced at rock art locations near to industry, with induced

cycles of heating, wetting and drying designed to emulate natural diurnal cycles on the Burrup Peninsula (CSIRO 2006b, 2007a; SKM 2009a).

CSIRO (2007a) noted there are significant challenges in replicating the conditions that contribute to ageing and weathering of rock surfaces in situ and acknowledged that the conditions used to simulate the effects of accelerated ageing did not take into account all the possible parameters that are involved in the natural situation. There was little reliable information available regarding the parameters involved, such as the periods of wetness experienced by rock surfaces and the surface temperatures of rocks, which required verification before establishing the cycling processes for the fumigation program (CSIRO 2007a).

The chamber cycle conditions were designed to induce the formation of condensation on the surface of the rocks through maintaining a high humidity and inducing temperature change in the rock (CSIRO 2007a). The humidity within the chamber was kept at about 86 per cent ± 3 per cent. The rock samples were arranged on a Peltier temperature-controlled pad to heat and cool the samples and introduce undercooling to achieve surface wetness through condensation, in a 21-litre (L) stainless-steel environmental chamber. The Peltier cycled between 18°C and 63°C and the surface rock temperature between 21°C and about 49°C (temperature inside the rock samples was not measured). The total cycle length was one hour and each test ran for 720 cycles. The chamber underwent a full air change every hour during the test period.

To evaluate the role that dust may play in rock surface modification, duplicate experiments were conducted with the addition of iron ore dust to the rock samples before the samples underwent the chamber fumigation exposures (CSIRO 2006b, 2007a). Iron ore dust was characterised using X-ray diffraction and ICP-AES.

Each test exposed six rock samples (three background and three engraved surfaces[2]) to a range of pollutants (SKM 2009a). The pollutants tested were nitrogen dioxide, sulphur dioxide, ammonia, xylene, benzene and toluene (CSIRO 2007a). Accelerated weathering was performed at two exposure levels: future industry and 10-times future industry levels (Table 1).

[2] Note these were not engravings from the Burrup Peninsula, but engravings made in the laboratory (SKM 2009a).

Table 1 Pollutant concentrations applied in the fumigation studies

Pollutant	Concentration (part per billion [ppb]) prescribed in work scope		Prescribed in-chamber concentration (ppb)	
	Current	Future Industry	1 x exposure level	10 x exposure level
Nitrogen dioxide	2.4 (annual)	4.5 (annual)	5	50
Sulphur dioxide	0.5 (annual)	1.6 (annual)	2	20
Ammonia	-	4.0 (annual)	4	40
Benzene	1.2 (annual)	1.9 (annual)	2	20
Toluene	6.7 (weekly)	7.7 (weekly)	8	80
Xylene	6.9 (24 hour)	7.4 (24 hour)	7	70

(Source: CSIRO 2007a)

Pollutants were supplied to the chamber as a pre-mixed gas; airflow and exchange rates were used to control the pollutant doses for the future and 10-times future doses (CSIRO 2007a). The concentration delivered to the chamber was verified by active sampling of the chamber air onto an activated carbon tube that was analysed for mono-aromatic hydrocarbons.

Before and after exposure, sub-samples of the rock samples (background and engraved surfaces) were analysed for physical, mineralogical and chemical changes (CSIRO 2006b, 2007a). Analytical tools included optical microscopy and scanning electron microscopy, environmental scanning electron microscopy/energy dispersive spectroscopy, X-ray diffraction, Raman spectroscopy, Fourier transform infrared spectroscopy and surface colour measurements.

Extreme condition exposures involved the application of concentrated solutions of the pollutants (organic solvents and acids) to the rock surface minerals (CSIRO 2006b, 2007a). Samples of iron ore (mineralogically similar to iron ore dust) were exposed to water, concentrated solvent (benzene, toluene, xylene) or acid/base (1 molar solution [M] nitric acid, concentrated nitric acid, 1M sulphuric acid, concentrated sulphuric acid, 1M ammonia and concentrated ammonia) individually in vials for 22 days. The study was undertaken at 25°C and 50°C. Samples were rinsed and dried in ambient conditions. The mineralogy before and after exposure was characterised by X-ray diffraction and surface colour change was measured.

For further information on the methodology and analysis refer to CSIRO (2006b, 2007a).

Key study findings

Key findings from the study included (CSIRO 2006b, 2007a; SKM 2009a):

- Fumigation did not induce any measurable change in the mineralogy of the background or engraved rock surfaces.
- The elemental concentrations of the background and engraved surfaces after the future pollutant exposure were not measurably different from the unexposed samples; and the 10-times future exposure did not produce a greater change in the concentrations of elements compared with either the future exposure or the unexposed samples.

- Colour change values were within the same range for unexposed and exposed rock samples; the samples exposed with dust similarly did not show a significantly different colour change. There was no consistent increase in the colour change value when the exposure concentration increased from future to 10-times future exposures.
- The mineralogy of the rock surfaces exposed to the experimental conditions in this study were compared with unexposed (control) samples and there were no significant differences observed between the two. This was substantiated by exposure of rock surface minerals to concentrated solutions of the pollutants and only in the case of concentrated sulphuric acid in combination with elevated temperatures was any mineralogical change observed.

Limitations

Bednarik (2004) considered that none of the commissioned studies addressed the key issue (the physical degradation of the surface patina on which the preservation of the rock art was dependent) and that the accelerated weathering study was simplistic, did not simulate the natural exposure conditions and was likely to lead to incorrect conclusions about the effects of exposure.

Hallam (2009) expressed concern that the study briefs did not include questions such as the effect of low pH levels on rock surface crusts on engravings of varying age, depth and degree of pre-existing weathering. She noted that while CSIRO (2007a) acknowledged the importance of the pH of moisture films, the study did not measure rainfall or rock surface pH and that pH could have easily continued to be recorded without the need for elaborate equipment or specialist personnel. Hallam (2009) noted that the fumigation study was undertaken "…to induce the most extreme pH levels possible…" but the pH levels were not provided and the study did not examine or discuss the effects of pH on the structure of surface crusts. Hallam (2009) concluded that it remained true that there was little knowledge of the impact of acid deposition on rock art under the climatic conditions of the Burrup Peninsula.

Black (2013a, 2017a) and Black et al. (2017a) identified several concerns with respect to the accelerated weathering study, including that:

- the maximum gas concentrations used were below those projected for new and existing industry on the Burrup Peninsula
- there was no or insufficient treatment replication for statistical analysis and the variability between measurements for the same treatment made it difficult to draw sound conclusions about the impact of pollutant mixtures on the surface of rocks or petroglyphs
- the assessment of the effects of immersing iron ore (rather than rock surfaces with desert varnish) in dilute or concentrated organic compounds, acids or ammonia and measuring changes in colour and mineralogy was of no relevance to understanding impacts on rock art.

Mulvaney (2017a) expressed concern that the accelerated weathering study was conducted on samples from a single gabbro rock with only a thin weathering rind and that the study was not conducted on the range of lithologies known to have rock art (granophyre, dolerite and gabbro) nor on differing surface weathering states. Mulvaney (2017a) noted that without this information it was difficult to assess the effects of emissions on the rock art or the impacts of increased loads. Mulvaney (2017b) emphasised that none of the studies undertaken to date targeted the specific situation of the rock art in relation to physical and chemical alteration and susceptibility to emission loads.

Mulvaney (2017b) considered that iron ore was not an ideal rock to use as a proxy for gabbro or granophyre, but acknowledged there may be some merit in that the fumigation study considered surficial material only. Mulvaney (2017b) proposed that the tests should have been undertaken on real rocks from the Burrup Peninsula.

CSIRO (2017b) noted that using iron ore dust as a proxy had its advantages as X-ray diffraction of the powder could be undertaken which provided an accurate mineralogy before and after exposure. CSIRO (2017b) acknowledged this was limited to iron dissolution and does not consider the other elements such as manganese and aluminium.

In response to the concerns that were raised about the accelerated weathering study through submissions to the Senate Inquiry into the Protection of Aboriginal rock art of the Burrup Peninsula, CSIRO (2017c) advised:

- the design of the study was based on the TAPM and CALPUFF dispersion models (Section 2.1), with the concentrations of fumigant gases tested 10-times the peak emissions levels generated by the TAPM model which was likely to over-predict. CSIRO was not aware of information from industry supporting the claim that the level of emissions were below those projected for industry
- the dust experiments were performed using the accepted scientific approach of observing spectral change by difference and were designed with sufficient statistical power for the required analysis. The study included one case of dust exposure on two types of rock surfaces; on each of the 18 samples of rock, replicate measurements were made at three different points, each separate point about 2 mm in diameter. A spectral comparison was undertaken on the samples in accordance with widely accepted standard scientific procedures and a statistical analysis of these kinds of results was not necessary
- as the rocks were unable to be directly tested given the need to use non-invasive or damaging techniques, iron ore was used as a suitable proxy to investigate discoloration as it contains a similar mineralogical profile to the rock patina.

Data availability

The following data are provided in CSIRO (2007a):

- Elemental composition (% or ppm) of iron ore dust (Table 4).
- Normalised intensities of peaks at 1,648 cm^{-1} and 1,369 cm^{-1} of engraved and background rock surfaces under control (unexposed), future and 10-times future exposures to pollutants before and after fumigation (Table 8).
- Intensity differences of engraved and background rock surfaces under control (unexposed), future and 10-times future exposures to pollutants before and after fumigation (Table 9).
- Elemental profiles (% composition) of engraved and background rock surfaces under control (unexposed), future and 10-times future exposures to pollutants before and after fumigation (Table 10).
- Average pre-exposure surface concentrations of engraved and background rock surfaces (Table 11).
- Percentage change in elemental composition of engraved and background rock surfaces under control (unexposed), future and 10-times future exposures to pollutants before and after fumigation (Table 12).
- Colour measurements of engraved and background rock surfaces under control (unexposed), future and 10-times future exposures to pollutants before and after fumigation (Table 13).
- Colour change (ΔE) measurements of engraved and background rock surfaces under control (unexposed), future and 10-times future exposures to pollutants before and after fumigation (Table 14).
- Colour measurements of pollutant-treated iron ore (hematite) under ambient conditions for 22 days (Table 15).
- Mineralogical products of pollutant-treated iron ore (Table 16).

2.4 Experimental extreme weathering study

Study objectives

The objective of the experimental extreme weathering study was to investigate the effect of exposure to air pollutants from industry on the Burrup Peninsula on the rock art and surrounding weathered rocks (CSIRO 2017b). The aim of the study was to provide an assessment of the concentrations and associated pH at which damage can occur, as well as an indication of the precision of the colour and mineralogical measurements.

CSIRO (2017b) noted this was a preliminary study using novel sample preparation methods to provide a new approach to determining the effects of solutions of different compositions and concentrations on rock weathering. The study was not intended to serve as an exhaustive or definitive analysis of the impacts of the selected solutions

on granophyre and gabbro rocks, nor was it intended as an indication for permissible pollution levels (CSIRO 2017b).

Sampling sites

Rock samples were collected from the rock art monitoring sites (Section 3.2): Dolphin Island, Gidley Island, Woodside, Burrup Road, Water Tanks, Deep Gorge and King Bay South (CSIRO 2017b).

Timing of study

The experimental extreme weathering study was undertaken in 2016.

Approach to the study

The study involved (CSIRO 2017b):

1. the collection of samples of weathered gabbros and granophyres from each of the rock art monitoring sites
2. characterisation of the weathered surfaces of the samples
3. exposure of the weathered surfaces of the rocks to solutions of different concentrations of nitric acid, sulphuric acid, ammonium nitrate and ammonia in reaction vessels at 50°C for exposure times of three days and one month
4. characterisation of the weathered surfaces of the samples after exposure.

A preliminary power analysis was undertaken to inform the experimental design of the study to ensure that sample size allowed more extensive statistical analysis of the results and to ensure that defined levels of effect could be detected (CSIRO 2013b).

The conditions of this study differed from the previous study (CSIRO 2007a; Section 2.3) as:

- natural samples from the Burrup Peninsula were used rather than iron ore dust
- benzene, toluene and xylene were not tested
- manganese, aluminium, silicon, sodium and potassium, as well as iron, were measured
- the maximal concentrations of sulphuric acid and nitric acid in this study were 0.0111 M and 0.0087 M, respectively
- the solutions in which the samples were exposed were measured (CSIRO 2017b).

Methodology

One or two (depending on size) loose rock samples were collected at each sampling site (CSIRO 2017b). Each rock sample was selected based on the similarity of the weathered surface of the sample with the background surfaces measured in the rock

art monitoring program (Section 3.2), as measured using an Analytical Spectral Device (ASD) FieldSpecPro spectrometer.

Cylinders of rock (10 mm diameter) were drilled from the rock samples (CSIRO 2017b). There were 55 weathered gabbro samples (45 samples from Dolphin Island and 10 from Deep Gorge) and 55 weathered granophyre samples (12 samples from Gidley Island, 22 from Woodside, two from Burrup Road, seven from Water Tanks and 12 from King Bay South). Only the samples with the flattest surface were used in the study. However, the surface of the rocks collected at each site was naturally variable in terms of colour and mineralogical characteristics, thus the surface of the rock cylinders differed within and between sites.

The samples were encased in resin so that only the weathered surface of the rock was exposed to the test solutions. Four samples of gabbro and four samples of granophyre were exposed to each test solution. Seven samples were tested in the case of the control, distilled water.

In addition, unweathered (fresh) samples were collected and tested to assess the weathering of fresh samples (CSIRO 2017b). The study included eight samples from fresh gabbro (two samples from Dolphin Island and six from Deep Gorge) and fresh granophyre (five from Gidley Island, two from Burrup Road and one from King Bay South).

The rock cylinders were submerged in plastic vessels containing 100 mL of test solutions (CSIRO 2017b). The details of the test solutions are provided in Table 2. Test solutions were heated to 50°C to reflect the temperatures reached on rock surfaces in the summer on the Burrup Peninsula. This temperature will also increase the kinetics of the reactions. Exposure times were three days (considered optimum as the minimum amount of time to conduct intensive analyses on the rocks after a large release from an industrial plant) and one month (considered optimum as a follow up large analytical study).

