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

Murujuga Rock Art Monitoring Program: Conceptual models

Department of Water and Environmental Regulation

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MURUJUGA Aboriginal Corporation

Stories from the Stones

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Executive summary

The Murujuga Rock Art Monitoring Program (the program) is a five-year project that aims to develop an Environmental Quality Management Framework (EQMF) to protect one of the largest collections of petroglyphs (rock art) in the world. Petroglyphs have been created over tens of thousands of years and are of immense cultural significance. All aspects of the program will be conducted with respect for, and be guided by, the cultural law, knowledge and practices of the Circle of Elders, Traditional Owners and Custodians of Murujuga collectively referred to as Ngarda-Ngarli.

The petroglyphs were formed by engraving into the thin surface layer, the patina. These markings on the patina form an image because of the colour contrast with the underlying surface, the weathered rind. The condition of the images can deteriorate or weather over time, through a combination of natural and anthropogenic processes, including human impact such as industrial, transport, tourism, site management and all other impacts that can be attributed to human activity. The term anthropogenic can also be considered to include distal or global human activity which may impact the natural environment through changes in climate.

Natural weathering occurs through exposure to climatic variables (e.g. sun, wind and rain) and emissions from natural sources such as vegetation and fires. Weathering of the petroglyphs may also be affected by anthropogenic activity such as industrial emissions, land-use and management practices (e.g. fire and agriculture) and impacts at the global scale such as climate change. While uncoupling these effects is challenging, a key objective of the program is to consider how anthropogenic emissions at Murujuga, from sources such as industry, shipping, vehicles and changes to land management, may affect the natural weathering of the petroglyphs.

The outcomes of the program will inform the management of environmental quality in relation to air emissions, to ensure ongoing protection and preservation of the petroglyphs. This document presents the conceptual models which depict our current understanding of how emissions may affect the petroglyphs. The models will be an important communication tool for a wide audience, including the Circle of Elders, Traditional Owners and Custodians, and the general public. They will also be used to inform the scientific framework for the monitoring studies and the development and implementation of the EQMF.

The current models consist of three main elements:

- **Framework model:** provides an overview of our current understanding of the potential impact of anthropogenic emissions on the condition of petroglyphs. It includes critical interactions that will be investigated during the monitoring studies.
- **Stressor model:** a model indicating the key sources and types of natural and anthropogenic emissions and their impact on the processes on the rock surface that may influence the condition of the petroglyphs.

- **Pressure-response model and narrative:** a communication tool to convey the key elements of the program, without the need for specialist technical or scientific knowledge. It is also selected to allow easy integration with the EQMF, particularly the selected environmental indicators.

While previous studies of rock art have informed the models, significant uncertainty exists about the effect of anthropogenic emissions on the Murujuga petroglyphs. The models will be refined over years 1–3 of the program as the outcomes of the extensive monitoring studies emerge and will include additional elements that convey more detail about the dynamics of the system.

Contents

1 Background

Murujuga (also known as the Dampier Archipelago, including the Burrup Peninsula and surrounds) is in the Pilbara region of Western Australia, about 1,500 km north of Perth (Figure 1, DWER 2019a). The area is home to one of the largest and most culturally significant collections of petroglyphs in the world. The area is included in the National Heritage Listing under the *Environment Protection and Biodiversity Conservation Act 1999* (Commonwealth), a listing that recognises cultural heritage values are strongly connected to the petroglyphs. The addition of the Murujuga Cultural Landscape to Australia's World Heritage Tentative List is another important step towards international recognition of Murujuga's cultural, spiritual and archaeological significance.

The area also has an extensive industrial estate that includes natural gas and fertiliser plants and associated infrastructure, including port operations. The potential impact of anthropogenic airborne emissions on the petroglyphs lies at the heart of this program and the outcomes of the program will play a critical role in the protection of the petroglyphs and the nomination of the area as a World Heritage Site. In the context of this research, anthropogenic comprises human impact, including industrial, transport, tourism, site management and all other impacts that can be attributed to human activity. It can also be considered to include distal or global human activity which may impact the natural environment through changes in climate.

Figure 1 Map of Murujuga and key industries (DWER, 2019)

The program is a key element of the Murujuga Rock Art Strategy (DWER, 2019a), which is a partnership between the Department of Water and Environmental Regulation (DWER) and the Murujuga Aboriginal Corporation (MAC) who represent the Traditional Owners and Custodians of Murujuga. The program will follow all aspects of the Murujuga Research Protocols that have been developed by MAC as the central organisation for developing and managing all research within the Murujuga National Park, Burrup Peninsula and Dampier Archipelago (MAC 2016).

The program will monitor, evaluate and report on changes and trends in the integrity or condition of the rock art and determine whether it is being subjected to accelerated change because of anthropogenic emissions in the area (DWER, 2019b). These findings will inform the development of the EQMF that will guide the ongoing management of environmental quality in the region, with the explicit purpose of protecting the rock art and recognising the contribution this can make to maintaining cultural heritage values.

Figure 2 provides a simplified illustration of how the petroglyphs were created and an example of how they weather over time. The engravings made into the patina form an image because of the colour contrast with the underlying weathered rind. These images can deteriorate over time because of several processes referred to as ‘natural weathering’ (see Glossary). Since the industrial revolution it is likely there is also a degree of anthropogenic influence; however, this can be difficult to completely decouple or isolate.

