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THE SURVIVAL OF THE MURUJUGA (BURRUP) PETROGLYPHS

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Abstract. The industrial development on Burrup Peninsula (Murujuga) in Western Australia is briefly outlined, and its effects on the large petroglyph corpus present there are described. This includes changes to the atmospheric conditions that are shown to have been detrimental to the survival of the rock art. Effects on the ferruginous accretion and weathering zone substrate on which the rock art depends for its continued existence are defined, and predictions are offered of the effects of greatly increasing pollution levels that have been proposed. The paper concludes with a discussion of recent events and a call for revisions to the planned further industrial development.

Introduction

The Burrup is an artificial peninsula that used to be called Dampier Island until it was connected to the mainland in the mid-1960s, by a causeway supporting both a road and rail track. In 1979 it was re-named after the island's highest hill, Mt Burrup. This illustrates and perpetuates the common practice in the 19th century of ignoring eminently eligible existing names of geographical features in favour of dull and insipid European names. Usually such features were renamed after surveyors, their wives, some general or regent or anyone else who came to mind to someone at the time. In the case of Mt Burrup, and ultimately the 'Burrup peninsula', it was named after one Henry Burrup, a 19th century bank clerk in Roeburne.

The traditional Aboriginal name of the island/peninsula, Murujuga, has historical precedence and should not be erased by colonial or post-colonial attempts to negate or ignore previous history. Moreover, in view of the Flying Foam Massacre (in 1868), when twenty-six Yaburara were murdered on the islands in a raid by Europeans, it seems even more inappropriate to erase their few preserved place names. That massacre was intended to be a reprisal for the spearing, in self-defence, of a police officer. The policeman had tracked a lone Yaburara warrior who managed to ambush him in the central part of Murujuga, at a location shown to me.

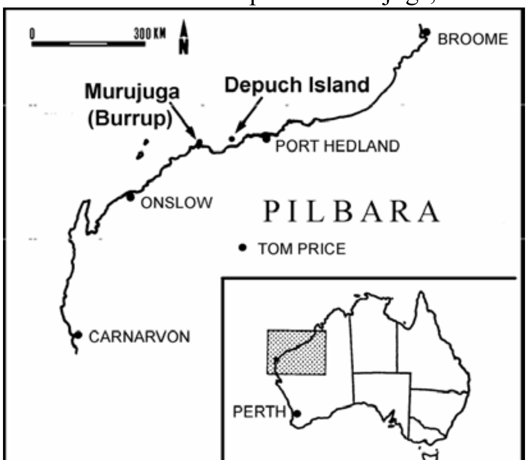

Figure 1. *Location of the Pilbara region.*

The Yaburara were the ethnographic group that traditionally occupied most of the Dampier Archipelago (Fig. 1) and the adjacent area of the mainland. Their language was closely related to that of the Ngaluma (or Ngarluma), the neighbouring major group (Tindale 1974). Their rather apt name of the island, Murujuga, means 'hip bone sticking out'—no doubt a reference to the boulder piles that dominate the island's landscape. I shall use this name henceforth and invite others who wish to similarly express their respect for Aboriginal history to do the same.

The petroglyphs of the Murujuga peninsula have been considered to constitute the largest gallery of such rock art in the world, although estimates of numbers of motifs have differed considerably, ranging up to Lorblanchet's (1986) excessive suggestion that there are 500 000 petroglyphs. Except for visits by whalers, pearlers, turtle hunters and navigators, this massive concentration remained unknown until the 1960s when some 570 sites, the majority of the sites known today, were located and examined by me. Systematic scientific study of any Pilbara rock art had only begun a few years earlier, with the expedition by the Western Australian Museum to Depuch Island in 1962 (Ride and Neumann 1964). Pilbara rock art has been known to Europeans for at least 162 years, and if the interpretation of an inscription in the Abydos region is correct, since before the arrival of James Cook on the east coast (Bednarik 2000). American whalers reached the west coast of New Holland first in the 1790s (probably the *Alliance* and *Asia*, both from Nantucket; pers. comm. S. M. Frank, New Bedford Whaling Museum). At the latest by 1840, the Americans had established a whaling station in the Dampier Archipelago. The first published reports of Pilbara rock art are those of Wickham (1843) and Stokes (1846: 166–77), recording the visit of Depuch Island by *H.M.S. Beagle* in 1840. The crew of that ship left at least three inscriptions behind. Capt. Wickham took a particular interest in the petroglyphs and Stokes republished his illustrations. Much earlier, in 1688, buccaneer Capt. William Dampier, after whom the Dampier Archipelago is named, visited the north-western coast and may well have seen rock art, but in his very brief account about Australia (under 2500 words) he makes no mention of it. Dampier named Rosemary Island in 1699. The first published mention of Murujuga rock art seems to be a very brief comment by Stow (1881).

Rock art in a few other parts of the Pilbara received some attention from the late 19th century onwards (Richardson 1886; Withnell 1901; Fox 1939; Petri 1954; Petri and Schulz 1951; Davidson 1952; Worms 1954; McCarthy 1961, 1962). These studies were the result of brief visits, most of them considered three specific areas (the site complexes of Port Hedland, Depuch Island and Abydos), and most provided no ethnographic information. The first study of Pilbara petroglyphs that made any use of scientific methods of investigation was the work of Ride and Neumann (1964), most especially the geomorphological study contained in it (Trendall 1964). This important study was in fact prompted by a proposal in 1961 to construct a deepwater port for loading iron ore on Depuch Island. The recommendations of the Museum's team effectively led to the abandonment of this plan, and to developing instead the loading facilities at Dampier during the mid-1960s—where no survey work at all had taken place prior to 1967. The fact that there was much more rock art in the vicinity of the Dampier facilities than on Depuch was conveniently overlooked by the developers, presumably to avoid further involvement of the Western Australian Museum. This is therefore the moment in the history of the Murujuga petroglyphs when their preservation became the subject of policies driven by developers rather than public authorities, and it is significant to note that this was the result of a deliberate cover-up. It has remained developer-driven to the present time, as recent consequences outlined by Vinnicombe (2002) and here below illustrate.

During the 1960s, Wright (1968) became the first researcher to conduct broadly based inter-site studies over a wide section of the Pilbara region, and thus to define this distinctive rock art province. My own study of Pilbara petroglyphs, commenced in 1967 (Henderson 1969; Bednarik 1973) and still continuing (Bednarik 2002a), differs from previous work in the region in various aspects. It is a long-term project that initiated archaeological studies in north-western Australia, with the first excavation undertaken in the continent's entire north-western quadrant (Bednarik 1973, 1977), but it soon focused on extracting scientific (1979) and ethnographic information (1998a: 26). Wanting to place Pilbara rock art into an archaeological context rendered it essential for me to focus particularly on the question of its antiquity, because rock art can only become an archaeologically meaningful resource if its age is known. From 1968 to 1970 I provided a series of progress reports of my findings to the Western Australian Museum, but this was after the development work on Murujuga had commenced and led to no action to effect protection of the rock art. The 570 sites I recorded during this period were defined in accordance with the convention then established by the Centro Camuno di Studi Preistorici in Italy: a concentration that is separated from any other by a minimum of 50 m of area free of any rock art. Therefore the number of sites I defined is necessarily very much smaller than numbers reported in later work by W.A. Museum personnel.