Table 2 Solutions used to simulate pollutants potentially occurring on the Burrup Peninsula

Solution	Concentration	pH
Distilled water (control)		7
Nitric acid (HNO_3)	0.00001 M	4.4
	0.0001 M	3.6
	0.001 M	2.8
	0.0087 M	2.0
Sulphuric acid (H_2SO_4)	0.00001 M	4.3
	0.0001 M	3.4
	0.001 M	2.6
	0.0111 M	1.9
Ammonium nitrate (NH_4NO_3)	0.001 M	4.8
	1 M	5.3
Ammonia (NH_3)	0.001 M	9.2
	1 M	11.5

(Source: CSIRO 2017b)

Test solutions were analysed for chemical composition (iron, manganese, aluminium, silicon, sodium and potassium) using simultaneous ICP-AES after three days and, for

a subset, after one month of exposure of the rock samples (CSIRO 2017b). The pH of the test solutions was recorded after three days and, for a subset, after one month of exposure. For a subset of samples, pH was also recorded initially (i.e. before introducing the rock sample into the solution), after four hours or after one and two days exposure.

Subsets of 26 rock samples (one for each test solution for gabbro and granophyre) were characterised before and after exposure to the test solutions using optical microscopy, scanning electron microscopy with Energy Dispersive X-ray Spectroscopy, spectrophotometry and reflectance spectroscopy (CSIRO 2017b).

For further information on sample preparation and analysis refer to CSIRO (2017b).

Key study findings

The key findings from the study included (CSIRO 2017b):

- for the majority of gabbro, after three days at 50°C, dissolution started at pH 3 or below for aluminium, manganese and iron; and at greater than (>) pH 11 for aluminium. For the majority of granophyre, dissolution started at pH 3.2 or below for aluminium, manganese and iron, and at > pH 11 for aluminium. The initial pH at three days was the critical pH and represented the pH from which dissolution started to occur
- for gabbro, iron did not dissolve in the highest concentration of nitric acid (0.0087 M) after either three days or one-month exposure, confirming the results from the previous study (CSIRO 2007a). For granophyre, some iron occurred in the highest concentration of nitric acid. Manganese and occasionally aluminium were in solution in 0.001 M nitric acid after one month
- iron was in solution in 0.011 M sulphuric acid. Manganese and aluminium were also dissolved. No dissolution of iron occurred in ammonia solutions. These results also confirmed those from the previous study (CSIRO 2007a)
- with the exception of one sample, the concentration of iron, manganese and aluminium in all the test solutions with fresh gabbro and granophyre was zero after three days exposure
- quantifying changes in rock samples before and after exposure was challenging as the variations in the methods used were often larger than the changes themselves. The colour measurements derived from the Konica Minolta CM-700d spectrophotometer and the ASD spectrometer did not provide good discrimination between the samples before and after exposure.

CSIRO (2017b) noted that Gillett et al. (2012) measured pH values between 4.3 and 7.5 in rainwater samples collected at Burrup Road, Water Tanks, Deep Gorge and King Bay South, which were slightly higher than the pH that resulted in the dissolution of Burrup Peninsula rocks in the experimental extreme weathering study. However, these values were recorded in 2004 and 2005 and may not be representative of current acidity levels (CSIRO 2017b).

CSIRO (2017b) also noted that Black et al. (2017b) measured pH (> 4) of water washings from rocks in 2003 and 2004 and compared this with the pH (6.8) of weathered rocks collected before industrialisation and kept in the Western Australian Museum. CSIRO (2017b) noted that as these rocks were not subject to natural conditions, it was difficult to ensure that the pH of 6.8 was representative of outdoor settings. CSIRO (2017b) considered that, based on the results from the experimental extreme weathering study, the theoretical pH of > 4 calculated by Black et al. (2017b) was not low enough to weather the rocks on the Burrup Peninsula. CSIRO (2017b) concluded that emissions capable of producing pH less than (<) 5.5 (the pH of rainwater) should be considered potentially harmful.

CSIRO (2017b) recommended that there should be a review and upscaling of the monitoring program implemented since 2004 and that regular measurements of the pH of the weathered surfaces of gabbro and granophyre should be undertaken as part of a larger monitoring program with additional sites and new control sites. CSIRO (2017b) also recommended that rainwater gauges should be installed at monitoring stations to measure rainfall volume, pH, concentration of cations and anions, as well as the wet and dry deposition flux of nitrogen and sulphur.

Limitations

Black et al. (2017c) identified several concerns with respect to the extreme weathering experiment, including:

- the experimental design (e.g. the scientific justification for the duration of exposure to test solutions; inadequate sample replication; allocation of samples to treatments; lack of measurement replication)
- the methods used (e.g. method of selection of rock samples; lack of information with respect to experimental procedures and conditions; use of silicon coating[3] to protect the rock surface; volume of test solution used; detection limit of the ICP-AES instrument; parameters measured; characterisation and processing techniques employed)
- inadequate presentation of the results and the limited statistical analysis of the data
- interpretation of the results and the selectivity of the measurements on which the report conclusions were based.

Black (2017b) and Black et al. (2017c) noted that a large amount of information had been collected in the study which had not been fully presented, analysed or discussed (and was often dismissed) in the report and that the results from these measurements would provide additional evidence of the effects of the tested pollutants on the rock surfaces and the likely impact on the petroglyphs. Black et al. (2017c) made several suggestions for additional work, including undertaking a

[3] CSIRO (2017d) advised there was an error in the draft report and it should be silicone, not silicon.

comprehensive statistical analysis of all the data collected in the study to determine the extent of change for each characteristic of the rocks measured and the pH at which these changes occurred.

In response to the review by Black et al. (2017c), CSIRO (2017d) advised this was a preliminary study using novel sample preparation methods to provide a new approach to determining the effects of solutions of different composition and concentrations on rock weathering. CSIRO (2017d) advised the study was not intended to serve as an exhaustive or definitive analysis of the impacts of the chosen solutions on granophyre and gabbro rocks, nor was it intended as an indication for permissible pollution levels. CSIRO (2017d) also advised the statistical analyses undertaken were appropriate for comparing before and after exposure data, were sufficient for this study and that a more comprehensive statistical analysis was beyond the scope of the study. CSIRO (2017d) acknowledged that measurements of more samples would be beneficial for furthering understanding of extreme weathering, but noted the number of samples and measurements undertaken was a balance with the available resources (including time) and budget.

Black (2017b) and Black et al. (2017c) considered that the conclusions from the study, with respect to the pH at which dissolution of rock surfaces commences, were not justified or supported by the data presented in the report and were a misrepresentation of the results from the statistical analysis. Black et al. (2017c) recommended the mineral dissolution measurements should be corroborated by fitting ‘threshold’ or ‘breakpoint’ statistical models to estimate the pH when dissolution of each ion occurs and the standard error or confidence limits of the estimates. CSIRO (2017d) considered this could be a valid option if the number of samples analysed was increased.

Data availability

The following data are provided in CSIRO (2017b):

- Chemical composition (mg/L) and pH of test solutions with fresh gabbro and granophyre after three days of exposure (Table 8).
- Chemical composition (mg/L) and pH of test solutions with weathered gabbro after three days and one month of exposure at 50°C (Table 9).
- Chemical composition (mg/L) and pH of test solutions with weathered granophyre after three days and one month of exposure at 50°C (Table 10).
- Comparison of the qualitative chemical composition of the rock surface (results from the scanning electron microscopy with energy dispersive X-ray spectroscopy [SEM/EDXS]) before and after exposure of gabbro to dissolved water (no dissolution observed in the solution) (Table 15).
- Comparison of the qualitative chemical composition of the rock surface (results from SEM/EDXS) before and after exposure of gabbro to 0.011 M sulphuric acid (dissolution observed in the solution) (Table 16).

2.5 Microbial activity

Study objectives

A four-year (2004–08) study was undertaken to assess the microbiology of rock surfaces, monitor any microbiological differences at sites in low and high emissions-risk areas, and characterise the gross number and diversity of micro-organisms on rock surfaces (O'Hara 2008; SKM 2009a).

Sampling sites

Sampling was undertaken at seven sites, five sites close to industrial emission sources (Woodside East, Burrup Road, Water Tanks, Deep Gorge and King Bay) and two sites distant from industrial emission sources on the northern Burrup (Dolphin Island and Gidley Island) (O'Hara 2008; SKM 2009a). The seven sites were at the same sites as the rock art monitoring (Section 3.2).

Samples were not collected directly from the rock art, but from rock surfaces adjacent to and in the vicinity (within 50 m) of the rock art being monitored in other studies (O'Hara 2008). In 2005, 2007 and 2008, rock samples were collected from shaded and exposed sites.

Timing of sampling

Samples were collected in July 2004, September 2005, August 2007 and August 2008 (O'Hara 2008).

Surveys of the abundance and diversity of lichens were undertaken in 2005, 2007 and 2008 (O'Hara 2008).

Approaches to the study

Three approaches were employed to study the microbial diversity on the rock surfaces (O'Hara 2006, 2008):

- Isolation and culture techniques to provide data on the microbial populations of major groups of chemolithoautotrophic, chemoorganoheterotrophic, photolithoautotrophic and photoorganoheterotrophic microflora.

  This approach enabled practical characterisation of microbial diversity, providing a general perspective of the dominant cultivable microflora at each site, but did not necessarily provide data on in situ microbial community structure because of the selective culturing conditions that may only isolate 1–5 per cent of organisms (O'Hara 2008).

- Molecular techniques (e.g. polymerase chain reaction (PCR) methods and 16S ribosomal deoxyribonucleic acid (rDNA) sequence analysis) to study the bacterial communities associated with the rock surfaces. The aim was to provide data for a molecular phylogenetic assessment of microbial diversity on the rock surfaces.

Several methods of direct extraction of deoxyribonucleic acid (DNA) from rock surfaces were tested without success in obtaining consistent levels of un-degraded DNA suitable for molecular analysis of community structure (O'Hara 2008). This was in part attributed to the low levels of microbial abundance, the high metal content of samples and the inherent challenges of extracting DNA from rock surfaces. O'Hara (2008) noted that in a more comprehensive study it would be possible to characterise the bacterial community structure using molecular approaches such as automated ribosomal intergenic spacer analysis.

- Electron microscopy to study the microbial abundance and diversity on rock surfaces.

Methodology

Two principal sampling strategies were used (O'Hara 2006, 2008):

- Microscopic rock samples were collected aseptically for direct assessment, viable counting and enrichment cultures.
- Samples for isolation of microbes were collected using sterile swabs, sterile filter paper discs and contact plates.

Sampled areas were photographed and described for relocation in subsequent field sampling.

Populations of major groups were enumerated using direct counts and Most Probably Number (MPN) viable counting techniques (O'Hara 2008).

Complex media (e.g. nutrient, tryptone soy and Pseudomonas isolation medium) and basal minimal media, with supplements (e.g. yeast extract, iron sulphate and tetrathionate) were used for isolation and enumeration of bacteria (O'Hara 2006). The media were selected with a view to examining the presence and diversity of a range of microbial groups at each site (O'Hara 2008). Isolates were characterised using isolation medium, microscopy, Gram staining, cultural morphology and biochemical tests.

Samples for scanning electron microscopy were air dried and sputter-coated with gold (O'Hara 2008).

For further information on the methodologies refer to O'Hara (2008).

Key study findings

Key findings from the study included (O'Hara 2006, 2008; SKM 2009a):

- all the sites had rock surfaces with similar very low populations of cultivable chemoorganotrophic and chemolithotrophic bacteria, usually < 10 viable bacteria per square centimetre (bacteria/cm^2). In addition, all sites had similar low numbers and broad types of diverse bacteria (Gram-positive bacteria, Gram-negative bacteria, spore-formers, actinomycetes, iron oxidisers, sulphate oxidisers) and low numbers of fungi

- lichens were never observed to have colonised the rock art. Lichens were observed to be relatively diverse and abundant near the site on Dolphin Island but were relatively rare at the other sites
- there were no differences evident in the gross number and broad diversity of micro-organisms associated with rock surfaces and samples collected from sites close to and distant from industrial emission sources. There appeared to be no relationship between the presence of lichens and site proximity to sources of industrial emissions.

O'Hara (2008) noted that low population numbers of bacteria and inherent variability were common features in this study and that the structure and composition of microbial communities on the rock surfaces may be influenced by mineral type and to a lesser extent sampling location. Environmental constraints (e.g. absence of water, extremes of temperature and lack of organic carbon) were likely to be the primary cause of the low numbers of bacteria recorded.

Data availability

Representative data on the number of samples (n = 50 at each site) showing no growth of bacteria and growth of bacteria; the number of samples containing Gram-positive, Gram-negative bacteria and chemolithotrophic bacteria; and the Most Probable Number estimates at each site are provided for July 2004 (Table 1), September 2005 (Table 2) and August 2007 (Table 3) (O'Hara 2008). Information on the broad types of bacteria isolated from rock samples collected in September 2005, August 2007 and August 2008 is provided in Table 4 (O'Hara 2008).

3 Summary of monitoring programs

3.1 Air quality (pollution) monitoring

Study objectives

To study objectives were to measure:

- concentrations of nitrogen dioxide, sulphur dioxide, nitric acid, ammonia and benzene, toluene, ethylbenzene and xylene isomers (BTEX) gases
- concentrations of total suspended particulates (TSP) and airborne particulate matter 10 µm or less in diameter (PM_{10}) and chemical composition
- temperature and humidity
- rainwater amount and composition (pH and soluble ions)
- dust deposition rates (CSIRO 2006a, 2007b, 2008a, 2010a; SKM 2009a).

Total acid deposition rates were estimated by calculating wet and dry deposition of nitrogen and sulphur in the gas and aqueous phases (CSIRO 2006a, 2007b, 2008a, 2010a; SKM 2009a).

Sampling sites

Sampling was undertaken at 10 sites (CSIRO 2006a, 2007b, 2008a, 2010a), consisting of:

- two local background sites distant from industrial development and anthropogenic influences (Dolphin Island and North Burrup)
- six sites on the lower Burrup Peninsula in the vicinity of industrial development (Woodside East, Burrup Road, Water Tanks, Deep Gorge, King Bay South, Hamersley Iron)
- one site in Karratha to provide a comparison of concentrations of air pollutants in an adjacent urban area
- one site at Mardie Station, about 80 km south-west of Dampier, to provide a comparison of concentrations of air pollutants in an area where there was no industrial activity. Note that sampling was not undertaken at Mardie Station in 2008/09.

Site selection was undertaken in conjunction with representatives from the Department of Industry and Resources and the Department of Conservation and Land Management, and several Aboriginal elders (CSIRO 2006a, 2008a, 2010a).