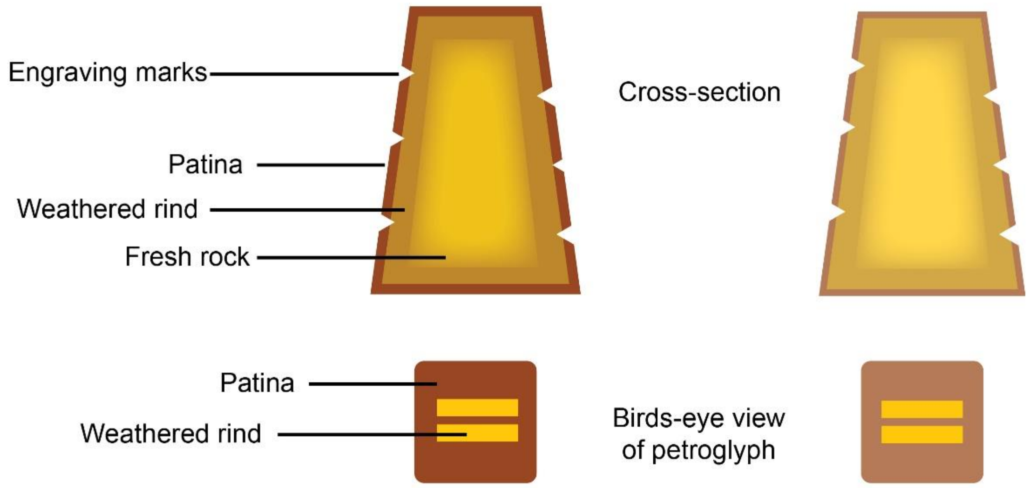

Figure 2 Example of petroglyph weathering by loss of patina

Current understanding of the rock art system at Murujuga is informed by previous studies in other locations as well as studies at Murujuga. A variety of monitoring campaigns have been conducted over the past 15 years at Murujuga in an attempt to characterise the environment in terms of air quality and the chemical and biological constituents on the rock surface, as well as assessments of selected petroglyphs using photospectrometry.

While many of these studies form useful datasets to include in subsequent analyses, in general these studies have been inconclusive or failed to show any significant impact of anthropogenic impact on the rock art or chemical/biological species composition and abundance (Commonwealth of Australia, 2018). Nor have they produced any definitive relationships to inform the conceptual model, which is instead reliant on fundamental scientific studies in other regions to inform the likely processes occurring at Murujuga (e.g. Dorn, 2020).

While much of the previous work has been well conducted, it is likely to have been impacted by insufficient sample size (Henstridge and Haskard, 2016) coupled with generally low levels of anthropogenic pollution detected (Gillett, 2010).

There are several key parts to the program including:

- development and refinement of a conceptual model or models
- monitoring studies related to anthropogenic emissions and the petroglyphs
- an ongoing monitoring program of anthropogenic emissions and the petroglyphs
- development and implementation of the EQMF (as informed by the first three points)

This report focuses on the development of the initial conceptual models. Further details related to the monitoring studies are included in the *Monitoring Studies Data Collection and Analysis Plan* (Curtin University, Puliyapang, 2020, in prep.) A glossary of terms and acronyms list is provided at the end of the document to provide definitions and additional explanation for the scientific terms and concepts.

2 Introduction to conceptual models

Conceptual models are used to summarise and communicate current understanding of complex systems and are widely used to inform monitoring programs of ecosystems (Miller et al, 2010). Given the complexity of the systems they aim to depict, they should be recognised as simplifications of reality (Henderson et al, 2016). They typically consist of a combination of elements, each with a different purpose (Gross, 2003).

The challenge of achieving both model generality and realism is discussed by Miller et al (2010). Generality refers to characterisation of the 'broad-scale influences and relationships', while realism refers to the more detailed information of change in the system that can inform the selection of monitoring indicators. Achieving this level of model realism has been 'likened to moving a magnifying glass around to focus on individual ecological systems or management issues' (Miller et al, 2010).

Given the gaps and contradictions in our current understanding of the rock art system at Murujuga, model realism is considered a challenge at this stage of the program. With the monitoring studies acting as the 'magnifying glass' to increase our understanding of the dynamic interactions between anthropogenic emissions and the petroglyphs, the outputs will lead to model realism that can better inform the selection of monitoring indicators. Consequently, the initial development of the conceptual models has focused on model generality, which aligns with the key tasks outlined below

2.1 Key conceptual model tasks as outlined in the request for tender

Years 1–3 of the program are focused on the development and refinement of the conceptual models and monitoring studies to support the design and implementation of the program in years 4–5. Year 1 is focused on informing the monitoring studies, and subsequent refinement based on the study outcomes, before progressing to the development of interim monitoring indicators in Years 2 and 3.

Year 1:

- Development of the initial conceptual models (this document).
- Documentation of the process and evidence base used to develop the conceptual models.
- Demonstration of how the conceptual models inform the monitoring studies.

Year 2 and 3: Monitoring studies

- Review and refine the conceptual models based on outcomes of the monitoring studies.
- Demonstration of how the conceptual models and monitoring studies inform the interim Environmental Quality Criteria (EQC) and the design of the program.
- Demonstration of how the conceptual models informs the development of the EQMF, including the identification of appropriate EQC.

3 Development of initial conceptual models

The initial conceptual models were developed through a series of workshops and ongoing consultations with the program team. The elements selected for inclusion in these models were guided by the Year 1 tasks and stated outputs of pictorial diagrams, narrative text and sub-models for finer representation (DWER, 2019b). The key objectives were to develop a model (or models) which could:

- communicate our current understanding of the Murujuga Rock Art System to a lay audience
- inform and demonstrate links to the monitoring studies
- show how the results from the studies will provide further input into the models that will underpin the EQMF.

Further adjustments were made in response to comments from peer reviewers.

The conceptual models consist of three elements, each with a different purpose and perspective of the Murujuga Rock Art System, as described below.

Framework model

This model provides an overview of our general understanding of the potential links between airborne emissions from a range of anthropogenic and natural sources and the condition of petroglyphs. It includes critical interactions occurring on the rock surface that will be investigated during the monitoring studies.

Stressor model

This model identifies natural and anthropogenic sources of air emissions that may result in changes to naturally occurring processes on the petroglyphs, which may in turn affect the rock art condition. The inclusion of environmental conditions and natural air emissions are necessary since the study must account for any changes in natural background sources before any observed deterioration can be attributed to anthropogenic effects.