A great deal of rock art was destroyed on the peninsula during the 1960s, especially in and around the initial town site and industrial estate of Dampier (Bednarik 1973, 1977). For instance, all of the coastline from the town to east of Parker Point was bulldozed and filled in, including several petroglyph concentrations. Among them were a major site on which the power station was erected in 1965–67, and concentrations at the site of the pelletising plant, conveyer systems and ship-loading facilities. Smaller sites fell victim to the construction of roads, rail tracks and buildings. The developments in the hills of western Murujuga, where the access road to the causeway connecting Mistaken Island was constructed in 1969, also resulted in the destruction of major petroglyph concentrations. In that year the first brief inspection by the W.A. Museum personnel occurred, but it was not until many years later that the first proposals for detailed investigations and for the preservation of the rock art began to appear (Wright 1974, 1979, 1980, 1982; Clarke 1979, 1980). By the time the immediate physical destruction through development abated, in the mid-1980s, I estimate that between 20% and 25% of the original population of petroglyphs on Murujuga had been destroyed. Almost 1800 decorated boulders were removed from their historical context near Withnell Bay and deposited in a fenced enclosure near Hearson Cove (Vinnicombe 1987). Thus some of the motifs I photographed in the 1960s no longer exist, or have been taken from their location. Nevertheless, others remain at their original sites and have not been damaged physically.

They are the basis of my ongoing monitoring program on the peninsula. This effort remains the only such program ever undertaken on Murujuga, and can fairly be described as the only attempt of seeking an acceptable solution to the management issues the rock art faces—acceptable in the terms of international standards for preserving heritage sites of such significance. The fact that this initiative was entirely funded and conducted by an independent scholar for the past thirty-five years illustrates the level of neglect of what amounts to the largest single cultural heritage site complex of Australia. In relation to this matter, millions of dollars of public money have been squandered on hundreds of consultants, lawyers, advisers, spin doctors and so forth, without producing any tangible outcome for the heritage in question. As of March 2002, there is no plan of management for the peninsula (Carpenter 2002) almost forty years after development commenced, no impact study has ever been attempted by the authorities responsible for the protection of the rock art, and no authority exercises any control over the rock art outside the lease of Dampier Salt. My endeavours to win support for a World Heritage nomination of the peninsula (e.g. Bednarik 1994a, 1994b, 1995, 1998b) have found no support from government agencies, archaeological lobbies or anyone else. My numerous requests to government agencies of Western Australia and also to three ministers of the federal government for a comprehensive management plan for the rock art, from the late 1960s to the present time, have led to no such initiative. Nor have the endeavours of others, such as Bruce J. Wright and Warwick Dix, to highlight the plight of the rock art led to any tangible measures, however minute (for a summary of this scandalous neglect, see paper by Vinnicombe, this issue of *RAR*). Similarly, the efforts of the conservationist group *Friends of the Burrup*, an NGO based in Karratha, to effect changes to the Burrup Peninsula Draft Land Use and Management Plan of 1994 (which contained no reference to the rock art) were to no avail. My proposals have consistently listed the following initiatives (e.g. Bednarik 1994a):

1. Nomination of the peninsula to World Heritage status.
2. The return of all untenanted land to the surviving Aboriginal communities, perhaps with a proviso that they lease part of it as a National Park to the Commonwealth.
3. The permanent installation of a rock art ranger, who should have full jurisdiction over any rock art on leased land, besides assisting the managers of the conservation zone and liaising with traditional custodians.
4. That the perpetual conservation and cultural integrity of this enormous cultural asset be safeguarded and supervised by a federal government agency of scientific repute, preferably the Institute of Aboriginal and Torres Strait Islander Studies.

The recent decision by the state government to grant permission to several companies to greatly extend the industrial complex on Murujuga was made without consideration of the natural and cultural heritage of the peninsula, having been made without an impact study of these developments and without the formulation of a comprehensive management plan. Subsequent to the granting of licenses, attempts have been made in recent months to evaluate the effects of the proposed expansion. I have examined a draft report and discussed aspects of the matters at hand with two consulting firms, only to discover that these consultants lack the necessary knowledge and means to comply with their professed briefs. They have no specific knowledge of rock art deterioration or its alleviation, they lack the means of assessing the impact of the proposed development on the rock art (other than to cite data from publicly available sources, such as those of environmental protection agencies and the Commonwealth Scientific and Industrial Research Organisation, or the National Pollutant Inventory of Australia), and they conduct no site visits or studies. Their reports are created in an information void, lacking any petrographic, geomorphological, geochemical or archaeological depth. The employment of such non-specialists in helping to decide matters concerning the survival of rock art should be of concern in Australia, a country that has expended considerable public resources on training rock art conservation specialists (Watchman 1989). The lack of transparency in the consulting process, the pattern of haphazard and ad hoc utilisation of relevant knowledge and data, the dependency of consultants on their corporate or political masters—all of the circumstances surrounding this 'culture of consultancies' render the process inadequate and its results largely flawed. Truly independent specialists or specialist bodies are either not consulted at all, or only in a most cursory fashion, even though their advice comes at no cost to the client bodies. It is necessary to bring these unpalatable conditions out into the open, because ultimately the neglect of threatened rock art, such as that on Murujuga, is largely attributable to them—here and elsewhere in the world. The endless succession of corporate, inexperienced and competitive consultants who lack long-term commitment and liability is the principal cause for the kinds of problems a corpus of rock art such as this one finds itself in. Instead of resolving conservation or management problems, this system tends to aggravate them because of the piecemeal approach it engenders, and particularly because the contributors and shapers of policies are reduced to acting in a vacuum of relevant knowledge.

Political and corporate decision makers need to appreciate that the consulting industry they rely upon often lacks the expertise to provide sound advice. In many cases better and much more independent advice can be obtained from relevant NGOs (most particularly IFRAO and its members), it is usually available free, and this certainly applies in the particular field of rock art research, conservation and management.

Industrial development on Murujuga

The first industry established on Murujuga were the iron ore processing (pelletising plant) and ship loading facilities of Hamersley Iron Pty Ltd at Parker Point and near Kangaroo Hill, which commenced production in 1966. The town Dampier and other service structures were constructed between 1964 and 1968. During the 1960s, the damage occasioned to Murujuga rock art was significant, but it was limited to physical damage. The level of air-shed pollution was initially negligible and largely limited to mineral dust. Nevertheless, subsequent expansion in 1971, at East Intercourse Island, increased the emission of particular matter, which now stands at 13 000 t/yr and is of concern. Moreover, Hamersley's emission of NO_x has risen to 440 t/yr by 2000-01 (NPID 2001) and is set to rise further.

Dampier Salt Limited constructed its salt production facilities between 1969 and 1971, Also destroying rock art in the process. However, its air pollution remains at low levels, although contributions of NO_x and SO_x is of some concern. Dampier Salt is the only company operating on Murujuga that adheres to a rock art protection program.