Timing of sampling

Monitoring was undertaken between August 2004 and September 2005 (2004/05), February 2007 and September 2008 (2007/08), and August 2008 and August 2009 (2008/09) (CSIRO 2006a, 2007b, 2008a, 2010a).

Methodology

Passive gas sampling

Concentrations of nitrogen dioxide, sulphur dioxide, nitric acid and ammonia were measured in duplicate with passive sampling devices (diffusion tubes) at Dolphin Island, North Burrup, Woodside East, Burrup Road, Water Tanks, Deep Gorge, King Bay South, Karratha and Mardie Station over sampling periods of about one month (CSIRO 2008a, 2010a; SKM 2009a). At each site an aluminium holder, mounted on a pole 1.5 m from the ground and fitted with a radiation shield, was used to house the samplers (Figure 3).

Figure 3 Passive samplers under lid with aluminium radiation screen (Source: CSIRO 2010a)

Blank samplers were used to determine errors associated with sampler preparation, contamination during sample transport and from reagents during analysis (CSIRO 2008a, 2010a). Blank samplers were also used to determine the limit of detection for gases measured by the passive samplers.

BTEX gas concentrations were measured at the same sites using sorbent tubes over sampling periods of 30 days (CSIRO 2008a, 2010a).

Refer to CSIRO (2008a, 2010a) for further information on the methods and analytical procedures.

Particulate sampling

Sampling for total suspended particulates (TSP) was undertaken at all sites with the exception of Karratha, Hamersley Iron and Mardie Station (CSIRO 2008a, 2010a). TSP samples were collected on 47 mm diameter Fluoropore polytetrafluoroethylene (PTFE) membrane filters using Mircovol 1100 low-volume samplers (Figure 4). These sampled at low flow rates and collected integrated particulate samples that were

used to determine gravimetric mass and particulate chemical composition. The sampling period was about 30 days, the same as for gas sampling.

Figure 4 Microvol sampler and rainwater sampler at Dolphin Island (Source: CSIRO 2010a)

At the King Bay South and Hamersley Iron sites, airborne fine particle (PM_{10}) concentrations were measured under particular preset wind directions[4] chosen to assess the PM_{10} concentrations resulting from the iron ore loading facilities at Parker Point (CSIRO 2008a, 2010a). PM_{10} samples were collected on 47 mm stretched Teflon filters using Microvol 1100 samplers fitted with a PM_{10} inlet. The sampling period was about 30 days.

The gravimetric mass of the filters was measured before and after sampling to determine the monthly averaged PM_{10} or TSP concentration for each sampling period (CSIRO 2008a, 2010a).

The particulate samples were analysed for 19 elements by particle-induced X-ray emission (PIXE) analysis to determine particulate composition and sources of particulates (CSIRO 2008a, 2010a). The PIXE analysis was carried out after the gravimetric measurements were completed and before the samples were analysed by ion chromatography. The pH of the particle extracts was also measured.

A modified DustTrak aerosol monitor (TSI model 8250) was installed at the King Bay South site to measure PM_{10} concentrations at sampling frequencies of two minutes (CSIRO 2008a, 2010a).

Refer to CSIRO (2008a, 2010a) for further information on the methods and analytical procedures.

[4] At the King Bay South site the conditional sampler operated when the wind direction was between 180° and 360°; at the Hamersley Iron site the sampler operated when the wind direction was between 225° and 315° (CSIRO 2008a, 2010a).

Rainwater sampling

Model 200 rainwater samplers were installed at all sites with the exception of Karratha, Hamersley Iron and Mardie Station, to collect rainwater during the wet season (Figure 4; CSIRO 2008a, 2010a). There were issues with the rainwater samplers at two sites during 2004/05 and one site during 2007/08, resulting in incomplete data sets for these sites. Complete data sets were gathered during 2008/09.

The wet-only samplers opened after 0.25 mm of rain had fallen in the tipping rain gauge and closed again once no rain had fallen for a 30-minute period (CSIRO 2008a, 2010a). Samples were collected in polyethylene bottles with thymol added to preserve the chemical species in the rain against degradation by bacteria. Bulk wet-only rainwater samples were collected over a sampling period of 30 days.

The total rainwater volume of each sample was measured (CSIRO 2008a, 2010a). The pH of the rainwater samples was measured and the samples were analysed for a range of soluble anions and cations by ion chromatography.

Refer to CSIRO (2008a, 2010a) for further information on the methods and analytical procedures.

Meteorological measurements

An automatic weather station was installed at the King Bay South site to measure wind speed and wind direction at two-minute frequencies (CSIRO 2008a, 2010a). These data were used with the DustTrak PM_{10} data to provide information on how the iron ore loading facilities at Parker Point influenced PM_{10} concentrations at King Bay South.

Temperature and relative humidity were measured at Dolphin Island, North Burrup, Woodside East, Burrup Road, Water Tanks, Deep Gorge and King Bay South using Hobo Pro sensors at three-minute intervals (CSIRO 2008a, 2010a).

Dust measurements

Dust deposition was measured at Dolphin Island, Woodside East, Burrup Road, Water Tanks, Deep Gorge and King Bay South using a passive dry Frisbee-type dust deposit gauge mounted on a pole about 1.5 m above the ground (CSIRO 2008a, 2010a). Measurements were made over three-month periods. Note the results were found to be inconsistent at all sites and were not included in the final report (CSIRO 2010a).

On one field visit in September 2005, a GRIMM Series 1.100 Aerosol Spectrometer was used to continuously measure particle mass-size distribution in several preset size ranges at the Dolphin Island, North Burrup, Woodside East, Burrup Road, Water Tanks, Deep Gorge and King Bay South sites (CSIRO 2008a, 2010a). Fifteen size ranges were used from 0.3–20 µm. Size distributions were converted to mass concentrations and deposition flux to estimate the magnitude of dust deposition at each site.

Refer to CSIRO (2008a, 2010a) for further information on the methods and analytical procedures.

Key study findings

The key findings from the study included (CSIRO 2010a):

Nitrogen dioxide, nitric acid, sulphur dioxide and ammonia

- Concentrations of nitrogen dioxide and nitric acid were slightly elevated at sites close to industry compared with local background concentrations. Average concentrations over the three sampling periods at the sites close to industry, were 2.1 ppb ± 0.1 ppb nitrogen dioxide and 232 parts per thousand (ppt) ± 19 ppt nitric acid. Local background concentrations, calculated from Dolphin Island, North Burrup and Mardie Station over the three sampling periods, were 0.7 ppb ± 0.1 ppb nitrogen dioxide and 172 ppt ± 26 ppt nitric acid.
- The average local background sulphur dioxide concentration over the three sampling periods was 124 ppt ± 12 ppt, compared with 183 ppt ± 19 ppt measured in the industrial area over the same period. The difference between the background sulphur dioxide concentrations and those in the industrial area was statistically significant.
- Annual and monthly average concentrations of nitrogen dioxide, nitric acid and sulphur dioxide varied little at each site between the three sampling periods.
- Ammonia concentrations showed little spatial variation, which indicated that most ambient ammonia had a natural source. The average ammonia concentration over the three sampling periods at sites close to industry was 0.7 ppb ± 0.1 ppb and the local background concentration was 0.6 ppb ± 0.4 ppb. During 2008/09, concentrations were higher than in the previous two sampling periods, although the change was not statistically significant. The highest annual average concentration of 1.2 ppb was recorded at Water Tanks in 2008/09. In June 2009, there was an increase in ammonia concentrations to about 3–8 ppb at all sites. The reason for this increase was unclear.
- Concentrations of ammonia, nitrogen dioxide, sulphur dioxide and nitric acid were very low compared with other remote locations and urban areas.

BTEX

- BTEX concentrations were very low at all sites and for all sampling periods. Benzene and other BTEX gas concentrations showed little indication of elevated concentrations over the background levels. This suggested the concentrations had a large natural component, probably because of emissions from plants. The average concentration of benzene at the background sites was 17 ppt ± 4 ppt and the average at the sites close to industry was 21 ppt ± 1 ppt.

Particulates

- TSP mass concentrations were higher at sites in proximity to industry and anthropogenic activities (annual average concentrations of about 34 micrograms per cubic metre (µg/m^3) in 2004/05 and 32 µg/m^3 in 2007/08 and 2008/09) compared with local background concentrations (annual average of about 22 µg/m^3 in 2004/05 and 18 µg/m^3 in 2007/08 and 2008/09).
- Annual average TSP concentrations ranged from 15.4 µg/m^3 at Dolphin Island in 2007/08 to 51.1 µg/m^3 at King Bay South in 2004/05.
- TSP at Woodside East, Burrup Road, Deep Gorge and King Bay South had a higher fraction of iron and less sea salt than at Dolphin Island. The average iron to salt ratio at Dolphin Island, the site least influenced by iron ore loading and most influenced by sea salt, was 0.10. At King Bay South, close to Parker Point, the iron fraction of the TSP was the highest compared with other sites and the sea salt fraction the lowest. The average iron to salt ratio over the three sampling periods was 1.61, indicating that TSP originating from iron ore loading was a significant fraction of the total TSP.

Dust deposition

- Average dust deposition measured with the GRIMM Aerosol Spectrometer in September 2005, was about 10 milligrams per square metre per day (mg/m^2/day) at Dolphin Island and North Burrup. Average dust deposition was about 68 mg/m^2/day at King Bay South and about 32 mg/m^2/day at sites close to industry. The results indicated that over the short sample period, sites close to industry experienced higher dust deposition than the background sites, in particular at King Bay South, which was closest to the iron ore loading facilities. The absolute values of dust deposition were quite low at all the sites.

Deposition of nitrogen and sulphur

- For areas of the Burrup Peninsula with little or no anthropogenic influence, the total wet and dry deposition flux of nitrogen and sulphur averaged 18 milliequivalents per square metre per year (meq/m^2/year) ± 5 meq/m^2/year with 44–84 per cent of the deposition contributed by dry deposition. The total nitrogen and sulphur flux was composed of about 88 per cent nitrogen and about 54 per cent of the total flux was wet and dry deposition of ammonia.
- At sites close to industrial influences, the deposition fluxes of nitrogen and sulphur ranged between 20–24 meq/m^2/year in 2004/05, 21–32 meq/m^2/year in 2007/08 and 19–37 meq/m^2/year in 2008/09. The increase in flux from 2004/05 to 2007/08 and 2008/09 was attributed to an increase in the amount of rainfall in the latter periods. This was a major variable in the flux of nitrogen and sulphur to the ground on the Burrup Peninsula.
- Given the overall precision of passive gas samplers measurements was about ±20 per cent, the average deposition flux of nitrogen and sulphur for all sites close to industry and over the three sampling periods was about 26

meq/m^2/year ± 5 meq/m^2/year, which is about the critical load for the most sensitive ecosystems. The annual nitrogen and sulphur deposition fluxes at sites close to industry varied between 19.3 meq/m^2/year at Deep Gorge in 2008/09 and 37.2 meq/m^2/year at Burrup Road in 2008/09. Given an uncertainty of 20 per cent, the highest deposition flux of nitrogen and sulphur would be about 45 meq/m^2/year.

- The deposition fluxes at each site were very low and lower than the critical load for even the most sensitive areas to nitrogen and sulphur deposition. The observed deposition fluxes were not of the magnitude that would be expected to cause deterioration of the rock on the Burrup Peninsula.

CSIRO (2010a) and Gillett et al. (2012) used the critical load concept to compare the buffering capacity of an ecosystem and its ability to tolerate an observed deposition flux, to determine if adverse effects could result to rock or rock art. In a global assessment of ecosystem sensitivity to acidic deposition, Cinderby et al. (1998, cited in CSIRO 2010a and Gillett et al. 2012) determined that areas having a critical load of 25 meq/m^2/year are the most sensitive to damage by acidic deposition and areas having critical loads of > 200 meq/m^2/year are the least sensitive. CSIRO (2010a) and Gillett et al. (2012) concluded that the critical acid load for the Burrup Peninsula was > 200 meq/m^2/year, placing it in the least sensitive class, and that since the observed deposition fluxes were much less than the critical load of at least 200 meq/m^2/year, they were unlikely to cause any deleterious effects to the rock or rock art on the Burrup Peninsula.

Summary of Results (Burrup Rock Art Monitoring Management Committee 2009)

- Concentrations of air pollutants were generally very low, with the exception of airborne particle (dust) concentrations, which were highest close to iron ore ship-loading facilities.
- Concentrations of air pollutants at the background sites in the far north of the Burrup Peninsula were slightly lower than at sites close to industry.
- At all locations, deposition rates were extremely low, close to the limits of detection.
- The chemical composition of dust collected from surfaces at rock art sites on the southern end of the Burrup Peninsula, close to industrial activity, was generally consistent with iron ore dust. Dust collected from rock art surfaces at the northern sites, far from industrial activity, was consistent with that of local soil-derived dust and sea salt.
- The acidity of the rainfall was naturally variable and generally similar to other remote areas, with small increases in levels of nitrogen and sulphur-containing compounds at sites close to industry.

Limitations

Bednarik (2007a, b) identified several concerns with the air quality monitoring, including:

- noting that gaseous air emissions such as nitrogen dioxide can travel large distances, the location of the 'control site' at Mardie Station so close to the source of emissions and within the zone affected by the Dampier fallout, was inappropriate. A minimum distance of 200 or 300 km would be advisable, although even that would not provide true control data. Similarly, the local background sites were only 7 km and 14 km from the principal pollution source, and would not provide good background data
- the passive sampling method provides only a rough guide of average level over exposure period and was unable to show maximum levels or daily variations. The selection of the less costly passive sampling methods over active and automatic sampling methods was at the expense of precision and reliability, and more sophisticated studies of the effects of industrial emissions on rock art have been conducted in other countries
- the argument raised in the report that the air quality at Dampier was better than in many polluted cities in South-East Asia or Perth was irrelevant given the purpose of the study was to establish the processes effecting the deterioration of the surface patina which would never survive or even form in the first place in such localities, not to determine the effects of pollution on the human population
- the monitoring data indicate the modelling predictions (Section 2.1) understated the level of air pollution.

With respect to the use of passive gas samplers, CSIRO (2008a, 2010a) noted these samplers have several features that make them the most suitable method for this study, including that the samplers were light and easy to install, require no power to sample and can therefore be deployed at a larger number of sites and be used to measure concentrations of several gases for periods of about one month. SKM (2009b) noted the uncertainty associated with passive sampling was significantly higher (between 20 per cent and 50 per cent) than direct gas measurements (online measurement systems have an uncertainty ranging between 1 per cent and 10 per cent). Continuous gas analysers can also provide measurements over much shorter averaging periods, down to five or 10 minutes, but at the cost of providing mains power supply and air-conditioned enclosures.