These types of models communicate links that are likely to be directly relevant to the program, rather than a model that depicts all elements or complex dynamics of the system (Gross, 2003). As the details of the interim monitoring program, including the selection of EQC, are developed, the stressor model may be simplified to focus on the variables that are central to the EQMF. The stressor model also has the advantage of highlighting the links that will be investigated as part of this work.

Pressure-response model and narrative

The overall aim of the pressure-response model is to provide a simple visual representation of the rock art system based on the stated Environmental Quality Objective that ‘weathering of the rock art is not accelerated beyond natural rates by anthropogenic emissions’. It has been designed as a single-page communication tool to convey the overall program without the need for specialist technical or scientific knowledge. The coloured arrows provide a simple visual representation that anthropogenic emissions (the pressure) may affect natural processes that take place on the rock surface, which may in turn lead to changes in the condition of the rock art (the response).

This type of model has also been selected because the format will be useful to communicate key aspects of the EQMF yet to be developed, such as the EQC. Pressure-response models are also used to inform other EQMFs in Western Australia (Environmental Protection Authority, 2016).

The pressure-response model is supplemented by a more detailed narrative which provides a summary of the key elements of the program. This element of the conceptual model should be tested by a non-specialist audience to highlight any sections that require clarification.

4 Element one: Framework model

This element consists of an overall conceptual framework that describes key relationships in the rock art system that are of relevance to the program. A more detailed description of the key features is also provided.

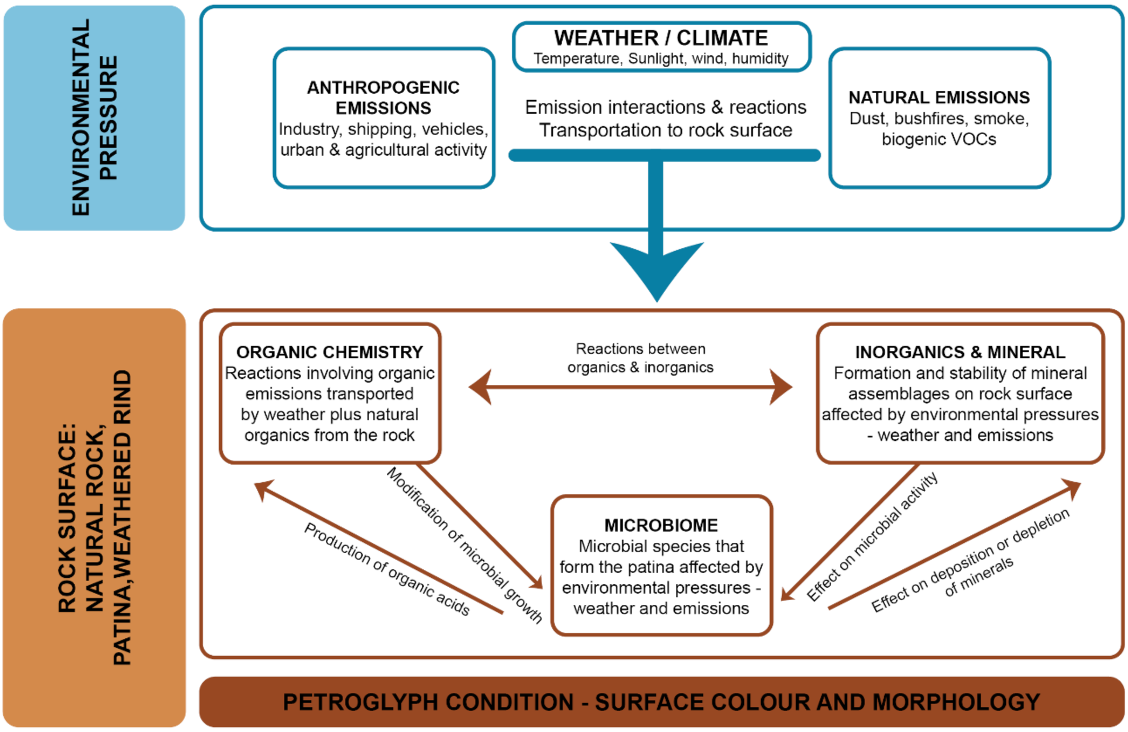

Figure 3 Framework model diagram

4.1 Environmental pressures – weather and air emissions (natural and anthropogenic)

The main environmental pressures of interest in this program are those that occur naturally (weather and natural airborne emissions) and those that occur as a result of human activities (airborne emissions from anthropogenic activities).

Air pollutants are complex mixtures of organic and inorganic particles, liquid droplets and gases. They are constantly changing in concentration, composition and distance from source through a range of physico-chemical processes (e.g. photolysis, secondary organic aerosol [SOA] formation). Air pollutants reaching Murujuga may be emitted by nearby industry, shipping, vehicles and other urban emissions, as well as natural sources (biogenic emissions, dust, bushfires) or from long-range transport from more distant sources.

There is a complex relationship between weather and air pollutants (Jhun et al, 2016). Variables such as temperature, sunlight, humidity, wind speed and direction, precipitation and inversion layer affect both the transportation (dispersion) of air pollutants, as well as influencing atmospheric chemistry (e.g. the formation of secondary pollutants and processes such as dilution and acidification (Dawson et al

2007). These variables also impact different pollutants in different ways, with higher temperatures, for example, increasing the oxidation of sulphate particles while reducing the levels of nitrate particles (Seinfeld and Pandis, 2006). Weather-related variables, such as humidity and rainfall, will also directly impact wet deposition.

Given the impact of human activity on global weather patterns broadly, it should also be noted that the impacts of human-induced climate change will likely impact natural weather conditions. It is already well established that climate directly impacts air quality, with transport, dispersion, deposition and chemistry all impacted by wind (speed and direction), temperature and humidity (Orru et al. 2017; Kinney 2008). Over time, climate change-driven effects on temperature, dew points, etc. will therefore have an impact on dispersion, atmospheric chemistry (e.g. nitrate chemistry, SOA formation), wet deposition and acidification. All of these feed into the processes which may impact rock art condition.