Subsequent to the discovery of major offshore deposits of natural gas in 1971, plans to install a gas processing plant on the peninsula led to an archaeological survey and salvage operation (Vinnicombe 1987). In practical terms this meant that Woodside Offshore Petroleum Pty Ltd chose its preferred site and then simply directed the archaeologists it hired to clear it of rock art-bearing boulders. There is no indication that Woodside was at that stage advised that its emissions might pose a threat to the rock art. This omission was the second fatal turn of events from the perspective of rock art preservation on the peninsula, and it illustrates the flaws of this client-driven 'consulting system'. This is because once an industry has been established in a vulnerable environment, it is extremely difficult and costly to have it relocated elsewhere, and future expansion plans are unlikely to find much opposition. Woodside is today by far the greatest polluter on Murujuga, or indeed in Western Australia. Its 231-ha-plant at Withnell Bay now emits 5 500 000 t/yr of greenhouse gases (CO_2 equivalent), 5800 t/yr of NO_x (primarily NO_2, which forms nitric acid in the atmosphere, a highly reactive oxidising agent), 120 t/yr SO_x (mostly as SO_2, forming sulphurous acid, H_2SO_3), and massive quantities of hydrocarbons (benzene, methylbenzene and xylenes total 4500 t/yr) (NDIP 2001).

These gaseous emissions are of great concern, but they are certainly dwarfed by those to be expected from the currently proposed expansion of the industrial complex on Murujuga. The various projects that have government approval will produce a combined output of at least 23.76 million tonnes of CO_2 per year (and that excludes the very substantial contribution by two desalination plants, which I could not ascertain). This represents an increase of 197% on the current level of 8 million tonnes for the entire complex. The overall pollution is thus proposed to be more than trebled. Of the total land area of the peninsula, 38% is to be occupied by industry. This industry has at present no obligation of avoiding the rock art concentrations in its siting of facilities, it is only concerned with aspects of convenience. It has learnt from previous experience that the legislative protector of the rock art, the Western Australian Ministry of Indigenous Affairs, lacks the political will to properly discharge its legislative responsibility (*Aboriginal Heritage Act* 1972) for the cultural heritage. Developers are encouraged by government subsidies currently standing at 221 million dollars of taxpayers' money. The Minister for Indigenous Affairs has made it clear that further wholesale removal of decorated rocks will take place where necessary, and that matters of heritage protection will be taken care of by the developers (Carpenter 2002: 1).

To perceive the scale of the increase in pollution in a proper perspective it must be considered that the proposed expansion of the Murujuga industry will amount to an increase of greenhouse gas emission of about 28% of the gross state emission (R. Chapple, pers. comm.). This highly concentrated industrial estate will add 28% to the greenhouse gas production of the entire state of Western Australia, an area almost a third the size of the U.S.A. But in addition to the carbon dioxide, the production of other and more potent contributors to atmospheric acidic pollution will also increase sharply. Emission of nitrous/nitric oxides will more than double, with just six of the proposed developers predicting an NO_x emission of 12 140 t/yr. This is almost three times the entire production of NO_x in the region of Perth, a large metropolitan area with extensive industry, which stands at 4800 t/yr. Greatly conflicting predictions are available for SO_x, but whichever estimates one chooses to believe, they all predict a significant increase. These gases result primarily from combustion of the natural gas on which all of these industries are based. The proposed polluters include the following present and future contributors: Austeel Consortium (iron ore processing), Burrup Fertilisers Pty Ltd (ammonia plant), Dampier Salt Limited (solar salt production), GTL Resources Plc (methanol), Hamersley Iron Pty Ltd (iron ore processing), Japan DME NKK Corp. (dimethyl ether), Methanex Australia Pty Ltd (methanol complex), Pinebrook Holdings Pty Ltd (hydrocarbon storage), Plenty River Corporation (ammonia and granulate urea plant), Syntroleum Sweetwater LLC (synthetic hydrocarbons plant), W.A. Water Corporation (desalination plants), Western Power Corp. (power generation), Woodside Offshore Petroleum Pty Ltd (gas treatment plant) (R. Chapple, pers. comm. March 2002). Five of these companies propose polluting emissions in the multi-million-tonnes/year range, of which four are new players, and the fifth wishes to increase production by two-fifths.

This significant expansion of industrial capacity over the next few years, reputedly at a cost exceeding $8 billion, is proceeding without any form of impact study. No investigation has been attempted to consider the impact on air quality for the populations of the nearby towns Dampier, Karratha and Roebourne, nor has the impact on the terrestrial or marine environment of the Dampier Archipelago been considered. The rock art or other cultural heritage assets of the Archipelago have never been subjected to a comprehensive study over the almost forty years of industrial development on Murujuga, and no records exist to indicate their distribution over the land area, except in specific designated areas (as listed by P. Vinnicombe, this issue of *RAR*). A management plan of the Archipelago and its assets has never been attempted, let alone formulated. Consequently there has not been any need for the corporate interests to consider alternative siting of the chemical industry complex. Bearing in mind that the coastal hinterland of the region consists of many tens of thousands of square kilometres of flat, featureless and essentially vacant spinifex plains, it is particularly difficult to understand why this complex should need to be located in such a small area next to towns and major heritage sites. Moreover, the Maitland Heavy Industry Estate on the mainland has been available for several years as an alternative site. Murujuga and the nearby area offers no natural freshwater deposits, whilst substantial aquifers and surface exposures of water occur along the Millstream River, some 50 or 60 km inland. It is clear that the planning of these ventures is inadequate, short-sighted and far too precipitate.

The high concentration of atmospheric pollution on Murujuga leads to deposition of emission products on the rock surfaces of the peninsula and nearby areas. In this region, with its average of only 30 days of rainfall per year, perhaps in the order of 90% of the fall-out is likely to occur as 'dry deposition' of gases and airborne particles. This forms a complex deposit of inorganic and hydrocarbon-derived substances on the rock surfaces. Nitrates would certainly be present and they promote microbial activity, which is likely to have secondary effects on the patination crust. 'Wet deposition' refers to the precipitation of acids formed in the atmosphere, by reactions between usually gaseous emissions and water. The main contributors of this 'acid rain' are sulphuric, sulphurous, nitric and carbonic acids, but there are also minor concentrations of organic acids, such as formic acid (derived from formaldehyde formed through conversion of isoprene by hydroxyl radicals which is then oxidised to HCOOH) and oxalic acid (derived from photochemical reactions). Murujuga industry emits now 91 tonnes of volatile gaseous hydrocarbon compounds, and that rate, too, is proposed to be more than trebled in the next few years.

Atmospheric precipitation on Murujuga is often heavy and cyclone related, averaging 261 mm per year. It has a dual effect at the interface between atmosphere and lithosphere. Arriving as an acidic solution it combines readily with the acidic pollution solids already deposited on the rock surface in preceding weeks or months, mobilising cations from most of the constituents of the dark-brown mineral crust present on the rock and flushing the solution products from the surfaces. Thus the mostly dry climate of the region provides no relief, it merely compounds the precarious conditions for the natural crust by permitting the build-up of dry atmospheric deposition. These cycles will inevitably lead to the complete removal of the surface patination and ultimately to the chemical erosion of most component minerals of the substrate. While its quartz will remain unaffected and its biotite only marginally etched by sulphuric acid (Acker and Bricker 1992), the hornblende, plagioclase (primarily of sodium species on Murujuga), orthoclase and especially augite will yield to the acids and a significant acceleration of physical weathering will be the inevitable outcome.

Deterioration of Murujuga petroglyphs

The rock art of Murujuga consists largely of percussion petroglyphs and most is assumed to have been made by direct impact (Bednarik 1998a, 2002a). For the purpose of considering their preservation, the petroglyphs can conveniently be divided into two types.