Hallam (2009) criticised the selection of local background locations on Dolphin Island and the north coast of Burrup Peninsula which modelling indicated were under threat from emissions. Hallam (2009) also questioned the justification for the conclusions from the study that compared pollutant concentrations at sites in the industrial area with these local background sites and suggested that Cape Grim in southern Tasmania could provide an internationally recognised standard. Comparing reported concentrations of nitrogen dioxide and sulphur dioxide against the concentrations at

recorded at Cape Grim, Hallam (2009) considered that CSIRO (2008a) was unjustified in concluding there were only small increases in concentrations of these pollutants at sites near industry.

Hallam (2009) considered that comparisons with urban and ecosystem studies were irrelevant; and that there had been no attempt to integrate the available data into a meaningful assessment of acidic pollutants on rock surfaces.

Hallam (2009) noted that while pH data for rainfall were presented, there was no discussion of the significance of the pH results. Hallam (2009) also noted that the figures showed "…very acid rain falls over Burrup, and the rest of the archipelago…" and that "...in the rain throughout Burrup hydrogen ions are 100 to 1000 times as concentrated as in neutral rain". Bednarik (2007a, b) considered that the study provided independent confirmation that acidic precipitation now occurred for most of the year on the Burrup Peninsula, but failed to investigate the effects on the rock art or the rock patina.

There has been criticism of the application of the Cinderby et al. (1998) global sensitivity map and critical loads with respect to the sensitivity of the rock art on the Burrup Peninsula to increased acidic deposition and that, therefore, the conclusion about the critical acid load for the rock art was incorrect (Hallam 2009; Black 2017a, c; Black et al. 2017a). In his submission to the Senate Inquiry into the Protection of Aboriginal rock art of the Burrup Peninsula, Dr Kuylenstierna, one of the co-authors of the Cinderby et al. (1998) report, noted that the assertion was incorrect because:

1. the basis for the critical load assessment was soil type only and did consider the characteristics of the rocks in the analysis, and therefore cannot be used to conclude anything about the rocks where the rock art is carved
2. the sensitivity referred to in the maps is the sensitivity of ecosystems (i.e. the vegetation or surface waters) not the sensitivity of the rocks to weathering
3. soil maps, not geology maps, were used in the assessment and the scale of the global soil maps used was 1:5,000,000 which show broad patterns but not local detail
4. weathering processes are complex and specific to rock types and to understand how the surface of rocks on which the rock art is carved will be affected by acidic inputs would require the development of a specific understanding of the weathering processes of the surface of these rocks.

Dr Kuylenstierna concluded that it was incorrect to use the Cinderby et al. (1998) global sensitivity map and critical loads to inform conclusions and justify decisions in regard to the rock art on the Burrup Peninsula. Dr Kuylenstierna suggested that an analysis of the rock art and its sensitivity to acidic inputs was required.

In response to the concerns that were raised through submissions to the Senate Inquiry, CSIRO (2017c) advised that as part of the air quality monitoring, the total deposition of sulphur and nitrogen from the atmosphere was assessed by measuring sulphur and nitrogen compounds in samples of gases, particles and rainwater at several locations. CSIRO (2017c) also advised that measurements of the acid load of

the rock and studies on buffering capacity were not undertaken as these were outside the contracted scope of work.

CSIRO (2017b) advised that, as with any scientific study, when information was produced it was important that the data, and the use of the data, be put into a context the end user can understand. This was done in two ways, by:

1. comparing the data from the Burrup Peninsula to other locations with similar measurements, including sites in the Northern Territory and Malaysia
2. using the critical load framework and the level of 200 meq to provide context for the air monitoring data and which was considered to be the best comparison to use at the time. CSIRO stated that 200 meq cannot be used as impact assessment criteria and this was never the intention of the comparison. CSIRO noted the report was peer-reviewed by an independent international reviewer.

There have been concerns expressed that the air quality monitoring did not continue to include periods of increased industrial and shipping activity on the Burrup Peninsula (Black and Diffey 2016a; Black 2017a, c; Black et al. 2017a; Mulvaney 2017a).

Data availability

The following data are provided in CSIRO (2010a):

- Concentrations of TSP (µg/m^3) at Dolphin Island, North Burrup, Woodside East, Burrup Road, Water Tanks, Deep Gorge and King Bay South, and PM_{10} conditionally sampled at King Bay South and Hamersley Iron during the 2004/05 sampling period (Table 8a).
- Concentrations of TSP (µg/m^3) at Dolphin Island, North Burrup, Woodside East, Burrup Road, Water Tanks, Deep Gorge and King Bay South, and PM_{10} conditionally sampled at King Bay South and Hamersley Iron during the 2007/08 sampling period (Table 8b).
- Concentrations of TSP (µg/m^3) at Dolphin Island, North Burrup, Woodside East, Burrup Road, Water Tanks, Deep Gorge and King Bay South, and PM_{10} conditionally sampled at King Bay South and Hamersley Iron during the 2008/09 sampling period (Table 8c).
- Rainfall amount, pH and concentrations of cations (µeq/L) in rainwater samples collected at North Burrup, Burrup Road, Water Tanks, Deep Gorge and King Bay South during the 2004/05 sampling period (Table 10a).
- Concentrations of anions (µeq/L) in rainwater samples collected at North Burrup, Burrup Road, Water Tanks, Deep Gorge and King Bay South during the 2004/05 sampling period (Table 10b).
- Rainfall volume, pH and concentrations of cations (µeq/L) in rainwater samples collected at Dolphin Island, North Burrup, Woodside East, Water

Tanks, Deep Gorge and King Bay South during the 2007/08 sampling period (Table 11a).

- Concentrations of anions (µeq/L) in rainwater samples collected at Dolphin Island, North Burrup, Woodside East, Water Tanks, Deep Gorge and King Bay South during the 2007/08 sampling period (Table 11b).
- Rainfall volume, pH and concentrations of cations (µeq/L) in rainwater samples collected at Dolphin Island, North Burrup, Woodside East, Burrup Road, Water Tanks, Deep Gorge and King Bay South during the 2008/09 sampling period (Table 12a).
- Concentrations of anions (µeq/L) in rainwater samples collected at Dolphin Island, North Burrup, Woodside East, Burrup Road, Water Tanks, Deep Gorge and King Bay South during the 2008/09 sampling period (Table 12b).
- Wet deposition fluxes (meq/m^2) of nitrogen and sulphur at North Burrup, Burrup Road, Water Tanks, Deep Gorge and King Bay South during the 2004/05 sampling period (Table 13a).
- Wet deposition fluxes (meq/m^2) of nitrogen and sulphur at Dolphin Island, North Burrup, Woodside East, Water Tanks, Deep Gorge and King Bay South during the 2007/08 sampling period (Table 13b).
- Wet deposition fluxes (meq/m^2) of nitrogen and sulphur at Dolphin Island, North Burrup, Woodside East, Burrup Road, Water Tanks, Deep Gorge and King Bay South during the 2008/09 sampling period (Table 13c).
- Concentrations of (ppb) ammonia and nitrogen dioxide at Dolphin Island, North Burrup, Woodside East, Burrup Road, Water Tanks, Deep Gorge, King Bay South, Karratha and Mardie Station during the 2004/05 sampling period (Table A1).
- Concentrations (ppb) of ammonia and nitrogen dioxide at Dolphin Island, North Burrup, Woodside East, Burrup Road, Water Tanks, Deep Gorge, King Bay South, Karratha and Mardie Station during the 2007/08 sampling period (Table A2).
- Concentrations (ppb) of ammonia and nitrogen dioxide at Dolphin Island, North Burrup, Woodside East, Burrup Road, Water Tanks, Deep Gorge, King Bay South and Karratha during the 2008/09 sampling period (Table A3).
- Concentrations (ppt) of sulphur dioxide and nitric acid at Dolphin Island, North Burrup, Woodside East, Burrup Road, Water Tanks, Deep Gorge, King Bay South, Karratha and Mardie Station during the 2004/05 sampling period (Table B1).
- Concentrations (ppt) of sulphur dioxide and nitric acid at Dolphin Island, North Burrup, Woodside East, Burrup Road, Water Tanks, Deep Gorge, King Bay South, Karratha and Mardie Station during the 2007/08 sampling period (Table B2).

- Concentrations (ppt) of sulphur dioxide and nitric acid at Dolphin Island, North Burrup, Woodside East, Burrup Road, Water Tanks, Deep Gorge, King Bay South and Karratha during the 2008/09 sampling period (Table B3).
- Concentrations (ppt) of benzene, toluene and ethyl benzene at Dolphin Island, North Burrup, Woodside East, Burrup Road, Water Tanks, Deep Gorge, King Bay South, Karratha and Mardie Station during the 2004/05 sampling period (Table C1).
- Concentrations (ppt) of benzene, toluene and ethyl benzene at Dolphin Island, North Burrup, Woodside East, Burrup Road, Water Tanks, Deep Gorge, King Bay South, Karratha and Mardie Station during the 2007/08 sampling period (Table C2).
- Concentrations (ppt) of benzene, toluene and ethyl benzene at Dolphin Island, North Burrup, Woodside East, Burrup Road, Water Tanks, Deep Gorge, King Bay South and Karratha during the 2008/09 sampling period (Table C3).
- Concentrations (ppt) of p-xylene, m-xylene and o-xylene at Dolphin Island, North Burrup, Woodside East, Burrup Road, Water Tanks, Deep Gorge, King Bay South, Karratha and Mardie Station during the 2004/05 sampling period (Table D1).
- Concentrations (ppt) of p-xylene, m-xylene and o-xylene at Dolphin Island, North Burrup, Woodside East, Burrup Road, Water Tanks, Deep Gorge, King Bay South, Karratha and Mardie Station during the 2007/08 sampling period (Table D2).
- Concentrations (ppt) of p-xylene, m-xylene and o-xylene at Dolphin Island, North Burrup, Woodside East, Burrup Road, Water Tanks, Deep Gorge, King Bay South and Karratha during the 2008/09 sampling period (Table D3).
- Elemental concentrations (µg/m^3; measured by PIXE analysis) in TSP/PM_{10} samples collected at Dolphin Island, Woodside East, Burrup Road, Deep Gorge and King Bay South and Hamersley Iron during the 2004/05 sampling period (Tables E1 and E2).
- Elemental concentrations (µg/m^3; measured by PIXE analysis) in TSP/PM_{10} samples collected at Dolphin Island, Woodside East, Burrup Road, Deep Gorge and King Bay South and Hamersley Iron, total elemental mass (µg/m^3), gravimetric mass (µg/m^3) and fraction (%) of iron in gravimetric mass during the 2004/05 sampling period (Table E3).
- Cation concentrations (µg/m^3) in TSP, pH, cation and anion sums (µeq/L) of TSP extracts in samples collected at Dolphin Island, Woodside East, Burrup Road, Deep Gorge, King Bay South and Hamersley Iron during the 2004/05 sampling period (Table E4).
- Anion concentrations (µg/m^3) in TSP samples collected at Dolphin Island, Woodside East, Burrup Road, Deep Gorge, King Bay South and Hamersley Iron during the 2004/05 sampling period (Table E5).

- Elemental concentrations (µg/m^3; measured by PIXE analysis) in TSP/PM_{10} samples collected at Dolphin Island, Water Tanks, Deep Gorge, King Bay South and Hamersley Iron during the 2007/08 sampling period (Tables F1 and F2).
- Elemental concentrations (µg/m^3; measured by PIXE analysis) in TSP/PM_{10} samples collected at Dolphin Island, Water Tanks, Deep Gorge, King Bay South and Hamersley Iron, total elemental mass (µg/m^3), gravimetric mass (µg/m^3) and fraction (%) of iron in gravimetric mass during the 2007/08 sampling period (Table F3).
- Cation concentrations (µg/m^3) in TSP, pH, cation and anion sums (µeq/L) of TSP extracts in samples collected at Dolphin Island, North Burrup, Woodside East, Burrup Road, Water Tanks, Deep Gorge, King Bay South and Hamersley Iron during the 2007/08 sampling period (Table F4).
- Anion concentrations (µg/m^3) in TSP samples collected at Dolphin Island, North Burrup, Woodside East, Burrup Road, Water Tanks, Deep Gorge, King Bay South and Hamersley Iron during the 2007/08 sampling period (Table F5).
- Elemental concentrations (µg/m^3; measured by PIXE analysis) in TSP/PM_{10} samples collected at Dolphin Island, Deep Gorge, King Bay South and Hamersley Iron during the 2008/09 sampling period (Tables G1 and G2).
- Elemental concentrations (µg/m^3; measured by PIXE analysis) in TSP/PM_{10} samples collected at Dolphin Island, Deep Gorge, King Bay South and Hamersley Iron, total elemental mass (µg/m^3), gravimetric mass (µg/m^3) and fraction (%) of iron in gravimetric mass during the 2008/09 sampling period (Table G3).
- Cation concentrations (µg/m^3) in TSP, pH, cation and anion sums (µeq/L) of TSP extracts in samples collected at Dolphin Island, North Burrup, Woodside East, Burrup Road, Water Tanks, Deep Gorge, King Bay South and Hamersley Iron during the 2008/09 sampling period (Table G4).
- Anion concentrations (µg/m^3) in TSP samples collected at Dolphin Island, North Burrup, Woodside East, Burrup Road, Water Tanks, Deep Gorge, King Bay South and Hamersley Iron during the 2008/09 sampling period (Table G5).
- Concentrations of gravimetric mass (µg/m^3), estimated chemical mass (ECM; µg/m^3) and iron (µg/m^3), fraction of ECM to gravimetric mass (%) and the fraction (%) of iron and sea salt in TSP/PM_{10} samples collected at Dolphin Island, Woodside East, Burrup Road, Deep Gorge, King Bay South and Hamersley Iron during the 2004/05 sampling period (Table H1).
- Concentrations of gravimetric mass (µg/m^3), estimated chemical mass (ECM; µg/m^3) and iron (µg/m^3), fraction of ECM to gravimetric mass (%) and the fraction (%) of iron and sea salt in TSP/PM_{10} samples collected at Dolphin Island, Water Tanks, Deep Gorge, King Bay South and Hamersley Iron during the 2007/08 sampling period (Table H2).