In addition to the complexity of the relationship between weather and pollutants – or because of this complexity – the exposure of the petroglyphs to pollutants may be very uneven. For example, it is suspected some weather conditions will allow industrial emissions to flow in very narrow plumes across the landscape, causing some rocks under the plume to be exposed to relatively high concentrations of pollutants while nearby rocks are less exposed.

There is a wide range of potential air quality indicators that will be measured at or near the rock surface, including:

- Na^+, NH_4^+, K^+, Mg^{2+}, Ca^{2+}, Cl^-, NO_3^- , SO_4^{2-} , $Fe^{2+,3+}$, pH and organic species in deposited samples
- gaseous species: ozone, ammonia, SO_2, NO, NO_2
- acid gases: HF, HCl, HNO_3, HBr, H_3PO_4, H_2SO_4
- other species and isotopes that may indicate the ratio of natural and anthropogenic sources.

We will also record weather data at the same locations, including:

- temperature
- humidity
- rainfall
- wind speed and direction.

4.2 Processes on rock surface

The organisation of the individual boxes in the bottom panel of Figure 3 indicate the connections and potential feedback between the chemical, geological and microbiological processes taking place on the rock surface. It also highlights that these may be considered as precursors to visually detectable changes. More information about changes to these processes that may occur as a result of exposure to anthropogenic emissions can inform the identification of early indicators, including EQC in the EQMF. A brief summary of each of these processes follows:

Organic reactions

As outlined above, organic compounds produced by both natural and anthropogenic processes are altered and transported by natural weathering processes. Organic geochemistry is the study of these organic compounds, their sources from natural and anthropogenic processes, and the alteration processes they undergo in the environment (Peters et al., 2005; Volkman, 2018). Organic compounds that can be traced back to biological precursors are known as biomarkers. These compounds indicate the presence of certain organisms in present or past environments, and give information on environmental conditions, climate, and the evolution of life (Brocks & Pearson, 2005; Grice & Eiserbeck, 2014). Other organic compounds cannot be linked to specific organisms but are produced by natural or anthropogenic processes such as combustion of biomass or fossil fuels (Venkatesan & Dahl 1989; Lima et al., 2005; Vitzthum von Eckstaedt et al., 2011, 2012; Karp et al., 2020). In cases where a specific organic compound may be produced from multiple sources (e.g. both natural and anthropogenic) measurement of the stable isotopic composition can be used to determine the predominant source (e.g. Hayes, 2001; Dawson et al., 2007; Grice et al., 2009; Grice & Brocks, 2011; Holman & Grice, 2018).

When organics are deposited on rock surfaces, they may combine with natural organics from the rock released by erosion or water dissolution, or produced by microbes living on the rocks (metabolites). It has been proposed certain organic compounds can influence the formation or degradation of rock patina (Perry & Kolb, 2004; Dorn 2009, 2020). The patina is also known to be host to communities of bacteria (Northup et al., 2010) and fungi (Parchert et al., 2012) which may be affected by deposited organics. Organics are known to interact with mineral surfaces (Melendez et al, 2013; Holman et al., 2014) and therefore may influence the natural degradation of petroglyphs by interaction with the patina microbiome (Macholdt et al., 2018; Rampazzi, 2019). Molecular and stable isotope techniques will be used to characterise and distinguish natural and anthropogenic organic compounds on rock surfaces, and to investigate the relationship between organics, the minerals and the microbiome.

Rock microbiome

Under natural desert environment conditions, slow-growing iron (Fe)- and manganese (Mn)-oxidising bacteria are likely to be involved in the deposition of red iron and/or black manganese oxides, which form the coloured patina. This occurs at a rate of tens of micrometres per tens of thousands of years (Liu and Broecker, 2000; Esposito et al., 2015). A study of the microbiome that colonises the rock surfaces (through the sequencing of genetic material present on the patina) (e.g. using similar approaches as described in Coolen and Orsi, 2015; Gong et al., 2018; More et al., 2019) will give an indication of both the past and present microbial communities that have lived on the patina, as well as improve our understanding of which microbes are involved with different biological processes that occur on the patina.

Our working hypothesis is that the deposition of organic and inorganic pollutants and possibly elevated CO_2 levels will trigger the formation of a highly diverse and fast-growing microbial biofilm (e.g. Kose et al., 2018). These communities are likely to produce organic acids that lower the pH to less than 4, which would result in the dissolution of the Fe and Mn oxides to reveal the lighter-coloured weathered rock below. Alternatively, the pollutants may increase the growth rate of patina-building Fe- and Mn-oxidising bacteria and/or fungi, including those that form lichens (e.g. MacLeod, 2005). These bacteria and/or fungi then start to overgrow the light-coloured carved, weathered rock. Both scenarios are likely to result in a reduced contrast between the rock art and the surrounding patina or between the rock art and the weathered rock.

Minerals

Rocks of the types that host cultural markings at Murujuga are characterised by low rates of change in response to natural weathering processes, as demonstrated by their preservation over billions of years (Colman, 1981). Exposure to air pollutants might increase the rate of change (Dorn, 2020) or alter weathering processes (Black et al., 2017). Detailed studies of the mineralogy may be able to reveal early microscopic effects of air pollution not recognisable in the field, and provide indicators of accelerated or anomalous weathering processes.

4.3 Condition of the petroglyphs

The visual characteristics of the petroglyphs are affected by the environmental pressures and the processes occurring on the rock surface. Changes to the colour and other spectral features of the patina (Schneider et al 2015; Thorn, A. 2020), the weathered rind and the contrast between them, the elemental distribution over time (Andrae et al 2020, Haugh et al 2017) and the surface morphology of the rock surface (Moses et al 2012, Earl 2011) are all important visual indicators of change. General features of the rock surface will also be documented in collaboration with the MAC Rangers (Thorn and Dean, 1995).