The *sgraffiti* are shallow petroglyphs, made chiefly by bruising the dark-brown mineral accretion covering the peninsula's extensive boulder piles. (A sgraffito motif was made by selectively removing differently coloured layers. Elsewhere such motifs were commonly made in cement render on building facades or on ceramics.) This treatment has removed the ferruginous accretion, which covers nearly all rock surfaces in the Pilbara, and exposed the whitish or buff weathering zone (sometimes called cortex) beneath it. The resulting sharp colour contrast forms the pounded or pecked designs, which possess almost no relief. Over a period of some millennia they repatinate gradually, first to a light-brown colour, and eventually the new patina matures to the dark colour matching the surrounding rock surface. At that stage the petroglyph design becomes practically invisible, due to its lack of depth. This process of repatination has attracted considerable interest for more than 180 years (Belzoni 1820: 360–1) and although its quantitative utilisation remains experimental, it is certainly a function of age and thus of great analytical importance. Recently the repatination state at some eastern Pilbara petroglyph sites has been calibrated against a series of engraved dates spanning more than two centuries (Bednarik 2000, 2001, 2002a).

The second basic type of petroglyphs we encounter on Murujuga consist of *deeply pecked designs*, which may be well in excess of 10 mm deep, but which most commonly have groove depths of between 5 mm and 12 mm. These relief petroglyphs may or may not have been hammered into patinated substrates, taking advantage of the structurally slightly weakened weathering zone. They, too, repatinate, but because of their relief they retain some degree of visibility, even though a fully repatinated deep design may be somewhat difficult to detect visually.

The ubiquitous dark-brown, sometimes orange or almost black and 'metallic' patinae found on Murujuga are attributable to a variety of processes. Alteration products, especially from the oxidation of cations present in the host rock, have contributed, but there are also secretionary deposits (leached cations precipitated on the surface) and accretionary deposits (derived from aeolian particles or precipitated by water, sometimes through the agency of micro-organisms). The best-known of the latter form is rock varnish (Engel and Sharp 1958) but I emphasise that whilst this does occur on the peninsula, it is quite wrong to extend the term, as archaeologists have done, to all ferruginous accretions found on Murujuga. Most are the result of more than one contributing process, and before commenting on their nature, or on what they indicate in archaeological terms, it is essential to conduct detailed microscopical examination of these patinae.

It was in fact in response of this need and during my early work at Dampier that I developed an appreciation of the need of using field microscopy in rock art studies (Bednarik 2001: 164–7). Since developing this methodology over a period of almost thirty-five years I have found it indispensable, yet amazingly I remain the only rock art scientist in the world who regularly uses field microscopy (for well over twenty years I have not been to a rock art site without a microscope).

This work has provided me with the means of a long-term study of the surface condition of Murujuga petroglyphs, particularly of the state of the patinae covering and surrounding them. My early analytical publications on rock patination were based largely on my geomorphological and geochemical work on the Murujuga peninsula, where I sought to identify the processes forming the vast boulder piles dominating the topography and analysed their patinae and weathering zones (Bednarik 1979). These huge accumulations of dark-brown patinated igneous clasts resemble glacial moraines. They have been incorrectly termed 'screes' (cf. Ollier 1969: 215; Bednarik 1979: 33), and provided that climatic connotations were ignored they could be defined as *Felsenmeere* (Bednarik 1979: 17). The Murujuga rock is commonly described as a granophyre, and while this is valid in part, the peninsula offers considerable diversity of igneous rocks, including dolerite, granodiorite, quartzdiorite, rhyodacite, diorite, gabbro and occasionally granite. These and related types of rocks represent not distinctive entities, they grade into one another, and their names are merely abstractions. For instance quartzdiorite, dacite and quartzporphyrite have the same components and in similar proportions, the differences are simply that one formed deeply in the magma, the two others are porphyric (formed near the surface), one being of original crystal structure, the other metamorphosed. On the other hand, diorite and gabbro formed both deeply, but gabbro contains much more augite, at the expense of plagioclase, and is almost free of quartz. There is a continuum between the two, their separation is purely arbitrary, and the same applies to all Murujuga facies.

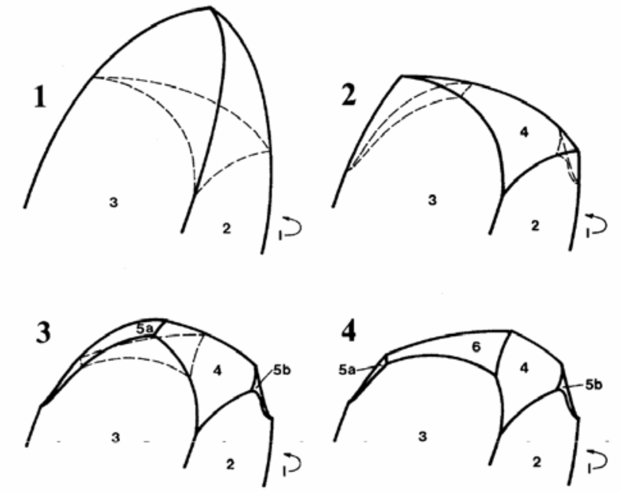

Figure 2. *Schematic depiction of the spalling process affecting the boulder piles of Murujuga. The sequence of reduction is documented by the preserved fracture facets, which in the case of decorated boulders facilitates the limited establishment of a relative chronology of the petroglyphs.*

When freshly broken, most of the rocks exhibit a bluish to greenish-grey colour. The spalling process the boulders are subjected to is non-random, it strives to achieve a rounding of angular forms: acute edges and projecting portions are detached by insolation stress, exposing convex facets. Figure 3 is an idealised depiction of this spalling process, which results in boulders bereft of angularity until they fall victim to *Kernsprung* or, less commonly, to lightning strike, enabling the cycle to begin anew. The facets are of greatly varying ages, and their chronological order can be established from their morphology (in the same way as knapping facets on stone tools are sequenced), their relative patination (the darkest facet is the oldest) and the relative thickness of their weathering zones (so thicker it is, so older the facet it covers). Significantly, any petroglyphs present on such facets can be temporally slotted into the sequence of spalling events, i.e. they can be dated relative to that chronology, which in turn can be accessible to numerical dating methods (Bednarik 1979; 2001: 61–6).