- Concentrations of gravimetric mass (µg/m^3), estimated chemical mass (ECM; µg/m^3) and iron (µg/m^3), fraction of ECM to gravimetric mass (%) and the fraction (%) of iron and sea salt in TSP/PM_{10} samples collected at Dolphin Island, Deep Gorge, King Bay South and Hamersley Iron during the 2008/09 sampling period (Table H3).
- Average, maximum and minimum temperatures (°C) and relative humidity (%) measurements at Dolphin Island, North Burrup, Woodside East, Burrup Road, Water Tanks, Deep Gorge and King Bay South during the 2004/05, 2007/08 and 2008/09 sampling periods (Table I1).
- Dry deposition fluxes (meq/m^2) of nitrogen and sulphur at Dolphin Island, North Burrup, Woodside East, Burrup Road, Water Tanks, Deep Gorge, King Bay South, Karratha and Mardie Station during the 2004/05 sampling period (Table K1a).
- Dry deposition fluxes (meq/m^2) of nitrogen and sulphur at Dolphin Island, North Burrup, Woodside East, Burrup Road, Water Tanks, Deep Gorge, King Bay South, Karratha and Mardie Station during the 2007/08 sampling period (Table K1b).
- Dry deposition fluxes (meq/m^2) of nitrogen and sulphur at Dolphin Island, North Burrup, Woodside East, Burrup Road, Water Tanks, Deep Gorge, King Bay South and Karratha during the 2008/09 sampling period (Table K1c).

3.2 Monitoring of change in the colour and spectral mineralogy of the petroglyphs

Study objectives

The potential for colour change of the rock art as a result of environmental modification because of industrial emissions, causing the colour contrast between the rock art and the background rock to be reduced or lost at a faster rate than that associated with normal weathering, was a key issue of concern (CSIRO 2006b, 2007a; SKM 2009a). The purpose of this study was to establish whether evidence of changes in the colour and contrast of images was measurable.

The objectives of the colour change monitoring were to:

- monitor the colour of the rock art and the surrounding background rock surface to evaluate changes in the colour and assess whether the colour contrast between the rock art engraving and the background rock surface was decreasing over time
- assess if any colour change was occurring at a rate greater than that because of natural weathering
- establish a scientifically valid baseline for future assessments (CSIRO 2006b, 2007a; SKM 2009a).

Each of the sampling points evaluated for colour change were also characterised by spectral mineralogy to evaluate whether changes in mineralogy were observed on the rock art and background rock surfaces (CSIRO 2006b, 2007a; SKM 2009a).

The objectives of the spectral mineralogy monitoring were to:

- characterise and compare the mineralogy of the surface of the rock art and the surrounding background rock surface
- monitor any surface mineralogical changes in the rock art and background rock surface over time (CSIRO 2006b, 2007a; SKM 2009a).

Sampling sites

Colour change and spectral mineralogy monitoring were undertaken at seven sites (Figure 5) consisting of:

- two distant 'control' sites on the northern Burrup Peninsula distant from industrial emissions sources: Dolphin Island (12 km from industry) and Gidley Island (16 km from industry)
- five sites further south on the lower Burrup Peninsula and close to the sources of industrial emissions: Woodside, Burrup Road, Water Tanks, Deep Gorge and King Bay South (CSIRO 2006b, 2007a, 2008b, 2009, 2010b, 2011, 2012, 2013a, 2014a, 2015a, 2017a).

The monitoring site locations were determined by the Burrup Rock Art Monitoring Management Committee (CSIRO 2006b, 2007a, 2008b, 2009, 2010b, 2011, 2012, 2013a, 2014a, 2015a, 2017a). The selection of sites close to industry and control sites was based predominantly on predicted gas concentrations derived from modelling undertaken by SKM (Section 2.1) (CSIRO 2017a).

In 2014, three additional sites (Yara West, Yara North East and Yara East) were incorporated into the monitoring program to meet the conditions under *Environment Protection and Biodiversity Conservation Act 1999* approval EPBC 2008/4546 for Yara Pilbara's Technical Ammonium Nitrate Production Facility (TANPF) (CSIRO 2014b, 2015a, 2015b, 2017a). Sites were selected within a 2 km radius of the TANPF and considering the main wind directions during the year. Selected petroglyphs were evaluated on the basis of their appropriateness for scientific study, including size and quality, direction of exposure, elevation and dominant wind direction (CSIRO 2014b). Final selection was determined by the elders of the Murujuga Aboriginal Corporation (MAC). After initial monitoring in February 2014, the three new sites were integrated into the existing monitoring program in July 2014.

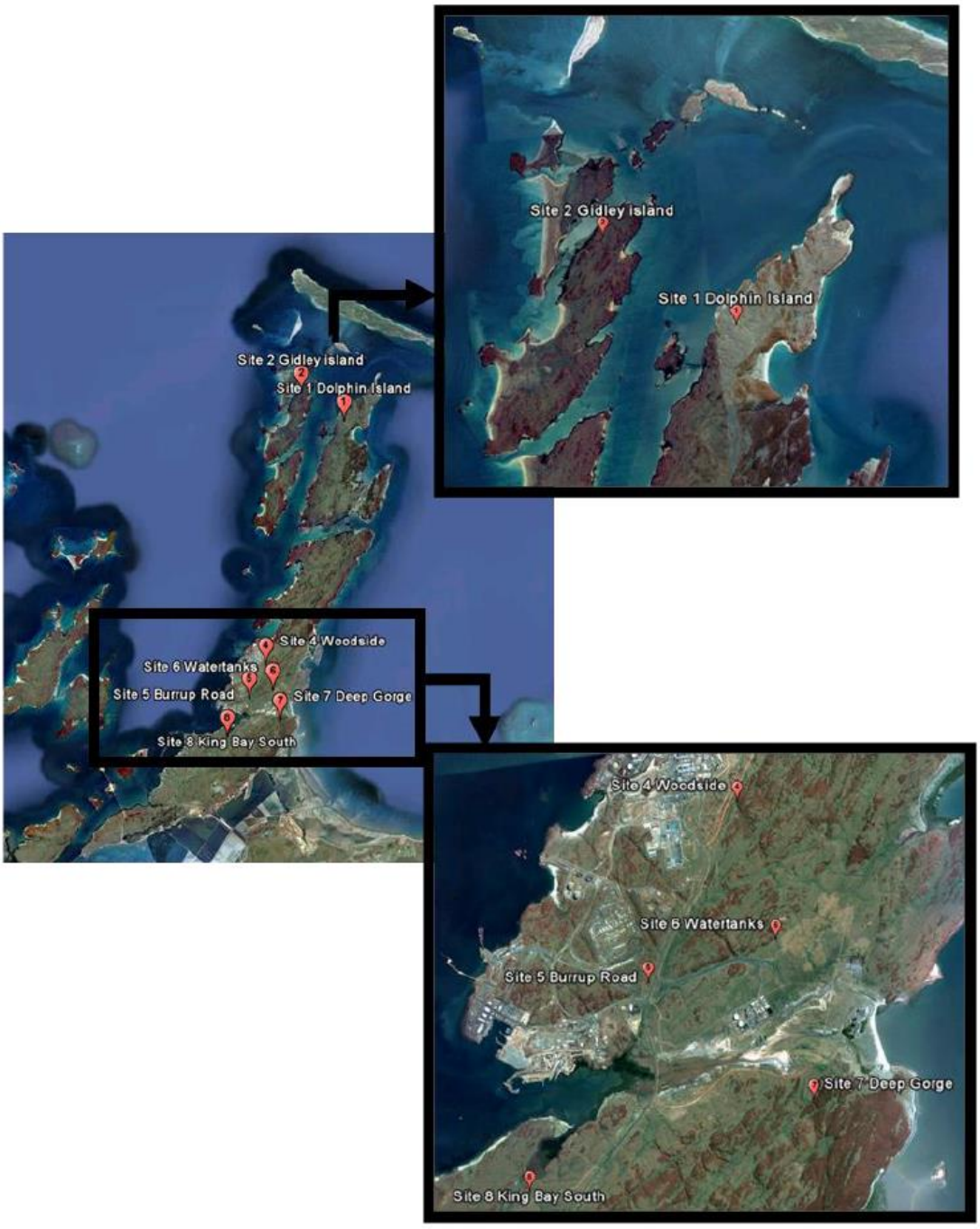

Figure 5 Location of rock art monitoring sites on the Burrup Peninsula (Source: CSIRO 2017a)

The final decision for the selection of a representative petroglyph at each site (Figure 6) was determined in consultation with the Rock Art Monitoring Management Committee's Technical Advisor and nominated representatives of the local indigenous communities, including members of MAC (CSIRO 2006b, 2007a, 2008b, 2009, 2010b, 2011, 2012, 2013a, 2014a, 2015a, 2017a; Ramanaidou and Fonteneau 2019). Respecting the cultural laws of the Traditional Owners for the entitlement of access, selected petroglyphs were evaluated for their suitability for scientific study,

including aspects such as distance from the sea, elevation, direction of exposure and cultural acceptability. Each site included one or more petroglyphs.

Figure 6 Monitored petroglyph at Dolphin Island showing the location of sampling 'spots' and sampling points (green dots) (scale bar = 50 cm) (Source: CSIRO 2017a)

Geology was also considered in the selection of sites to ensure that both of the major rock types (granophyre and gabbro) that support the rock art were included (CSIRO 2017a). At the Dolphin Island, Deep Gorge, Yara North East and Yara East sites the petroglyphs are engraved on gabbros and on granophyres at the other sites (CSIRO 2013a, 2014a, 2015a, 2017a).

Timing of sampling

Colour change and spectral mineralogy measurements were collected annually between 2004 and 2016 (CSIRO 2006b, 2007a, 2008b, 2009, 2010b, 2011, 2012, 2013a, 2014a, 2015a, 2017a; SKM 2009a).

Approach to the study

The approach was to employ in situ non-destructive/non-invasive testing strategies so there would be no impact on the measured surfaces (CSIRO 2006b, 2007a, 2008b, 2009, 2016). Field instruments were also required to be portable for use in remote field locations (in particular Gidley and Dolphin Islands). Of the available instruments, two were selected as being the most appropriate:

1. A spectrophotometer for colour measurement. A BYK-Gardner spectrophotometer was used between 2004 and 2012, and from 2009 a Konica Minolta spectrophotometer.

2. A reflectance spectrometer for visible and short-wave infrared spectral analysis (ASD spectrometer).

The measuring head (the part of the instrument in contact with the petroglyph) of the spectrophotometer was made of plastic; and of rubber for the reflectance spectrometer. The area measured by the Konica Minolta spectrophotometer was 28 mm^2; and 314 mm^2 by the ASD spectrometer.

Measurement of colour

Portable, hand-held spectrophotometry was identified as a suitable technique for the repeatable recording of colour using an artificial light source (CSIRO 2006b, 2007a, 2008b, 2009, 2010b, 2011, 2012, 2013a, 2014a, 2015a, 2017a). The method removes errors associated with seasonal and diurnal variation in light levels and the natural difference in colour perception characteristic of the human eye (Burrup Rock Art Monitoring Management Committee 2009).

Colour was recorded in units of standard Commission Internationale de l'Éclairage (CIE) chromaticity coordinates (CSIRO 2006b, 2007a, 2008b, 2009, 2010b, 2011, 2012, 2013a, 2014a, 2015a, 2017a). CIE chromaticity coordinates are an internationally recognised numerical system of objectively describing the colour of a surface or material as a point in three-dimensional L*a*b* colour space,[5] identifying a tristimulus value (L*a*b*) for each sampling point. The scales of L*, a* and b* are designed so that a change of about two units in any of these variables would be just noticeable to the human eye.

The difference between two colours measured spectrally is ΔE, which is the standard CIE colour difference method, measuring the distance between two colours, calculated in three-dimensional L*a*b* colour space (CSIRO 2006b, 2007a, 2008b, 2009, 2010b, 2011, 2012, 2013a, 2014a, 2015a, 2017a). Colour differences can be evaluated through measuring the tristimulus values of points over time and calculating ΔE to evaluate the colour difference with time. A ΔE value of zero represents an exact match.

The colour difference between the petroglyph and the background rock surface is an indication of the colour contrast, and to some extent, the 'readability' of the petroglyph (CSIRO 2008b, 2009, 2010b, 2011, 2012, 2013a, 2014a, 2015a). The 'readability' is also provided by the depth of the image engraving and texture of the image lines. The colour contrast between the rock art engraving and the background rock surface can thereby be monitored to evaluate whether it is decreasing over time, with a consistent trend towards smaller colour differences indicative of either background fading or darkening of the petroglyph, or both (CSIRO 2008b, 2009, 2010b, 2011, 2012, 2013a, 2014a, 2015a, 2017a).

[5] L* = degree of lightness from 0 (black) to 100 (white); a* = degree of red/green, with higher a* values corresponding to increasing red colour and lower values to increasing green colour; b* = degree of yellow/blue, with higher b* values corresponding to increasing yellow colour and lower values to increasing blue colour.

The difference between two colours (ΔE) was evaluated using the 1976 CIE colour difference formula (CSIRO 2006b, 2007a, 2008b, 2009, 2010b, 2011, 2012, 2013a, 2014a, 2015a, 2017a). In CIE L*a*b* space, the difference is:

$$\Delta E^*_{ab} = [(\Delta L^*)^2 + (\Delta a^*)^2 + (\Delta b^*)^2]^{0.5}$$

The colour change of single sampling points between the consecutive years over which monitoring was undertaken was evaluated, as well as an overall comparison between the first year and most recent year of monitoring (Figure 7).[6]

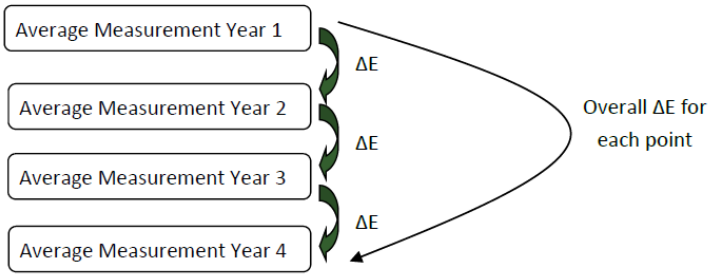

Figure 7 Evaluation of colour change (Source: CSIRO 2017a)

Data was calculated relative to the D65 standard illuminant, intended to represent average daylight (CSIRO 2017a).