Appendix 1 provides examples of questions that will be addressed during the monitoring studies stage of the program and which will inform the ongoing development of this conceptual model.

5 Element two: Stressor model

This element consists of an overview of key sources of air emissions and the potential impact that increases in organic and inorganic pollutants may have on intermediary effects on the petroglyphs that may in turn lead to changes in the rock art condition.

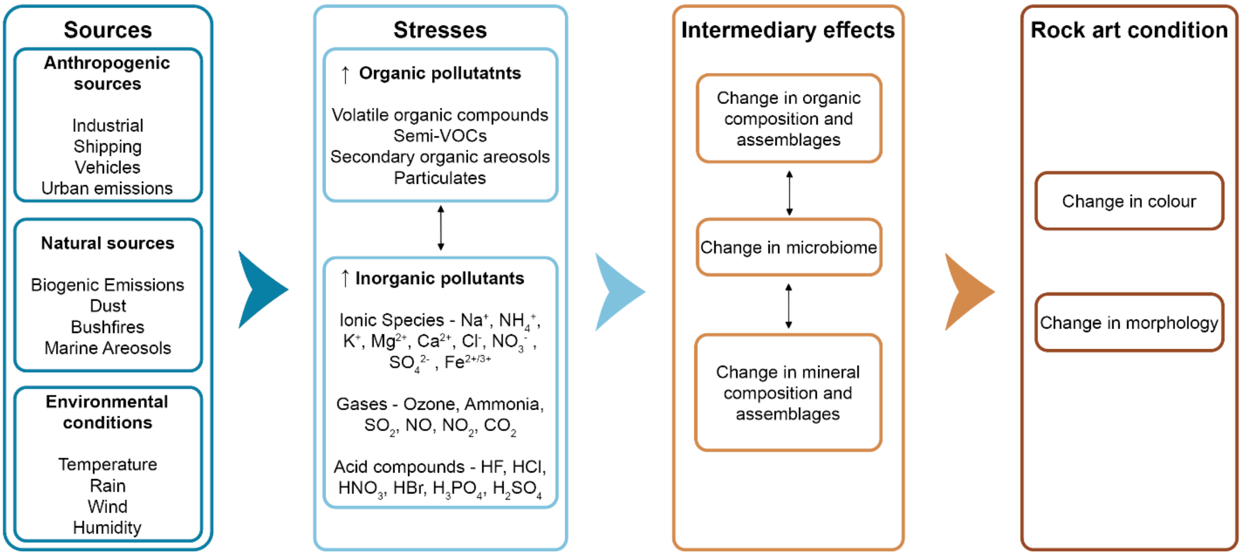

Figure 4 Stressor model

6 Element three: Pressure-response model and narrative

The Murujuga rocks are characterised by a weathered rind overlaid by a patina or mineralisation layer formed over hundreds of thousands to millions of years by reactions of the fresh rock with water, air and living organisms. The rind forms a pale layer 2–20 mm thick that is covered to varying extents by an orange, dark-brown or black patina. The patina varies in thickness from absent up to 1 mm thick. Petroglyphs have been created using techniques such as engraving or pecking to form the images we see today.

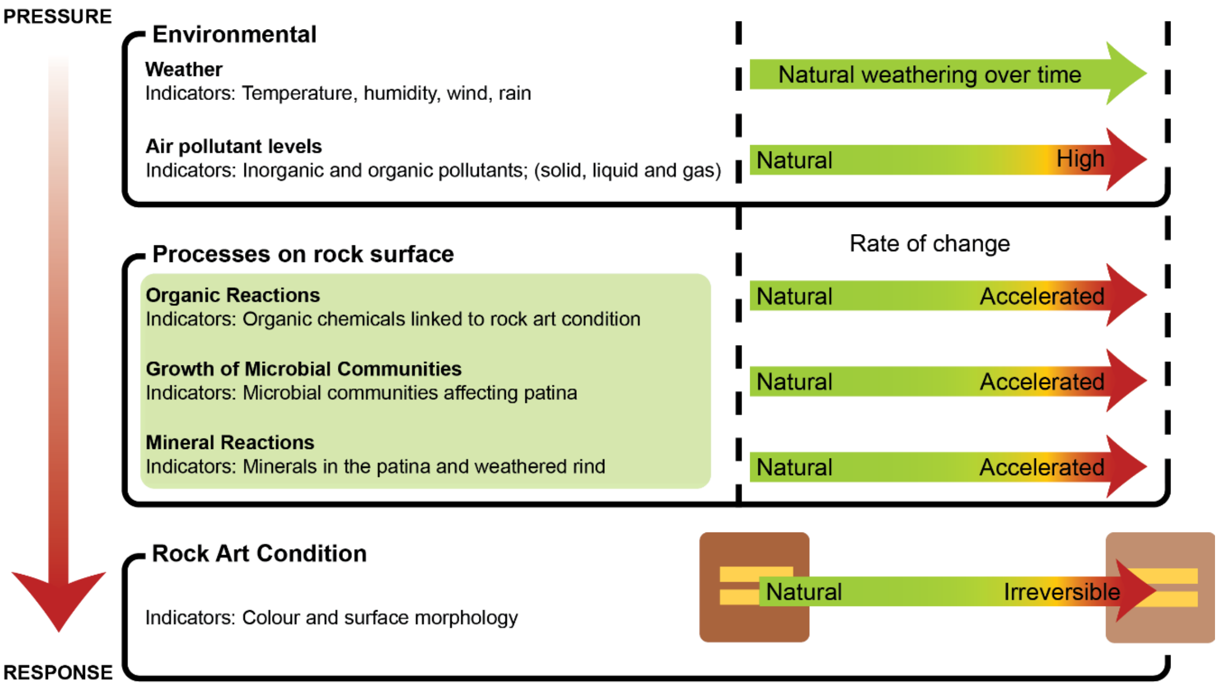

Figure 5 Pressure-response model

Environmental pressures

The condition of the rock art is affected by a number of different pressures, two of which are relevant to this model. The first is the natural weathering that has occurred over thousands of years because of geological and atmospheric weathering processes. The second pressure is from exposure to air pollutants. Natural pressures include those from sources such as gases from plants, dust (e.g. from the land or terrain) and bushfires. Anthropogenic sources include those from human activities such as industry, shipping, traffic and tourism. These human activities have expanded significantly over the past few decades, resulting in increases in both the level and type of air pollutants that are emitted. This change is represented by the arrow gradually changing from green (natural levels) to red (high levels). The pollutants include different types of chemicals in either solid, liquid or gas form that are transported across the area by wind and dispersion. The compounds can be altered through the effects of environmental variables such as temperature, sunlight and moisture in the atmosphere. The compounds may then be deposited on the surfaces of the rock where they can influence a range of processes that may impact on the condition of the rock art.