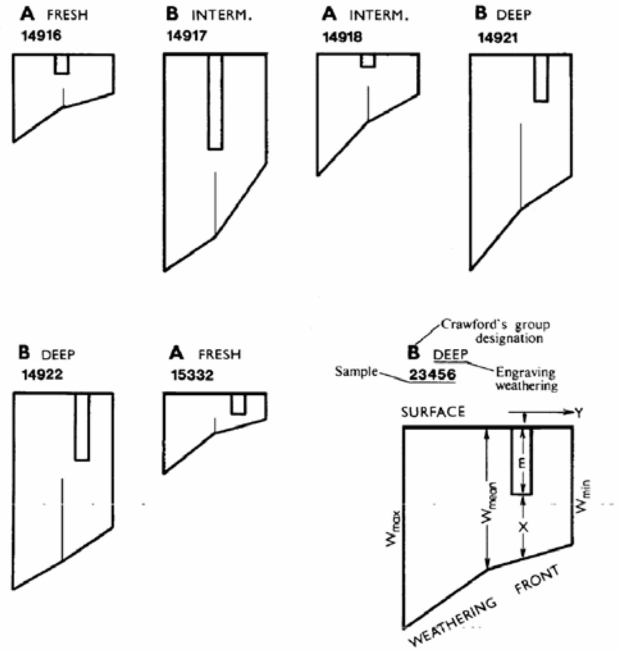

Figure 3. *Schematic depiction of the relationships of weathering depth (W_{max}, W_{mean}, W_{min}), pecked groove depth (E), weathering zone thickness under pecked groove (X) and position of groove depth relative to weathering depth (Y), using the sample of Trendall (1964).*

The last-mentioned variable, weathering zone thickness, can only be measured by drilling (although the use of the Schmidt hammer could be considered as a non-destructive alternative; cf. Bednarik 2001: 119), as conducted by Trendall (1964) on nearby Depuch Island and by myself at Dampier. Such data are most effectively presented by the graphic method I proposed (Bednarik 1979), as depicted in Figure 4. The importance of these data is illustrated by the documented difficulties of archaeologists in understanding the relationships between petroglyph groove depth, weathering zone thickness and rate of repatination. It is also of great importance to appreciate the type and composition of the patina, which can vary considerably. The ubiquitous reddish-brown patination of the entire Pilbara region is generally neither a purely intrinsic alteration product nor entirely an accretion, it is a combination of the two. On the dolerites, the magnetite component takes under a century for an initial crust of iron oxides and hydroxides to form in situ, but on the iron-poor facies there is only limited inherent potential for the development of alteration products. The accretionary matter is selectively deposited, sometimes its distribution is determined by aeolian factors, and its microscopic morphology is closely related to whether the support surface is vertical or horizontal. Distinctively 'laced' or 'terraced' morphologies are common, suggesting the involvement of re-precipitation processes. Under adequate magnification (>60×), the accretionary matter often reveals a diversity of airborne materials, including widely transported mineral grains and charcoal detritus, and this is caked together mostly by iron salts and amorphous silica. These deposits have been found to form fairly consistently as a function of time. An incipient film becomes microscopically evident after a surface has been exposed for 30–40 years, and after about 100 years, the patchy deposit can locally reach a thickness of 30–50 microns (µm). However, on granite such deposits remain often so discontinuous that fracture surfaces that have remained exposed can usually be found on all but the very oldest rock art motifs.

Thus the ubiquitous rock patinae on Murujuga are most effectively defined as heterogeneous ferromanganeous crusts. Like rock varnish itself, which has often contributed to their formation, they form in the near-neutral conditions that are found especially in arid and semi-arid regions (hence the former term 'desert varnish'). From the rock art researcher's point of view, the crust has three crucial functions: it provides the colour contrast between the petroglyph motifs and their fully patinated background, it assists in the protection of the substrate (usually an inherited weathering zone) from erosion, and it can provide several types of quantifiable variables that are by some considered to assist in estimating the age of the rock art concerned (e.g. organic carbon inclusions, bulk chromatic data, cation ratios). This patina is highly susceptible to even minor downward fluctuations in ambient environmental pH, especially in the range from pH 7 to 6. Its crucial iron cations occur generally as goethite, haematite, lepidocrocite and similar salts, and the solubility of iron increases about 100 000-fold through a lowering of pH from 8.5–6.0 (Ollier 1969: 28; Bednarik 1979: 25). Much of this change occurs in the pH 7–6 range, which represents a ten-fold increase in acidity. The abrasion pH values of the Murujuga rocks fall generally between pH 8 and 10—augite, olivine and hornblende providing the highest values, of about pH 10—and granophyre and similar rocks typically lack acid neutralising capacity. The alkalinity of the environment is strikingly illustrated by the peninsula's substantial travertine layers, which can be up to a metre thick. They are the result of carbonate solution from the rock substrate, indicating how rock surfaces were in the past regularly buffered by saturated bicarbonate solutions. The overall natural rain pH of the Pilbara was in the order of pH 6.8 prior to industrial development, and reached about pH 7.0 to 7.2 at Murujuga. It now averages about pH 6.5 for the

Pilbara, but is probably significantly lower at Murujuga (no current values are available to me as it did not rain during my recent surveys there).

It is relevant to note that in the Kimberley, a rock art region that typically lacks the ferruginous crusts of the Pilbara, the rain water ranges from pH 4.5 to 5.0, which is precisely the reason for the absence of such crusts in that region. In central Australia, the acidity of the rain is comparable to that of the Pilbara, and ferruginous crusts are widespread. To provide a comparison, the atmospheric pollution of the Hunter Valley in New South Wales has led to rain water fluctuating seasonally between pH 4.9 and 5.2, while that of the Latrobe Valley in Victoria ranges from pH 5.4 to 6.4.

The effects of a reduction in ambient pH on the crusts can readily be illustrated by a common natural process of buffering with weakly acidic solution. Local erosion of the ferruginous crust occurs throughout the Pilbara where particular elevated points on boulder piles are favoured perching sites of birds, especially large birds of prey. Their droppings are slightly acidic (Bednarik 1979: 30 reports pH 5.9; see also MacLeod et al. 1995: 61), but perhaps they also attract micro-organisms that facilitate further cation mobilisation. Such patches are usually free of crust, and erosion of the substrate can also be evident in them. Lightning strikes, too, can affect the patina, sometimes 'bleaching' the brown deposit or even converting it to a light-green colour (this can occur at extremely high temperatures; R. Connick, pers. comm. 1988), besides yielding the typical surface glazing of silicas and peculiar fracture patterns.

The effects of the introduction of massive industrial pollution on the Murujuga mineral crusts can be readily demonstrated from the data collected over the past thirty-five years. My monitoring program suggests limited and barely quantifiable changes to the integrity of the iron-rich mineral crusts between the commencement of my observations in late 1967 (i.e. prior to the effects of the environmental changes) and 1988 (i.e. shortly after the liquefied natural gas facilities at Withnell Bay began production). However, between 1988 and 2001 there was a marked change, observable and quantifiable both at the microscopic and macroscopic level. Microscopically, the deposition of airborne solids varies locally, but is not as prominent as expected from the known volume of emission of particulate matter (<10 μm), 14 000 tonnes per year (NPID 2001). More than 90% of this derives from the ore processing and loading facilities. More noticeable is the selective removal of salts from the crust, most particularly oxides and hydroxides of iron. The degree of this 'bleaching' can vary considerable on a single boulder facet. Where this is most developed, the crust has become superficially friable, its amorphous silica skeleton has become more prominent. The terraced and 'laced' microscopic formations often present on such deposits show signs of degradation. The effect can be quantified as a reduction of mass that varies from <5% to around 30%. Clearly, some surface aspects are far more susceptible than others, and research into what factors account for these differences is of the highest priority as it could form the basis off palliative intervention.