An alternative technique for in situ monitoring of degradative change through colour measurement, the template-matching technique (digital image comparisons with a reference image), was considered unsuitable and impractical for application in this program (CSIRO 2006b, 2007a, 2008b, 2009, 2010b, 2011, 2012, 2013a, 2014a, 2015a, 2017a). The technique was considered unsuitable and impractical for two reasons:

1. The technique requires the collection of digital images with repeatable and controlled spectral illumination, angle of incidence and collection. Given the remote and exposed location of the rock art on the Burrup Peninsula, it would not be possible to control the colour, temperature and angle of the ambient lighting easily without blocking all the ambient daylight, or collecting images in the night with ambient moon and starlight removed.
2. The effect of metamerism in relation to the reference template and rock surface needs to be accounted for. Surfaces appearing similar in colour under one set of illumination conditions can appear different with another spectral illuminant or angle of incidence. The reference template is a glossy (laminated) smooth surface, while the rocks in this study were significantly rougher.

[6] Ramanaidou and Fonteneau (2019) used ΔE as a proxy for the age of monitored petroglyphs: high ΔE for the younger ones and low ΔE for the older ones.

Measurement of spectral mineralogy

Field reflectance spectroscopy, an in situ materials characterisation technique that provides information about the chemistry of a mineral from its reflected light, was identified as a suitable technique to measure changes in the diagnostic mineral spectral features of the rock art and background rock surfaces (CSIRO 2006b, 2007a, 2008b, 2009, 2010b, 2011, 2012, 2013a, 2014a, 2015a, 2017a; SKM 2009a). The technique is suitable for the quantitative/qualitative analysis of many geological materials. Advantages of the technique include minimal (if any) sample preparation and rapid (average scanning time to acquire a spectrum is one second) accurate mineral characterisation, although the measurement is restricted to the surface of samples (< 50 µm).

Using field reflectance spectrometry, the mineralogy of samples can be characterised based on key spectral features. The information derived from the ASD spectrometer (CSIRO 2006b, 2007a, 2013a, 2014a, 2015a, 2017a; Ramanaidou and Fonteneau 2019), using proprietary software developed by CSIRO, included:

- L*, a*, b* colour measurements equivalent to the measurements obtained from the spectrophotometer
- spectral features in the form of absorption bands corresponding to certain mineralogical features, consisting of:
    - the depth of the spectral absorption band centred at about 900 nanometres (nm) (depth 900 nm) associated with iron oxides
    - the minimum wavelength (Min Wav 900 nm) associated with the spectral absorption band centred at about 900 nm, diagnostic of hematite or red pigment and goethite or yellow pigment[7]
    - the depth of the chlorite absorption band at 2,250 nm (Depth Chlorite) (residual mineral from the fresh rocks)
    - the depth of the kaolinite absorption band (Depth Kaolinite) at 2,206 nm (secondary mineral resulting from the weathering of the primary minerals)
    - when present, the depth of the gibbsite absorption band (Depth Gibbsite) at 2,267 nm (secondary mineral resulting from the weathering of the primary minerals).

Each of the sampling points being monitored for colour change was also characterised on the basis of spectral mineralogy to evaluate whether changes in mineralogy were observed on the petroglyph and adjacent rock surface.

[7] The Min Wav 900 nm feature is correlated to the hematite-geothite ratio and shifts towards shorter wavelengths for higher concentrations of hematite and towards longer wavelengths for higher concentrations of goethite (Ramanaidou et al. 2008, cited in Ramanaidou and Fonteneau 2019).

Methodology

There have been several changes in the monitoring program since it first commenced in 2004, including the instruments used for colour measurements; the number of sampling 'spots' measured on each petroglyph and adjacent rock surface; the number of repeat and replicate readings made at each sampling point; and the measurement procedures (whether the instrument head was removed and replaced on the sampling point after each reading).

Refer to Appendix 1 for a chronology of the monitoring methods and implemented changes.

Key study results

The key findings from the study included (CSIRO 2017a):

Year-to-year colour differences

- The colour change for the northern control sites and the southern sites close to industry were reasonably consistent over the 2004–16 monitoring period. At any given time interval, the average change at the southern and northern sites was comparable, indicating accelerated weathering at the southern sites within close proximity to industrial activity was not observed.
- The colour differences appeared to have the largest values overall at Burrup Road and Deep Gorge, which was partially attributed to the surface roughness of the rock, which influenced the placement of the spectrophotometer. This was supported by the improvement in the consistency of the results at these sites from 2009 onwards, with the use of the Konica Minolta spectrophotometer with an improved head configuration. The site with the smoothest rock surface (Water Tanks) did not consistently record the lowest colour change values, indicating measurement repeatability was dependent on more than surface roughness.
- The data from the BYK-Gardner spectrophotometer were unreliable for drawing conclusions on colour change in the rock art.

Spectral parameters

- The spectral parameters extracted from the reflectance spectra for the northern control sites and the sites close to industry showed relatively large variations but no systematic changes or trends.

Statistical analysis of colour measurements

- The data from the Konica Minolta spectrophotometer indicated a significant trend over time in L* (degree of lightness) measurements, but not in a* (degree of red/green) or b* (degree of yellow/blue) measurements.
- Lightness decreased at a modelled average rate of 0.31 units per year, across both background and engraving of all sampling spots at all sites. A total

decrease of about two units on this scale would be just noticeable to the human eye. The 95 per cent confidence interval for this decrease in lightness was (0.11, 0.52) units per year.

- The data from the ASD spectrometer indicated there was a possible change over time in L* and a* measurements, but not in b* measurements. The evidence was not as strong as for the Konica Minolta spectrophotometer.
- There was no indication that trends in any of the colour measurements, or in the contrast between background and engraving, differed significantly at northern control sites and southern sites close to industry. None of the instruments indicated a difference in the rate of colour change between northern sites and southern sites (i.e. sites closer to industry were not changing colour at a rate statistically significantly different to control sites further from industry).

CSIRO (2017a) noted the conclusion of colour change would be clearer if it was detected across all dimensions of colour, given that it would be natural for colour change to be evident in all dimensions, L*, a* and b*, not only in one or two. CSIRO (2017a) considered the results were not fully conclusive and that if the measurements did reflect real colour change, as the data suggested, then further observations would more clearly identify the trend; and, if not, observations would likely continue to fluctuate over time, making the randomness of the recorded variation more apparent.

CSIRO (2017a) made several recommendations for further work and there should be:

- statistical analysis of the full spectral range of each individual ASD spectrometer spectrum, not just the visible portion (i.e. *L**, *a** and *b**)
- assessment of how many additional sites and petroglyphs should be incorporated into the monitoring program to increase the quality of the monitoring on the Burrup Peninsula. In particular, consideration should be given to including additional control sites with similar rock types. Noted there will need to be a balance between statistical endeavour and petroglyph protection from potential adverse effects of increased independent measurements
- collection of one rock sample from each site, stored under 0 per cent humidity (no water), in an argon atmosphere (no oxygen or oxidation) and in darkness. This would enable comparison between the control sites where natural weathering occurs and these reference samples
- colour and mineralogical monitoring complemented with atmospheric and microbiological monitoring.

In response to questions at the Senate Inquiry into the Protection of Aboriginal rock art of the Burrup Peninsula, CSIRO (2017e) advised that analysis of the data for every year back to 2010 showed there was statistically significant evidence of change over time in the Konica Minolta spectrophotometer L* measurements in

2014. CSIRO (2017e) advised this should have been reported at the time. Before this, no trends met the 0.05 level of significance after applying the Bonferroni correction (CSIRO 2017e). CSIRO (2017e) noted that 2016 was the first year both the Konica Minolta spectrophotometer data and the ASD spectrometer data indicated a significant change in the same variable, although only the trends in the Konica Minolta spectrophotometer data met the 0.05 level of significance after applying the Bonferroni correction.

CSIRO (2017e) noted that the small changes observed could be the result of natural weathering or potentially other causes and that, while the indication of colour changes was important and warranted closer consideration, it could not be assumed that it represented the impact of pollution from industrial plants. Sites further from industrial activity, included in the monitoring program to test whether change was more rapid at sites more prone to pollution effects, showed no statistically significant difference from the other sites.

DAA undertook the analysis of 2017 colour change and spectral mineralogy data collected by Yara Pilbara at sites in proximity to the TANPF, to meet the requirements of EPBC Approval 2008/4546 (Data Analysis Australia 2018). Key findings included:

- Analysis of the data from the Konica Minolta spectrophotometer and the ASD spectrometer suggested colour changes may have occurred over the monitoring period at a different rate for the control and industry sites. However, there was no common structure to this possible change, casting doubt on its true significance. DAA (2018) noted:
    - the lack of sufficient control sites weakened the weight that can be given to this result
    - the colour changes recorded by the ASD spectrometer appeared to be significantly affected by the past few years' measurements at Gidley Island (a control site) and the effect on the analysis was therefore disproportionate
    - the ASD spectrometer appeared to be more strongly affected by the rock type compared with the Konica Minolta spectrophotometer. While neither the data or the statistics can confirm why this was so, the most likely cause was the different illumination and geometry of the receptor.
- Analysis of the near infrared spectral line data suggested some statistically significant changes. The analysis was strongly affected by rock type (gabbro versus granophyre), suggesting this factor should have been incorporated into the monitoring program early on. DAA (2018) noted that while it might be expected that different rock types give rise to significantly different spectral data, it was not so obvious that changes in the spectral data over time were similarly affected.

DAA (2018) concluded that, overall, the analysis suggested that some changes may have occurred, but the finding remained inconclusive.

DAA (2018) noted the reservations previously identified (Data Analysis Australia 2016, 2017) with respect to the monitoring program were confirmed. This included the inadequate number of sites being monitored, in particular the number of control sites; the difficulty in reliably measuring at the same sampling points year after year; and the wasted effort associated with the high number of replicates measured at each sampling point.

Analysis of the BYK-Gardner and Konica Minolta spectrophotometer colour change data from 2004–14 by Black and Diffey (2016a) found that, with some variation between sites, the rocks had become lighter, more red and more yellow over the 11 years of measurement. Changes in the colour space variables were significantly different between sites, with the greatest change recorded at Deep Gorge and the least at Water Tanks. With the exception of the colour changes at Water Tanks, all colour changes were sufficient to be perceived by the human eye (Black and Diffey 2016a).

The change in colour across all sites was significantly greater for engravings than for background rock (Black and Diffey 2016a). The type of rock on which the engravings were made also significantly affected colour change, with the greatest change recorded on gabbro than granophyre rocks.

There was no significant difference in colour change at the two northern sites compared with the five southern sites closer to industry (Black and Diffey 2016a). However, the numbers of sites in the northern and southern areas were too small to determine significant differences with the observed variation in measurements within and between sites. Black and Diffey (2016a) determined that, with the variance in the data collected, six northern and six southern sites would be required to show a 15 per cent difference in colour to be significant ($P = 0.05$); and 44 replicate control and industry sites would be needed to show a 5 per cent change to be significant.

The ability to perceive petroglyphs on rocks was enhanced when the contrast in colour between the background and engraving was greater (Black and Diffey 2016a). The contrast in colour between engraving and background declined from 2004 to 2014 at all sites, with a significant decrease in colour differentiation at Dolphin Island and Deep Gorge. The decrease in colour contrast between background rock and engravings indicated that petroglyphs at the monitored sites had become more difficult to distinguish from the background rock over the 11 years of measurement (i.e. the rock art was less visible). In the absence of associated measurements of air emissions or changes to the chemical or microbial composition of the rocks, a cause for the colour changes cannot be determined (Black and Diffey 2016a).

Limitations

There has been criticism of the colour change and spectral mineralogy monitoring program (e.g. Bednarik 2004, 2009; Hallam 2009; Black 2013b, 2013c, 2014, 2017b; Black and Diffey 2016a, b; Black et al. 2017a). The criticisms related to:

- the experimental design of the monitoring program, including:
    - the suite of parameters monitored
    - collection of repeat measurements and the lack of/inadequate replication (e.g. insufficient sampling points to represent the highly variable rock surface), including the absence of an assessment of the required number of replicates
    - the assumptions underlying the selection of sampling points on unengraved rock as ‘background’ measurements against which changes on engravings can be compared
    - the selection of the rock art to be monitored did not adequately account for the variety of engravings (e.g. age, depth and degree of pre-existing weathering)
    - the number, spatial distribution, location and position in the landscape of the monitoring sites (e.g. gabbro and granophyre rock types, near and far islands, valley sides facing different directions, horizontal and near-vertical rock faces)
    - the number and location of control sites and other options for controls
    - lack of consideration in the design of the environmental factors known to affect measurement variability
- the instruments used and measurement procedures employed, including:
    - the physical limitations of the selected instruments and their suitability and reliability for undertaking measurements under the prevailing field conditions (temperature, humidity, etc.) on the Burrup Peninsula
    - the measurements involved physical contact between the rock art and the instrument
    - the requirement to exclude natural daylight because rock surfaces were not flat, introduces potential distortion, which was difficult to safeguard against and the procedure does not detect or permit compensation for such distortion
    - the measurement variance introduced by the inhomogeneity (morphological, visual, chemical) of the rock surfaces
    - inconsistencies in field procedures for collecting measurements and the lack of apparent standardisation of measurement procedures
    - insufficient detail provided on the measurement procedures, including maintenance, calibration and cross-calibration of instruments, and the use of appropriate reference standards
    - issues with the accurate repositioning of the instrument to ensure precisely the same sampling points were remeasured on each

occasion, which resulted in measurement error and a lack of repeatability

- the absence of measurement of ancillary variables that influence the primary measurements).

These issues led to questions about the quality and reliability of the data.

- inconsistencies in the results, inappropriate or inadequate presentation of monitoring results and the lack of, limited, inappropriate or inadequate statistical analysis of the data in earlier reports resulting in failure to appropriately present or interpret results.
- conclusions in earlier reports were subjective, non-verifiable by third parties and not supported by the monitoring data and/or statistical analysis.

Other issues that have been identified included:

- the proposed four-year duration of the monitoring study was inadequate to establish whether rock engravings were or were not being affected by industrial activities and the study should be considered as establishing a baseline for petroglyph condition (Hallam 2009)
- the timing of the commencement of the monitoring program (2004) given that industrial emissions started in the 1960s (Hallam 2009)
- the lack of transparency around the independent peer review of the monitoring program (Mulvaney 2017a).

Black et al. (2017a) also noted that while monitoring changes in rock surface colour and mineralogy were selected as appropriate macroscopic means for assessing likely changes to rock art because of industrial emissions, the magnitude of change considered detrimental for rock art appeared not to have been set.