Processes on rock surface

As described above, the surface of the rock represents a dynamic system that has evolved over thousands of years. The processes taking place on the surface are depicted by the three central arrows. The green end represents the natural state of processes affected by natural weathering and natural air emissions. The rate of change in these natural conditions is very slow. The transition to red indicates that the air pollutants deposited on the rock may result in changes to these processes that may contribute to accelerated weathering of the rock art. Each of the processes are connected and explained below.

- *Organic reactions* **–** organic compounds are produced by both natural and human processes. As they are deposited on the rock surface, they may combine with natural organics from the rock that are released by erosion or water dissolution. Organics can also interact with minerals and the microbial communities to contribute to the natural weathering of the rock art. The organics can be used as a source of food for organisms living on the rock. All of these processes can be altered as the type and level of organic pollutants on the rock surfaces and in the surrounding air increases.
- *Growth of microbial communities* **–** microbial communities such as bacteria and fungi have lived on the rock surface for thousands of years. These organisms grow very slowly and contribute to the formation of a biofilm and the coloured patina. The increase in air pollutants may favour different microbial communities that not only outgrow the communities that contribute to the formation of the patina, but also produce acids that dissolve the existing patina. Alternatively, the pollutants may stimulate the growth of existing microbial communities, which can also change the condition of the existing patina and rock surfaces.
- *Mineral reactions* **–** under natural conditions, the different minerals present in the rock and rock surfaces change slowly. However, exposure to air pollutants can alter the minerals that normally occur and result in the presence of short-lived or unstable minerals. In turn, the change in the mineral composition on the rock surface can affect the microbial communities, as well as the type and rate of chemical reactions taking place.

Rock art condition

The above pressures and processes combine to determine the overall condition and appearance of the rock art. Any effect on the colour of the patina or weathered rind affects the contrast that is critical to the visual appearance of the petroglyphs. As well as natural weathering that can affect the colour over thousands of years, variations to colour can also occur because of the seasonal flux in the growth of microbial communities. The surface condition of the rock can also be affected by these pressures, including granular loss and formation of salts. Our key interest in this system is to determine if the anthropogenic emissions accelerate the natural change in the composition of the rock to cause a reduction in the quality of the rock art condition.

7 Element four: Pictorial representation

The final element is a pictorial representation of the key aspects of the rock art system. It is supported by the text from the framework model. This element will also be tested with a range of audiences and updated accordingly.