At the macroscopic level, the degradation is much more readily quantifiable, particularly through the application of the calibrated colour monitoring system established by IFRAO in the 1990s (Bednarik and Seshadri 1995). This can eliminate all distortions of the photographic process and re-constitute original colour information at the time a photograph was taken. Moreover, it converts these data into mathematical matrices that provide a precision significantly exceeding the human ability of discriminating between colours. Since this methodology has become available I have begun to apply it to the extensive photographic record I have compiled of Murujuga rock art since 1967. The initial results show little or no changes to patina bulk colour up to 1988, but a clear change of both chroma and value in the years since 1988. In referring to the Munsell Charts, chroma decreases numerically while value increases consistently as a function of time, at the Murujuga motifs so far sampled. However, the degree of change can vary greatly over a single panel or motif. I have been unable to confidently attribute these variations to readily identifiable conditions, such as inclination, exposure, crust thickness or orientation. It is again apparent that research into the factors that may accelerate or retard the removal of crust is of vital importance to determining the feasibility of delaying the rock art deterioration process.

Nevertheless, even the limited data now available do permit a first quantified glimpse of the patina degradation, which is important in creating a predictive model of future effects. Figure 5 presents the first colorimetric data matrix, derived from four panels so far surveyed. This was constructed by determining the change on twenty-four reference points and calculating average values from them. In each case, an aliquot of thirty-six pixels (six by six pixels) was randomly selected from a digitised image (re-constituted where the required device profile had been included), and its location in the colour space determined. When plotted as a function of time, the fading towards the buff colour (expressed as an increase on the RGB values towards 256) of the substrate revealed a distinct trend over recent years. A proposition was then made that the predicted trebling of acidic gaseous emissions over the next few years would result in a corresponding three-fold intensification of the destruction of the ferruginous veneer. In Figure 5, curve (*c*) attempts to predict the deterioration if emissions continued at their present level, which the model predicts would result in the disappearance of those petroglyphs that depend on colour contrast for their visibility (i.e. the sgraffiti) during the second half of the 21st century. Alternative curve (*d*) attempts to predict the effects of the proposed trebling of emissions and suggests that the shallow petroglyphs will disappear between about 2025 and 2035. Under these conditions, the fully exposed substrate will have commenced disintegration by the middle of the century, which is likely to lead to extinguishing almost the entire corpus of rock art by the end of the present century.

Discussion

The destruction of protective mineral accretions or substrate by 'acid rain' caused by major industrial development is of course not a newly appreciated phenomenon, it is particularly well known in Europe and North America (Winkler

1973). In Australian rock art conservation, the influence of acidic rain has so far been largely ignored (e.g. Rosenfeld 1985), perhaps because it was considered negligible. As the most arid continent bar Antarctica, Australia has a high-ambient-pH regime, which has greatly facilitated the preservation of rock art. Clarke (1978), however, does deal with industrial pollution in the Pilbara, estimating that it has increased site destruction at the Port Hedland limestone ridge tenfold. The effects of atmospheric emissions on rock art have been investigated especially in Scandinavia (Åberg et al. 1999; Coles 1992; Michelsen 1992; Walderhaug 1998; Walderhaug and Walderhaug 1998), where the lowering of precipitation pH is often largely attributed to atmospheric pollution originating in Britain. The rainwater pH of 4.0–5.5 at the Begby and Litseby sites, for instance, is directly related to atmospheric SO_2 and NO_2 levels (Löfvendahl and Magnusson 2000: 54). Scandinavian researchers emphasise the role of 'throughfall', which is the rainwater that is charged by dry pollution deposited in the tree canopy, an issue that is not relevant in the Pilbara. In the low vegetation density typical for Murujuga, the dry deposition occurs largely direct on the rock surfaces.

The experience in Saudi Arabia, where I work currently (Bednarik 2002b), is perhaps more relevant to the situation in the Pilbara. Not only is the deterioration of rock art due to pollution from major industrial installations attributable to very similar types of emissions as those in Murujuga, that region is even more arid and thus very susceptible to an increase of air-shed acidity. Moreover, Saudi efforts to preserve rock art are comparable in magnitude to those of most Australian states—Western Australia being the conspicuous exception. This brings us to the perhaps most pertinent issue: the practice of the Western Australian government, being after all responsible for the 1964 establishment of the Murujuga industrial estate in the first place, to consistently abrogate its responsibilities under the *Aboriginal Heritage Act*. In the years since then it has left the protection of the rock art entirely to the corporate interests operating on Murujuga. It has never produced a management plan for the natural or cultural environmental assets of the Dampier Archipelago, nor has it ever presented an independent impact study, or commissioned a study of the condition of the rock art—clearly the most significant heritage component of the area. In fact this government, which by legislation is charged with the protection of the rock art, has made no attempt even to create an inventory of the Dampier rock art. Most of the archipelago has not been surveyed systematically, even though it has been known for over three decades that it contains in all probability the world's largest concentration of petroglyphs. In Australia, a country that prides itself in possessing the greatest treasure of traditional art in the world, and that looks after this asset in all other states, this neglect is particularly perplexing. It seems to be the outcome of a an embarrassing coincidence: this art treasure happens to coincide geographically with a favoured site for a harbour, and any mention of it reminds the culprits of the 1960s of their complicity in the destruction of the rock art. If the harbour had then been located somewhere else, the present proposal of enlarging the industrial estate would be of no concern, Marajuga would still be an island and would now be part of a National Park with World Heritage listing.

Instead we have the unfortunate state of affairs defined here and by Vinnicombe (2002), and a government that continues to avoid taking charge of it. In his most recent letter to me, the Minister of Indigenous Affairs states:

> Each aspect of a [future] comprehensive environmental impact assessment will be reviewed and audited periodically. The process is proponent driven [i.e. driven by the industrial developers]. … The proponent uses best practice environmental management; expert advice is sought from appropriate government agencies … if a condition is inadequate, it is corrected … the performance of environmental impact assessment in protecting the environment is examined, and improved (Carpenter 2002: 2).

This breathtaking naivety seems to confirm that the Minister lacks the means of complying with his brief of protecting the state's rock art, and he quite explicitly nominates the Department of Environmental Protection as the authority supposedly monitoring the activities of the developers, i.e. he passes on his responsibility to another department. In response to my question, will there be any further destruction of rock art sites by removal of decorated boulders, he advises:

> [I]f development is unable to modify the location of infrastructure, some material may be salvaged for relocation (Carpenter 2002: 1).

He is, however, subsequently contradicted by the Premier of Western Australia, who on the subject of boulder relocation says this:

> The approach is to avoid damage to sites by modifying the location of infrastructure and to minimise the impacts wherever possible (Gallop 2002: 2).

In his subsequent paragraph, Dr Gallop MLA provides a hint of the kind of positive measures that will be adopted:

> These plans include workshops and awareness raising for contractors and site staff about existing [rock art] sites and the finding of new material (Gallop 2002: 2).

So here at last is an indication of how the government hopes to instil some token awareness in the employees of the developers and perhaps even find some new sites from time to time, by recruiting the developers' staff and contractors for site locating surveys. We can visualise the occasional incident when a bulldozer driver finds a cluster of decorated boulders in his path and, recalling that great awareness raising event the other day, pushes them gently into a neat pile for salvage.

The Egyptian government would not tolerate any plans to erect a petrochemical plant next to the pyramids of Giza, the French would never quarry the limestone containing Lascaux Cave for building blocks, and the Taliban of Afghanistan would never dream of dynamiting a monumental Buddha statue. Western Australia lacks the ancient structures of the Old World, but it has cultural heritage sites rivalling in value those anywhere else. Some of its Pilbara petroglyphs are three times older than the ages of the Pyramids, Lascaux art and the Buddha figure added together. They were created by the oldest living culture on earth, and these timeless sentinels are trenchant reminders of the transience of our own society and culture. By comparison to these witnesses of our ephemeral existence the cultural works we, the invaders of this continent, have managed to erect in Western Australia—our museums and statues and

Lang Hancock's mansion—are worthless trinkets.