Independent reviews

In 2016, DER commissioned DAA to undertake a review of the statistical aspects of the rock art monitoring program. In undertaking this review, DAA also considered the design of the monitoring program, measurement processes and data management.

DAA (2016) acknowledged that the 12 years of monitoring data was a valuable resource and should not be discarded as it is irreplaceable, but that it would not be appropriate for any decisions, including whether or not changes have taken place in the rock art, to be based on the data in its current form. DAA's (2016) primary recommendation was that problems with the data be repaired to the fullest extent possible and the limitations be clearly documented. DAA (2016) also concluded there was a need for improved statistical methods in the monitoring of the rock art to enable the examination of longer-term trends, to understand whether there were issues affecting multiple sites and to potentially contrast sites close to and far from industrial developments.

DAA (2016) made several recommendations, including that:

1. the historical data should be systematically archived and held by DER with consistent naming conventions, both to provide a baseline record and to facilitate comparisons with future data. The archival data format should enable ready access to the data using standard statistical software such as R[8]
2. the cross-calibration issues with the BYK-Gardner and Konica Minolta spectrophotometers should be revisited to ensure the historical data were properly understood and to confirm whether or not the historical BYK-Gardner spectrophotometer data were capable of comparison with current and future measurement instruments
3. statistical analysis, based on the standard statistical approach of setting up of a predictive model whereby the observed measurements were expressed as a function of the explanatory variables and a random or error term to represent the impossibility of absolute precision, should be conducted[9]
4. consideration should be given to using the ASD spectrometer as the primary measurement instrument. The analysis should use the verified ASD estimates of L*, a* and b*; ideally the original ASD spectra should be used rather than the averaged spectra
5. future work should be based upon an agreed analysis plan certified by a competent statistician. It would be appropriate for the next annual report to incorporate this improved analysis and, in doing so, make it clear that it replaces analyses in previous reports
6. consideration should be given to expanding the number of measured sites to improve the balance of the monitoring program design to include more effective controls, if feasible
7. to maintain scientific rigour, future data collection should follow a fully documented and detailed protocol, and ensure that departures were documented.

CSIRO (2016) broadly agreed with DAA's recommendations and undertook to address the issues raised. With respect to the recommendation to increase the number of sites, CSIRO (2016) noted this would raise substantial logistical and funding issues that would require discussion with DER.

In responding to DAA's report, Black and Diffey (2016b) were of the view that the results from the Konica Minolta and ASD instruments were likely to be highly inaccurate and the data derived from the BYK-Gardner instrument were more likely to accurately reflect true colour than the data derived from the other two instruments. Black and Diffey (2016b) did not agree that it was valid to undertake statistical

[8] R is a language and environment for statistical computing and graphics (www.r-project.org/).

[9] DAA supported the general approach adopted by Dr J. Black and Dr S. Diffey in their paper *Reanalysis of the Colour Changes from 2004 to 2014 on Burrup Peninsula Rock Art Sites* (14 May 2016), but noted the analysis as presented had several significant drawbacks primarily related to the data used.

analysis based on L*, a* and b* calculated from the ASD spectra. This was because the data collected from the ASD instrument were considered to be dubious, noting the instrument was not used as described in the manual, the dataset was incomplete, the algorithms used to convert the ASD wavelengths were not made available by CSIRO and the variance for the predicated values was not given.

In 2017, DAA was commissioned by DER to review the draft CSIRO report *Burrup Peninsula Aboriginal Petroglyphs: Colour Change & Spectral Mineralogy 2004–2016* (February 2017) which was intended to implement the recommendations in DAA's previous review and present the most recent monitoring data and its statistical analysis.

DAA (2017) found that a considerable amount of work had been undertaken to address some of the concerns identified in their previous review. In particular, there were improvements in the statistical analysis of colour changes using linear mixed models, with greater care taken to highlight the problems associated with the BYK-Gardner spectrophotometer used in the early years of the monitoring program. There were also indications of improvements in data management, both to make the data available for analysis and to preserve it for future years.

DAA (2017) noted, however, that significant work remained to be undertaken to address the previous recommendations. DAA (2017) recommended that, at the very least, the report should be identified as a work in progress so the reader was not given to think the draft report was complete or the report conclusions final. DAA (2017) noted in particular that the conclusions in the draft report, namely that there was no evidence of a significant change affecting the rock art near to the industrial developments, was not convincing in their current form.

DAA (2017) made several recommendations with regard to the draft report, including that:

1. the report should include a succinct description of the data collection framework
2. the section on Colour Measurement should more directly address the poor quality of the BYK-Gardner spectrophotometer data. DAA recommended that the BYK-Gardner spectrophotometer data not be used, in particular not as a reference for changes since 2004, and that it be recommended to readers not to rely on these data
3. in the section on Colour Measurement and other parts of the report, less reliance should be placed on the ΔE measure
4. the report should include a proper statistical analysis of the spectral parameters to determine whether or not there have been significant changes
5. the findings in the section comparing the BYK-Gardner and Konica Minolta spectrophotometers should be given greater prominence overall in the report, with the clear message that the BYK-Gardner spectrophotometer data has limited, if any, value

6. the comments that the BYK-Gardner spectrophotometer data does not indicate change should be deleted or have strong caveats placed on it.
7. the report should provide substantially more information on the mixed models considered to demonstrate reasonable support for the conclusion that there was no evidence of impact of industry on the rock art
8. the report should properly document all changes in measurement practices and, where appropriate, incorporate these into the analyses
9. a formal design document should be produced before the next period of data collection, based upon established principles of the design of experiments. This document should fully explain any departures from the ideal, including the need to maintain a certain level of consistency with the existing data that, despite all its limitations, must remain part of future analysis
10. a formal analysis document should be produced in parallel to the design document before the next period of data collection.

In considering the draft report, DAA also reviewed the design of the monitoring program and noted:

> "…*It is unfortunate that, for whatever the reasons, this was not based upon firmer statistical principles. More sites should have been monitored, especially more control sites and the number of replicate measurements taken at each point seems excessive (or unnecessary). Furthermore, as there are concerns that the measurement process is damaging the engravings, a fractional design is indicated where not all spots were measured each year. It is not possible to fix the historically collected data but moving forward consideration should be given to redesigning the monitoring scheme.*" (Data Analysis Australia 2017, Executive Summary).

Data availability

Data to be published on DWER's website.

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Appendix 1: Summary of colour change and spectral mineralogy monitoring program methods (2004-16)

Sampling Year	Sites	Instruments		Methods		Additional information	Reference
		Colour change	Spectral mineralogy	Colour change	Spectral mineralogy		
2004 (July)	Dolphin Island (Site 1) Gidley Island (Site 2) Woodside (Site 4) Burrup Road (Site 5) Water Tanks (Site 6) Deep Gorge (Site 7) King Bay South (Site 8)	Measured in situ using a portable BYK-Gardner spectrophotometer with inbuilt spectral illuminants: CIE illuminant A (mathematical representation of tungsten halogen (incandescent)), D65 (mathematical representation of a phase of daylight recommended by the CIE if daylight is of interest) and F2 (similar to fluorescent light sources). A CIE standard illuminant represents an aimed spectral power distribution of a theoretical real light source. Artificial light source used for reproducibility and determination of colour change, as fluctuations in natural daylight	Measured in situ using an Analytical Spectral Device (ASD) FieldSpecPro field spectrometer. Instrument covers visible to short-wave infrared wavelength range (350) 400–2,500 nm with spectral resolution of 3 nm at 700 nm using three detectors: a 512 element Si photodiode array for the 400–1,000 nm range and two separate, thermal emission cooled, graded index InGaAs photodiodes for the 1,000–2,500 nm range. ASD may be operated using external source of light (sun or artificial) or internal source of light. Absolute measurements obtained using a white reference plate made of compressed	At each site, selected petroglyph(s) measured at three sampling 'spots'. At each sampling 'spot', measurements taken at two (fixed) sampling areas (i.e. six sampling points per petroglyph(s) at each site). Sampling areas defined as: • 'engraving' refers to area defined by engraving that constitutes the image; or • 'background' refers to adjacent rock surface unmarked by the petroglyph and which provides visual contrast to the petroglyph. Sampling areas selected to have relatively uniform colour over a minimum area of 20 mm^2, so comparative measurements could be made by spectrophotometer and reflectance spectrometer. Digital photography with a macro-lens used to relocate instrument to within a millimetre (SKM 2009a). As permanent markers could not be used on the rocks,	At each site, measurements taken on petroglyph (engraving) and associated background sampling points at each of the three sampling 'spots' used for colour measurements. Measurements acquired simultaneously. Seven spectra acquired for each sampling point and averaged to obtain a single spectrum for each area of engraving and background (n ≈ 7–8). Colour values measurements from spectrophotometer cross-checked with the colour values calculated by ASD spectrometer. ASD intended for characterisation of minerals rather than colour, but as wavelength range includes visible spectrum, can be used to calculate L*a*b data to validate spectrophotometer data (CSIRO 2016).	*Colour measurement:* Independent measurements acquired (i.e. head of instrument placed on rock, measurement taken, instrument head removed from surface being measured and replaced) to account for possible variation due to location and to distinguish this variation from the variation in year-to-year measurements (CSIRO 2016). Noted that every time measurement acquired, head of instrument in a slightly different location. *Spectral mineralogy measurement:* Measurements of background and engraving at each sampling point undertaken without moving head of spectrometer (CSIRO 2016). Careful placement of head of instrument and large footprint of measurement (314 mm^2) considered sufficient to avoid removing head between measurements, thereby preventing repeated contact with the rock surface.	CSIRO (2006b, 2007a, 2008b, 2009, 2010b, 2011, 2012, 2013a, 2014a, 2015a, 2016, 2017a) SKM (2009a)

Sampling Year	Sites	Instruments		Methods		Additional information	Reference
		Colour change	Spectral mineralogy	Colour change	Spectral mineralogy		
		spectrum because of time of day, season and weather means naturally illuminated measurements would be inconsistent and unreliable. Geometry of instrument measuring head designed to exclude light on flat surfaces. As rock surfaces not always flat, a compressible collar of black fabric used when necessary for complete exclusion of natural light. Refer to Table 8 (CSIRO 2006b) for instrument specifications.	polytetrafluoroethylene (PTFE), commercially known as Spectralon, which reflects 100% of light in 400–2,500 nm wavelength range. Internal source of light used at constant irradiance to eliminate any external light interference.	sampling points were selected at locations that could be easily recognised on detailed photographs and the rock faces (CSIRO 2016). Original intent to take average of seven colour measurements (L*a*b) from each sampling point (n ≈ 3–4).[1] In field became apparent additional measurements would be useful to enable statistical evaluation of variability of measurements. *Note 1: Number of measurements as reported; 'n' is indicative number of measurements in the data set.*			
2005 (September)	Dolphin Island Gidley Island Woodside Burrup Road Water Tanks Deep Gorge King Bay South	BYK-Gardner portable spectrophotometer Refer to Table 8 (CSIRO 2006b) for instrument specifications.	Analytical Spectral Device (ASD) FieldSpecPro field spectrometer	In second year, 21 independent repeat measurements collected from each sampling point (n ≈ 21), to reduce sample variance introduced by surface inhomogeneity or roughness and by systematic error, and to improve statistical robustness of data.	At each site, measurements taken on petroglyph (engraving) and associated background sampling points at each of three sampling spots used for colour measurements. Seven spectra acquired for each sampling point and averaged (n ≈ 9–11).	*Colour:* At sites where colour difference appeared to have larger values overall, may be partially because of surface roughness of rock which influenced placement of spectrophotometer (CSIRO 2006b). Site with smoothest rock surface did not consistently record lowest colour change values, indicative that measurement repeatability dependent on more than just surface roughness. *Spectral mineralogy:*	CSIRO (2006b, 2007a, 2008b, 2009, 2010b, 2011, 2012, 2013a, 2014a, 2015a, 2017a) Ramanaidou and Fonteneau (2019) SKM (2009a)

Sampling Year	Sites	Instruments		Methods		Additional information	Reference
		Colour change	Spectral mineralogy	Colour change	Spectral mineralogy		
						Changes in amount of reflected light detected (in visible (380–750 nm) and near infrared (>750 nm) ranges) could be explained by: • surface variation (relative change in mineral abundance, organic growth, moisture content, mineral heterogeneity at the rock surface) • probe not positioned at exactly the same sample locations as measured in 2004 (CSIRO 2006b).	
2006 (August)	Dolphin Island Gidley Island Woodside Burrup Road Water Tanks Deep Gorge King Bay South	BYK-Gardner portable spectrophotometer Refer to Table 20 (CSIRO 2007a) for instrument specifications.	Analytical Spectral Device (ASD) FieldSpecPro field spectrometer	At each site, selected petroglyph(s) measured at three sampling spots (three background and three engraving sampling points). Measurements based on average of minimum of seven readings at each sampling point (n ≈ 7–10).	At each site, measurements taken on petroglyph (engraving) and associated background sampling points at each of three sampling spots used for colour measurements. Seven spectra acquired for each sampling point and averaged (n = 7).	*Colour:* Colour change average for southern sites over 2004–05 period higher than 2005–06 period, which considered consequence of improved experimental practice during measurement taking over successive years CSIRO 2007a).	CSIRO (2007a, 2008b) SKM (2009a)
2007 (August)	Dolphin Island Gidley Island Woodside Burrup Road Water Tanks Deep Gorge King Bay South	BYK-Gardner portable spectrophotometer Refer to Table 1 (CSIRO 2008b) for instrument specifications.	Analytical Spectral Device (ASD) FieldSpecPro field spectrometer	At each site, selected petroglyph(s) measured at three sampling spots (three background and three engraving sampling points). Measurements based on average of minimum of seven readings at each sampling point (n ≈ 20–21).	At each site, minimum of seven measurements taken on petroglyph (engraving) and associated background sampling points at each of three sampling spots used for colour measurements (n = 10). Number of measurements increased to 10 at each sampling point to improve statistical robustness of the data. Spectra acquired at each sampling point averaged.	*Colour:* Colour change average for southern sites over 2004–05 period higher than 2005–06 period, which originally considered consequence of improved experimental measurement practice over successive years. Colour change average for period 2006–07 increased again, suggested represents actual degree of experimental error (CSIRO 2008b). At site where there was a patch of black patina at a sampling point,	CSIRO (2008b) SKM (2009a)

Sampling Year	Sites	Instruments		Methods		Additional information	Reference
		Colour change	Spectral mineralogy	Colour change	Spectral mineralogy		
						colour measurement more dependent on instrument placement (CSIRO 2008b). May also account for greater overall year-to-year variance observed at sampling point compared with other sampling points on the same petroglyph. Site with relatively moderate surface roughness recorded lowest colour change value. Additional factor, such as sample area colour inhomogeneity, may be responsible for influencing spread of individual colour measurements (CSIRO 2008b). Variance in data at some sampling points suggested measurements influenced by surface roughness (which affected spectrophotometer placement) and surface colour inhomogeneity/heterogeneity (CSIRO 2008b). *Spectral mineralogy:* Supplementary experiments to assess effect of moisture on spectral behavior undertaken to assess variation in albedo reported previously. Key findings included: • at each sampling point at a site, engraving contained less moisture than associated background rock surface • moisture content lowest in mid-afternoon • moisture impacts on spectral behavior–brightness decreased with increased moisture (CSIRO 2008b).	