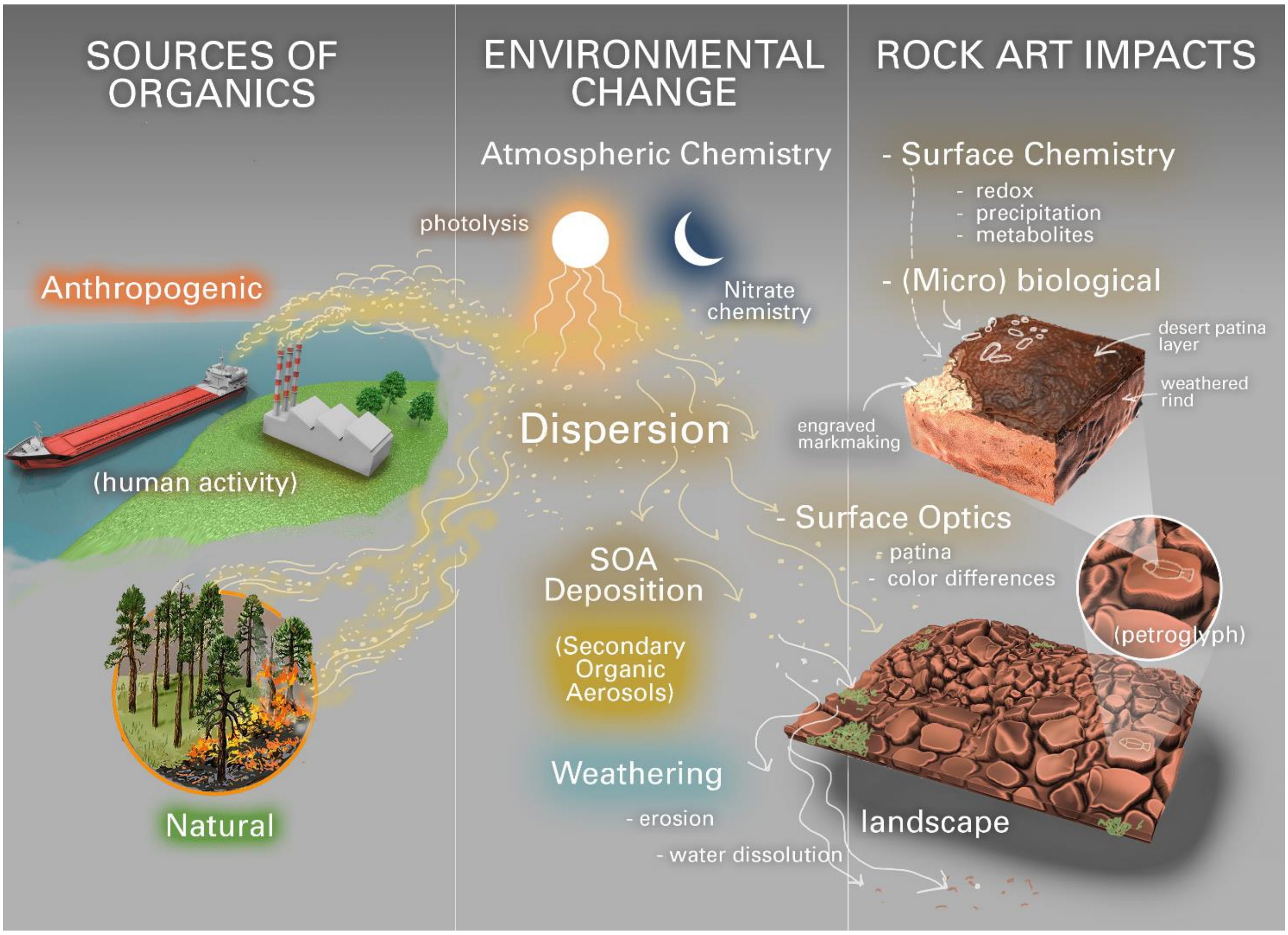

Figure 6 Pictorial representation of rock art system

8 Role of conceptual models in overall program

The role of the conceptual model across the phases of the program is summarised in Figure 7. The initial conceptual models presented in this report are informed by the review and synthesis of existing data, as well as the boundaries set by the Request for Tender (DWER, 2019b). These models will inform the design of the monitoring studies components, as reflected by the sample questions provided in Appendix 1.

Outcomes from the monitoring studies will be used to refine the conceptual models, including the development and integration of the interim EQC that will then be tested throughout a trial monitoring period. In the final step, the findings from the monitoring studies will inform the development of the final EQMF.

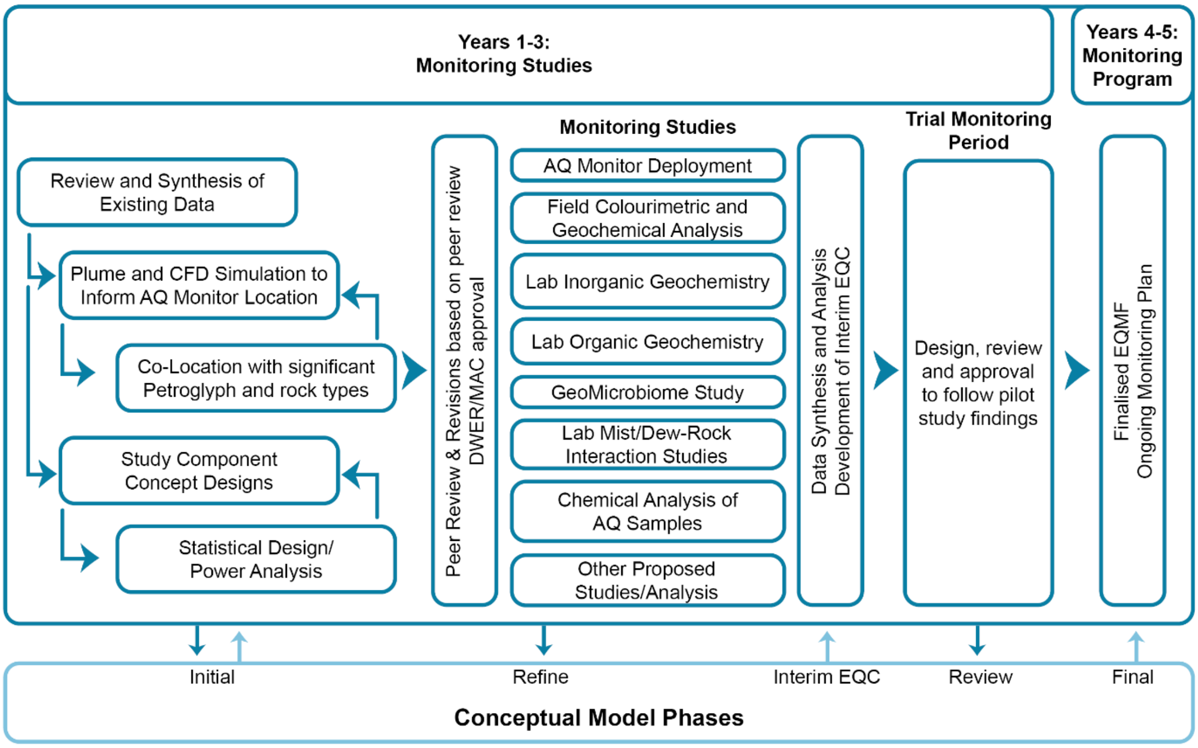

Figure 7 Relationship between the conceptual models and other elements of the program

9 Conclusion

The conceptual models presented here have been guided by the EQO that 'weathering of the rock art is not accelerated beyond natural rates by anthropogenic emissions'. Embedding the EQO and other aspects of the EQMF in this version of the models will help to ensure ongoing development of the conceptual models clearly serves the objectives of the Murujuga Rock Art Monitoring Program.

The collaborative process of developing the models has led to a greater shared understanding among the program team of the respective aspects of the system and elements of the program. The models will continue to act as an overarching framework to guide discussions and investigations over the course of the program with the ultimate aim of contributing to the EQMF for the Murujuga Rock Art System.