In Europe it may be difficult to avoid exposing rock art to acid rain, geographically and demographically. In the Pilbara, with its vast coastal hinterland plains, it is entirely unnecessary to install the state's greatest polluter at precisely the same location as the world's greatest concentration of petroglyphs. Bearing in mind the vastness of the country (Western Australia is four times the size of Texas), it is perverse to insist doing this with such tenacity. Much more sensible solutions are clearly available, and they involve either no or negligible additional expense. It appears that the state government is not aware of the range of options available to it, that it is badly advised, and that there is a need for a truly independent advisory body on these and other aspects of the Pilbara cultural heritage. There is 'no neutral agency to act as referee, and no authority to assess the broader picture and make informed provision for the future' (Vinnicombe 2002), the government seems captive to the advice of powerful corporate interests and the consultancy industry these interests exercise control over. Clearly there is a need for independent advice, even for advice weighted in favour of the rock art.

Such an advisory body should receive no monetary reward for its activity (to ensure its impartiality), it should be better familiar with the rock art and its preservation than the consultancy industry, and it should be capable of providing advice on world-best practices. It should also combine the views of the local indigenous communities as well as the conservation movement generally, locally and abroad. In an effort to create such a corpus I have proposed to the Western Australian government that a small committee be formed, whose members would be honorary and unpaid. It would comprise one representative each from the Roebourne indigenous community, a Green politician, a senior AURA delegate, a senior representative of IFRAO, a rock art archaeologist and a conservation scientist. This seems to be the most constructive measure to break the vicious cycle of neglect that has characterised the management of Murujuga rock art for the past four decades. It is hoped that this can lead to more carefully considered policies and to amicable solutions to the issues Patricia Vinnicombe and I have canvassed here.

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Résumé. *Le développement industriel de la presqu'île de Burrup (Murujuga) en Australie-Occidentale est d'abord brièvement retracé, et l'on expose ses effets sur l'important ensemble de pétroglyphes qui s'y trouve. Ce développement a entre autres provoqué une modification des conditions atmosphériques, et l'on montre ici que cette modification a eu un effet désastreux sur les conditions de conservation de l'art rupestre. On décrit les effets sur les dépôts ferrugineux et sur le substrat de la zone d'altération superficielle, effets qui conditionnent en totalité les possibilités de survie des figurations rupestres. On précise les conséquences prévisibles dans le cas de niveaux de pollution notablement accrus, tels que ceux qui sont envisagés. L'article conclut par une discussion des événements récents et appelle à une revision des plans du développement industriel futur.*

Zusammenfassung*. Die industrielle Entwicklung der Burrup Halbinsel (Murujuga) in Westaustralien wird kurz umrissen, und ihre Wirkungen auf das dortige große Petroglyphenvorkommen werden beschrieben. Dies schließt Änderungen zu den atmosphärischen Bedingungen ein, von denen gezeigt wird, daß sie für das Überleben der Felskunst schädlich gewesen sind. Wirkungen auf die eisenhältige Ablagerung und Verwitterungs-Substrate, von denen die Felskunst für ihre weitere Existenz gänzlich abhängt, werden definiert, und Aussagen der Wirkungen wesentlich vergrößerter angekündigter Verunreinigungsniveaus werden vorgelegt. Der Aufsatz schließt mit einer Diskussion jüngster Ereignisse und einem Aufruf für Revisionen zu der geplanten weiteren industriellen Entwicklung.*

Resumen. *El desarrollo industrial en la Península Burrup (Murujuga) en Australia Occidental es brevemente presentado, y sus efectos en el vasto conjunto de petroglifos existentes allí son descritos. Esto incluye cambios en las condiciones atmosféricas que se demuestra han sido perjudiciales para la sobrevivencia del arte rupestre. Efectos en los acrecentamientos ferruginosos y en el substrato de la zona de desgaste por exposición a la intemperie de la cual el arte rupestre depende totalmente para su continua existencia son definidos, y se ofrecen pronósticos de los efectos de aumentos grandes en los niveles de polución como ha sido propuesto. El artículo concluye con una discusión sobre eventos recientes y un llamado para revisiones de posteriores planes de desarrollo industrial.*

REFERENCES

ÅBERG, G., E. M. DAHLIN and H. STRAY 1999. Impact of pollution at a Stone Age rock art site in Oslo, Norway, studied using Pb and Sr isotopes. *Journal of Archaeological Science* 26: 1483–8.

ACKER, J. G. and O. P. BRICKER 1992. The influence of pH on biotite dissolution and alteration kinetics at low temperature. *Geochimica et Cosmochimica Acta* 56: 3073–92.

BEDNARIK, R. G. 1973. Wohnhöhlen bei Tom Price (Nordwest-Australien). *Die Höhle* 24: 140–5.

BEDNARIK, R. G. 1977. A survey of prehistoric sites in the Tom Price region, northwestern Australia. *Archaeology and Physical Anthropology in Oceania* 12: 51–76.

BEDNARIK, R. G. 1979. The potential of rock patination analysis in Australian archaeology – part 1. *The Artefact* 4: 14–