Sampling Year	Sites	Instruments		Methods		Additional information	Reference
		Colour change	Spectral mineralogy	Colour change	Spectral mineralogy		
2008 (August)	Dolphin Island Gidley Island Woodside Burrup Road Water Tanks Deep Gorge King Bay South	BYK-Gardner portable spectrophotometer Refer to Table 1 (CSIRO 2009) for instrument specifications.	Analytical Spectral Device (ASD) FieldSpecPro field spectrometer	At each site, selected petroglyph(s) measured at three sampling spots (three background and three engraving sampling points). Measurements based on average of minimum of seven readings at each sampling point (n ≈ 7–10).	At each site, minimum of seven measurements taken on petroglyph (engraving) and associated background sampling points at each of three sampling spots used for colour measurements (n ≈ 10). Spectra acquired for each sampling point averaged.		CSIRO (2009)
2009 (August)	Dolphin Island Gidley Island Woodside Burrup Road Water Tanks Deep Gorge King Bay South	BYK-Gardner portable spectrophotometer Refer to Table 1 (CSIRO 2010b) for instrument specifications.	Analytical Spectral Device (ASD) FieldSpecPro field spectrometer	At each site, selected petroglyph(s) measured at three sampling spots (three background and three engraving sampling points). Measurements based on average of a minimum of seven readings at each sampling point (BYK-Gardner: n = 7; Konica Minolta: n ≈ 21–23).	At each site, measurements taken on petroglyph (engraving) and associated background sampling points at each of three sampling spots used for colour measurements. Seven spectra acquired for each sampling point and averaged (n ≈ 10).	*Colour measurement instruments:* 2004–08 colour measurements acquired using BYK-Gardner. In 2009, some of automated memory retention function of the BYK-Gardner became less reliable, requiring manual data saving (CSIRO 2013a, 2014a, 2015a). Calibration and instrument performance were unaffected; quality of colour measurements not affected. BYK-Gardner paired with Konica Minolta spectrophotometer and measurements collected with both instruments to assess possibility of substituting instruments for field measurements. From 2009, colour measurements undertaken in duplicate using BYK-Gardner and Konica Minolta spectrophotometer. *Spectral mineralogy:* Brightness (or amount of reflected light) changed between sampling periods (sometimes brighter and sometimes darker) (CSIRO 2010b). Observed in visible (380 to 750 nm)	CSIRO (2010b)

Sampling Year	Sites	Instruments		Methods		Additional information	Reference
		Colour change	Spectral mineralogy	Colour change	Spectral mineralogy		
						and near infrared (> 750 nm). Changes attributed to variation in moisture content.	
2010 (August)	Dolphin Island Gidley Island Woodside Burrup Road Water Tanks Deep Gorge King Bay South	BYK-Gardner portable spectrophotometer Refer to Table 1 (CSIRO 2011) for instrument specifications.	Analytical Spectral Device (ASD) FieldSpecPro field spectrometer	At each site, selected petroglyph(s) measured at three sampling spots (three background and three engraving sampling points). Measurements based on average of minimum of seven readings at each sampling point. Number of independent measurements increased in 2010–21 to increase statistical precision (CSIRO 2016) (BYK-Gardner: n ≈ 21–22; Konica Minolta: n ≈ 21–22).	At each site, measurements taken on petroglyph (engraving) and associated background sampling points at each of three sampling spots used for colour measurements. Seven spectra acquired for each sampling point and averaged (n ≈ 10–11).		CSIRO (2011)
2011 (August)	Dolphin Island Gidley Island Woodside Burrup Road Water Tanks Deep Gorge King Bay South	BYK-Gardner portable spectrophotometer Refer to Table 2 (CSIRO 2012) for instrument specifications.	Analytical Spectral Device (ASD) FieldSpecPro field spectrometer	At each site, selected petroglyph(s) measured at three sampling spots (three background and three engraving sampling points). Measurements based on average of minimum of seven readings at each sampling point (BYK-Gardner: n ≈ 22; Konica Minolta: n ≈ 22–23).	At each site, measurements taken on petroglyph (engraving) and associated background sampling points at each of three sampling spots used for colour measurements. Seven spectra acquired for each sampling point and averaged (n ≈ 10–11).	*Comparison between spectrophotometer and reflectance spectrometer:* Colour difference between background and petroglyph (an indication of colour contrast) different between the two spectrometers, the ASD and the BYK-Gardner (CSIRO 2012, 2013a, 2014a, 2015a). Degree of variance within measurements attributed to instrument design: •ASD larger measurement window (20 mm area measured) and exhibited less measurement variance from year to year •BYK-Gardner smaller measurement window (4 mm area	CSIRO (2012)

Sampling Year	Sites	Instruments		Methods		Additional information	Reference
		Colour change	Spectral mineralogy	Colour change	Spectral mineralogy		
						measured) and exhibited greater measurement variance. Some sites with rougher surfaces had greater variance with both instruments compared with sites with smoother surfaces, indicating consistency between instruments (CSIRO 2012, 2013a, 2014a, 2015a). Most obvious discrepancy between two techniques observed at site with roughest surface (CSIRO 2013a, 2014a, 2015a). Larger measurement window of ASD may have been more effective at negating instrument placement effects on colour measurements and resulting in less measurement variance. Smaller measurement window of BYK-Gardner meant measurements more likely to be impacted by colour inhomogeneity/heterogeneity of sampling area, resulting in greater measurement variance. Also has larger planar surface, which more susceptible to coarse grain surface roughness.	
2012 (September)	Dolphin Island Gidley Island Woodside Burrup Road Water Tanks Deep Gorge King Bay South	BYK-Gardner portable spectrophotometer Refer to Table 3 (CSIRO 2013a) for instrument specifications.	Analytical Spectral Device (ASD) FieldSpecPro field spectrometer	At each site, selected petroglyph(s) measured at three sampling spots (three background and three engraving sampling points). Measurements based on average of minimum of three readings at each sampling point (BYK-Gardner: n ≈ 21–22; Konica Minolta: n ≈ 22).	At each site, measurements taken on petroglyph (engraving) and associated background sampling points at each of three sampling spots used for colour measurements. Seven spectra acquired for each sampling point and averaged (n ≈ 10–12).	*Comparison between two spectrometers*: Two ASD spectrometers (“old” one used for previous measurements and “new” instrument of the same model) used to measure both engravings and background at a subset of sites. Good correlation between old and new ASD for all spectral parameters (CSIRO 2013a). Note same instrument used throughout monitoring	CSIRO (2013a)

Sampling Year	Sites	Instruments		Methods		Additional information	Reference
		Colour change	Spectral mineralogy	Colour change	Spectral mineralogy		
						program.	
2013 (August)	Dolphin Island Gidley Island Woodside Burrup Road Water Tanks Deep Gorge King Bay South	Konica Minolta CM-700d spectrophotometer with inbuilt spectral illuminants (D65, simulates daylight) Refer to Table 4 (CSIRO 2014a) for instrument specifications.	Analytical Spectral Device (ASD) FieldSpecPro field spectrometer	At each site, selected petroglyph(s) measured at three sampling spots (three background and three engraving sampling points). In 2013, to increase accuracy of statistical analysis of measurements: • 4th engraving and background sampling point added on each petroglyph • number of measurements at each sampling point increased to 21 (n ≈ 22) • instrument head/detector in contact with the sampling point was removed and then replaced after each measurement so that 21 independent measurements taken at each sampling point to reduce sample variance introduced by surface heterogeneity or roughness and by systematic error (CSIRO 2017a).	At each site, measurements taken on the petroglyph (engraving) and associated background sampling points at each of the three sampling spots used for colour measurements. To increase accuracy of statistical analysis of measurements, 4th engraving and background sampling point measured on each petroglyph from 2013. Measurements based on average of minimum seven readings at each sampling point (n = 25).	*Colour measurement instruments:* In 2009, Konica Minolta used to evaluate suitability and practical handling features (CSIRO 2014a, 2015a). Instrument found to be reliable and well suited to purpose of the program. Konica Minolta has flat, conical head configuration, which provided improved repeatability on rougher rock surfaces. Measurement head of Konica Minolta has diameter of 10 mm, half of head diameter of ASD (head diameter 20 mm) (CSIRO 2017a). Increased measurement field diameter reduced effect of surface heterogeneity on overall averaged colour measurement (CSIRO 2014a, 2015a). Among reasons for replacing BYK-Gardner was high variation in measurements taken with it (CSIRO 2017a). Variation generally larger on engravings, partially attributed to engravings not being very wide and rougher than background rock. Therefore harder to place instrument perfectly flat against the rock surface. Problem does not affect Konica Minolta, which has a smaller head, to the same extent as it does BYK-Gardner. BYK-Gardner also recorded some very dark colours, even on engravings, which generally lighter than background rock (CSIRO	CSIRO (2014a)

Sampling Year	Sites	Instruments		Methods		Additional information	Reference
		Colour change	Spectral mineralogy	Colour change	Spectral mineralogy		
						2017a). May indicate instrument unable to be placed flat on rock surface. Low lightness values can indicate some reflected light escaped through gap between instrument and rock surface. Overall variance reduced using Konica Minolta; less effective reducing variance when already low using BYK-Gardner (CSIRO 2014a, 2015a). Ability to discern colour change on rock surfaces dependent on differences in measurement and a reduction in variance is critical factor for achieving this. Given difficulties with the BYK-Gardner, coupled with planarity of measurement surface of Konica Minolta contributing to reduction in variance, colour measurements from 2013 collected using Konica Minolta. *Colour:* At sites where colour differences larger values overall, partially attributed to surface roughness of rock, which influenced placement of spectrophotometer (CSIRO 2014a). Supported by improvement in consistency of results at these sites from 2009 onwards when Konica Minolta with an improved head configuration used.	
2014 (July)	Dolphin Island Gidley Island	Konica Minolta CM-700d spectrophotometer Refer to Table 4 (CSIRO 2015a) for	Analytical Spectral Device (ASD) FieldSpecPro field spectrometer	At each site, selected petroglyph(s) measured at four sampling spots (four background and four engraving sampling points).	At each site, measurements taken on the petroglyph (engraving) and associated background sampling points at each of the four sampling	*Colour:* Decreasing trends in colour difference reported at some spots at new sites attributed to difficulty associated with precise replication	CSIRO (2014b, 2015a, b)

Sampling Year	Sites	Instruments		Methods		Additional information	Reference
		Colour change	Spectral mineralogy	Colour change	Spectral mineralogy		
	Woodside Burrup Road Water Tanks Deep Gorge King Bay South Yara West (Site 21) Yara North East (Site 22) Yara East (Site 23)	instrument specifications.		Twenty-one replicate measurements at each sampling point (n ≈ 22). Instrument head lifted off the surface between each measurement, to reduce sample variance introduced by surface heterogeneity or roughness and by systematic error (CSIRO 2014b, 2015b).	spots used for colour measurements. Measurements based on average of minimum seven readings at each sampling point. In 2014, sampling changed to become similar to methodology for spectrophotometer, with 21 independent measurements acquired (CSIRO 2016) (n = 11). Note measurements at the six sites in Yara Pilbara's monitoring program involved 10 sets of measurements at each sampling point; five readings taken for each set, sampling head lifted off and repositioned on the surface for the next set (CSIRO 2014b, 2015b).	of analysis location as contrast of petroglyphs with rock background was low because of age of the rock art (CSIRO 2015a).	
2015 (August) and 2016	Dolphin Island Gidley Island Woodside Burrup Road Water Tanks Deep Gorge King Bay South Yara West Yara North East Yara East	Konica Minolta CM-700d spectrophotometer Refer to Table 3 (CSIRO 2017a) for instrument specifications.	Analytical Spectral Device (ASD) FieldSpecPro field spectrometer	Initially, measurements based on average of 10 replicate measurements at each sampling point (CSIRO 2017a). From 2013, number of spectral measurements recorded at each sampling point increased from 10 to 21 readings (2015: n ≈ 21–23; 2016: n ≈ 21–23); and instrument detector/head in contact with sampling point was removed and then replaced after each measurement so that 21 independent measurements taken at each sampling point	Initially, measurements based on average of a minimum of seven readings recorded at each sampling point (CSIRO 2017a). In 2015, number of measurements increased to 21 to be consistent with spectrophotometer (2015: n ≈ 22–23; 2016: n ≈ 22). To minimise impact of measurements, detector/head of the ASD spectrometer (rubber) not moved (i.e. measurements collected with instrument head not removed and replaced on sampling point after each measurement) (CSIRO 2017a). These data	*Measurement impacts:* Increased number of measurements on each sampling occasion and removal/replacement of instrument detector/head between measurements might improve statistical analysis of data but may damage sampling point as repeated 21 times for spectrophotometer and 21 times for reflectance spectrometer. In 2015 and 2016, heads of Konica Minolta and ASD showed colouring, indicating instrument measurements might be affecting sampling points (CSIRO 2017a). Balance required to be found between statistical endeavor and	CSIRO (2016, 2017a)

Sampling Year	Sites	Instruments		Methods		Additional information	Reference
		Colour change	Spectral mineralogy	Colour change	Spectral mineralogy		
				to reduce sample variance introduced by surface heterogeneity or roughness and systematic error (CSIRO 2017a).	provided a measure of internal instrument variability. From 2015, instrument detector/head in contact with sampling point removed and replaced on sampling point after each measurement (CSIRO 2017a). Twenty-one independent measurements taken to reduce sample variance introduced by surface heterogeneity or roughness and systematic error. Measurements co-located with sampling points for colour measurements and acquired simultaneously.	protection of the petroglyphs.	