Appendices

Appendix 1 — Sample questions linked to the monitoring studies

Environmental pressures
• Which pollutant species are the most relevant? It is generally believed that acidification (acids formed from nitrogen and sulfur oxides and ammonia) are likely to be the dominant mechanism affecting the rock art; however, this may be incorrect. • Are long-term averages or transient peaks of air pollutants more important? Noting that measurement of real-time peak values is challenging. • To what extent do mist/dew events concentrate air pollutants in mist droplets and hence on rocks? • Does environmental or iron ore dust play a role in petroglyph weathering? Dust is a known carrier of bacteria, but the rock microbiome itself is not likely to be iron limited.
Overarching questions – Framework model
• What is the nature/state of each process under natural weathering? • How does exposure to different anthropogenic emissions change the processes and interactions? • What are the types of reactions taking place on the rock surface? • What is the relationship between the organics, the minerals and the microbiome? • What are the impacts of these effects on the condition of the petroglyphs?
Processes on the rock surface
• What are the different sources, types and proportions of organics and minerals present on the rock surface? • What are the organic components and their stable isotopic ratios in the various source end members? • Which bacteria and fungi are involved in stabilising and/or dissolution of the patina? • Which environmental parameters (if any) trigger the development of acidic microbial biofilm that causes the dissolution/degradation of the patina? • Which environmental parameters trigger the development of patina-building bacteria that cause an accelerated overgrowth of the rock art? • What are the threshold concentrations of the pollutants that could degrade or overgrow the patina? • How do the minerals on the rock surface relate to the composition of the atmosphere and water that formed them?

• How do the minerals relate to the microbiome? • How are the minerals related to the colour and surface roughness?
Petroglyph condition
• To what extent is colour change occurring and are the colour changes trending in a natural direction (mineralisation) or in an altered direction (dissolution)? • What are the changes to the surface condition at the microscopic scale? • How are the non-visual changes occurring on the rock surface related to the visual condition of the rock art?

Shortened forms

AQ	Air quality
DWER	Department of Water and Environmental Regulation (WA)
EQC	Environmental Quality Criteria
EQMF	Environmental Quality Management Framework
EQO	Environmental Quality Objective
MAC	Murujuga Aboriginal Corporation
SOA	Secondary organic aerosol

Glossary

Anthropogenic – from human activity. In the context of this research anthropogenic includes human impact, including industrial, transport, tourism, site management, and all other impact that can be attributed to human activity. It can also be considered to include distal or global human activity which may impact the natural environment through changes in climate.

Biomarkers – organic compounds produced from natural degradation of biochemicals produced by living organisms. The structure of a biomarker can sometimes be linked to a biochemical produced by a specific organism or group of organisms, while others are more general. They are known as ‘molecular fossils’ as they can be used to infer the presence of certain organisms in ancient environments.

Dispersion – the spreading out of emissions from a localised source (e.g. industry stack, wildfire) over a wide area because of the effect of wind.

End member – a pure chemical compound (/mineral) component entering into solid solution with other pure chemical compounds to form a series of minerals.

Environmental Quality Criteria (EQC) – scientifically-based limits of ‘acceptable’ change within an EQMF.

Environmental Quality Management Framework (EQMF) – a framework to guide the assessment and management of activities related to a particular environmental value.

Environmental Quality Objective (EQO) – a specific management goal for a designated part of the environment that signals the level of environmental quality needed to protect the environmental value of an EQMF.

Environmental Value (EV) – a beneficial use or an ecosystem health condition which requires protection from the effects of emissions or environmental harm.

Microbiome – an integrated community of micro-organisms (bacteria, archaea, unicellular eukaryotes and fungi) occupying a particular habitat.

Microbial metabolites – breakdown products of larger complex organic compounds that the microbial communities use as energy sources and for growth.

Mineral assemblages – the presence and abundance of mineral species in a given spatial region (either across the rock surface or from the rock surface to the ‘fresh’ rock below the outer weathered rind.

Murujuga – Ngarluma-Yaburara name referring to land and sea country comprising the Burrup Peninsula and surrounding islands of the Dampier Archipelago.

Petroglyph – literally ‘rock mark’; describes any cultural marking into a rock surface. The marks can be produced by a range of techniques, including pecking, pounding, incising, scratching or abrading, or a combination of two or more techniques. Techniques such as scratching can be very shallow (<1 mm), while pecking can be 100 mm or more deep.

Patina – In the Murujuga context the texture and colour of the rock surface is referred to as a patina. This is a deliberately broad definition, which encompasses other characterisation such as rock varnish or desert varnish, including any biota which may be present on the rock surface. The patina has been shown to form over a depletion zone, referred to as the crust, which generally has a lighter appearance than both the patina and the underlying rock. An engraving is formed by breaking through the naturally formed patina to expose the lighter crust beneath. There may be cases where the engraving has exposed the underlying rock, which may result in a darker engraved channel.

Photospectrometry – An instrumental technique for measuring the chromatic reflectance of a surface by scanning at frequencies that cover the visible spectrum and beyond. Photospectrometry provides both a single value colour designation and spectral data that can indicate non-chromatic change. The technique has been applied to both the measurement of change and the characterisation of unknown minerals and compounds.

Photolysis – the process by which molecules are broken into small fragments by exposure to sunlight (typically UV radiation)

Secondary organic aerosol (SOA) – solid organic molecules produced in the atmosphere by the reaction of smaller, gaseous organic molecules with oxygen (and often ozone and UV/OH radicals).

Stable isotopes – atoms of the same element which contain a different number of neutrons in the nucleus. Most elements consist of more than one stable isotope, the ratios of which can be measured using specialised instrumentation. Stable isotope ratios in organic compounds are affected by the processes of formation and alteration, hence their measurement gives information on source and alteration history.

Weathered rind – the outer portion of the rock that is sufficiently close to the surface to have interacted with oxygen or other environmental conditions. This layer is significantly thicker than the layer forming the patina and has different colouration to the underlying fresh rock (core).

Weathering – in the Murujuga context the concepts of weathering are differentiated as natural weathering and accelerated weathering/potential degradation. However, these effects may be difficult to decouple.

- **Natural weathering:** the alteration of a rock surface through natural agents such as the impacts of temperature cycles and interactions with water and aerosols/gases released by the surrounding terrestrial and marine environments. Weathering can be subtractive (erosion) or additive (mineralisation or accretion).
- **Accelerated weathering:** because of anthropogenic (human) activity and not to be considered as natural weathering.

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