BEDNARIK, R. G. 1994a. Dampier rock art under siege. *AURA Newsletter* 11(2): 14–15.
BEDNARIK, R. G. 1994b. Dampier petroglyphs under siege. *The Artefact* 17: 79.
BEDNARIK, R. G. 1995. Radio interview on ABC Radio, concerning planned industrial development on Burrup Peninsula, on 25 January 1995.
BEDNARIK, R. G. 1998a. The technology of petroglyphs. *Rock Art Research* 15: 23–35.
BEDNARIK, R. G. 1998b. Radio interview on ABC Northwest, concerning theft and destruction of rock art, on 25 November 1998.
BEDNARIK, R. G. 2000b. Earliest known Historical rock art in Australia. *Rock Art Research* 17: 131–3.
BEDNARIK, R. G. 2001. *Rock art science: the scientific study of palaeoart*. IFRAO-Brepols, Turnhout.
BEDNARIK, R. G. 2002a. About the age of Pilbara rock art. *Anthropos* 97: 201–15.
BEDNARIK, R. G. 2002b. The Saudi Arabian rock art mission of November 2001. *Atlal* (in press, in Arabic).
BEDNARIK, R. G. and K. SESHADRI 1995. Digital colour re-constitution in rock art photography. *Rock Art Research* 12: 42–51.
BELZONI, G. 1820. *Narrative of the operations and recent discoveries within the pyramids, temples, tombs and excavations in Egypt and Nubia*, Vol. 1. London.
CARPENTER, A. 2002. Letter of the Minister for Indigenous Affairs to the author, 20 March 2002.
CLARKE, J. 1978. Deterioration analysis of rock art sites. In C. Pearson (ed.), *Rock art conservation*, pp. 54–64. Institute for the Conservation of Cultural Material, Sydney.
CLARKE, J. 1979. Dampier Archaeological Liquefied Natural Gas project: a survey for Aboriginal sites: quarry, communications station and access roads. Unpubl. report, W.A. Museum, Perth.
CLARKE, J. 1980. Dampier Archipelago Liquefied Natural Gas Project. A survey for Aboriginal sites in the vicinity of a proposed access road Dampier to King Bay, W.A. Unpubl. report, W.A. Museum, Perth.
COLES, J. M. 1992. The dying rocks. *Tor* 24: 65–85.
DAVIDSON, D. S. 1952. Notes on the pictographs and petroglyphs of Western Australia and a discussion of their affinities with appearances elsewhere on the continent. *Proceedings of the American Philosophical Society* 96: 78–117.
ENGEL, C. E. and R. P. SHARP 1958. Chemical data on desert varnish. *Bulletin of the Geological Society of America* 69: 487–518.
FOX, D. C. 1939. Einige Bemerkungen über die Felsbildkunst der Ungarinyun. Die Frobenius-Expedition nach Nordwest-Australien 1938–39. *Frankfurter Wochenschau* 29.
GALLOP, G. 2002. Letter of the Premier of Western Australia to the author, 2 April 2002.
HENDERSON, S. 1969. Slowly the Pilbara yields its art treasures. *Daily News* 10 February: 9.
LÖFVENDAHL, R. and J. MAGNUSSON 2000. Research and development – degradation and care. In K. Kallhovd and J. Magnusson (eds), *Rock carvings in the borderlands*, pp. 47–72. Interreg IIA Project, Bohuslän /Dalsland and Østfold.
LORBLANCHET, M. 1986. Comment on F. Soleilhavoup, 'Les paysages de l'art rupestre de plein air'. *Rock Art Research* 3: 82–3.
MCCARTHY, F. D. 1961. The rock engravings of Depuch Island, north-west Australia. *Records of the Australian Museum* 28: 121–48.
MCCARTHY, F. D. 1962. *The rock engravings at Port Hedland, north-western Australia*. Papers of the Kroeber Anthropological Society 26, University of California, Los Angeles.
MACLEOD, I. D., P. HAYDOCK and E. CHARTON 1995. Avian guano and its effects on the preservation of rock paintings. In A. Thorn and J. Brunet (eds), *Preservation of rock art*, pp. 60–64. Occasional AURA Publication 9, Australian Rock Art Research Association, Melbourne.
MICHELSEN, K. 1992. Conservation of rock art in Norway. *Arkeologiske skrifter fra Historisk Museum, Universitet i Bergen* 6: 17–52.
NPID 2001. National Pollutant Inventory Database. Environment Australia. *http://www.environment.gov.au/epg/npi*
OLLIER, C. D. 1969 (revd edtn 1975). *Weathering*. London.
PETRI, H. E. 1954. *Sterbende Welt in Nordwest-Australien*. Kulturgeschichtliche Forschungen 5, Limbach.
PETRI, H. E. and A. S. SCHULZ 1951. Felsgravierungen aus Nordwest-Australien. *Zeitschrift für Ethnologie* 76: 70–93.
RICHARDSON, A. K. 1886. The Nickol Bay tribe. In E. M. Curr (ed.), *The Australian race*, Vol. 1, pp. 269–301. Government Printer, Melbourne.
RIDE, W. D. L. and A. NEUMANN (eds) 1964. *Depuch Island*. Special Publication 2, The Western Australian Museum, Perth.
ROSENFELD, A. 1985. *Rock art conservation in Australia*. Special Australian Heritage Publication Series 6, Australian Government Publishing Service, Canberra.
STOKES, J. L. 1846. *Discoveries in Australia during the voyage of H.M.S. Beagle in the years 1837-38-39-40-41-42-43*, Volume 2. T. and W. Boone, London.
STOW, J. P. 1881. *The voyage of the* Forlorn Hope *from Escape Cliffs to Champion Bay 1865*. Sullivan's Cove, Adelaide.
TINDALE, N. B. 1974. *Aboriginal tribes of Australia*. Australian National University Press, Canberra.
TRENDALL, A. F. 1964. Examination of rocks with Aboriginal engravings. In W. D. L. Ride and A. Neumann (eds),

Depuch Island, pp. 83–88. Special Publication 2, The Western Australian Museum, Perth.
VINNICOMBE, P. 1987. *Dampier Archaeological Project. Resource document, survey and salvage of Aboriginal sites, Burrup Peninsula, Western Australia*. Department of Aboriginal Sites, Western Australian Museum, Perth.
VINNICOMBE, P. 2002. Petroglyphs of the Dampier Archipelago: background to development and descriptive analysis. *Rock Art Research* 19: 3 (this issue).
WALDERHAUG, O. 1998. Chemical weathering at rock art sites in western Norway: which mechanisms are active and how can they be retarded? *Journal of Archaeological Science* 25: 789–800.
WALDERHAUG, O. and E. M. WALDERHAUG 1998. Weathering of Norwegian rock art—a critical review. *Norwegian Archaeological Review* 31: 119–39.
WATCHMAN, A. 1989. The post-graduate diploma course in rock art conservation. *Rock Art Research* 6: 104.
WICKHAM, G. 1843. Notes on Depuch Island. *Journal of the Royal Geographical Society* 12: 79–83.
WINKLER, E. M. 1973. *Stone: properties and durability in man's environment*. Springer Verlag, New York.
WITHNELL, J. G. 1901. *The customs and traditions of the Aboriginal natives of Western Australia*. Private printing, Roebourne.
WORMS, E. A. 1954. Prehistoric petroglyphs of the Upper Yule River, north-western Australia. *Anthropos* 49: 1067–88.
WRIGHT, B. J. 1968. *Rock art of the Pilbara region, north-west Australia*. Occasional Papers in Aboriginal Studies 11, Australian Institute of Aboriginal Studies, Canberra.
WRIGHT, B. J. 1974. Dampier Archipelago Aboriginal sites. Unpubl. report for incorporation into the Pilbara Study Report, W.A. Museum, Perth.
WRIGHT, B. J. 1979. Dampier Archaeological Liquefied Natural Gas Project: a survey for Aboriginal sites. Unpubl. report, W.A. Museum, Perth.
WRIGHT, B. J. 1980. A proposal for the archaeological investigation of, and preservation of, Aboriginal sites in the Dampier Archipelago. Unpubl. report, W.A. Museum, Perth.
WRIGHT, B. J. 1982. A proposal for the archaeological investigation of and preservation of Aboriginal sites in the Dampier Archipelago. Unpubl. report, W.A. Museum, Perth.

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Figure 3. *Schematic depiction of the spalling process affecting the boulder piles of Murujuga. The sequence of reduction is documented by the preserved fracture facets, which in the case of decorated boulders facilitates the limited establishment of a relative chronology of the petroglyphs.*

Figure 4. *Schematic depiction of the relationships of weathering depth (W_{max}, W_{mean}, W_{min}), pecked groove depth (E), weathering zone thickness under pecked groove (X) and position of groove depth relative to weathering depth (Y), using the sample of Trendall (1964).*

Figure 5. *Deterioration of ferruginous crust on Murujuga rock surfaces as determined by measurement (b); as predicted at the present level of atmospheric pollution (c); and as predicted in the event of a trebling of the ambient air-shed pollution (d). The average value of the buff-coloured substrate, the threshold at which the rock art becomes imperceptible, is indicated by (a).*