Effects of water vapour and rock substrates on the microclimates of painted rock art surfaces and their impact on the preservation of the images

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Abstract
Microclimate data from typical sandstone and limestone rock art sites in the west Kimberley region of Western Australia were recorded in both the wet and the dry seasons. The research described in this paper shows that the climatic behaviour in rock shelters is more amenable to direct interpretation when the relative humidity at any given temperature is converted to absolute humidity or water vapour pressure. It has been shown that many of the sites act as 'closed systems' with little input or output of moisture until water bearing fronts or drying winds change the local microenvironment. The rate of cooling of points within the shelters is largely determined by exposure to the sky, which facilitates cooling by emission of long wave radiation and by the heat capacity of the moisture in the air. It was found that the heating and cooling rates for limestone sites in the Napier Ranges are more sensitive to changes in moisture than the sandstone sites in the Mitchell Plateau. The survival of painted images on the rock surfaces is directly linked to the way in which the substrates respond to changes in the moisture content of the sites.

Keywords: rock art, preservation, water vapour, rock substrate

Introduction

The fieldwork to remote areas of the West Kimberley consisted of dry season data collection in 1990 and wet season data from 1992. This study was undertaken to identify and examine the conservation problems that rock paintings have suffered and to try and determine the major variables that control the rate of decay of the images. In the decade since the results were reported to the Australian Institute for Torres Strait and Aboriginal Islander Studies (AIATSIS) in an unpublished report (MacLeod and Haydock 1996) the authors have continued research into the causes of deterioration of Aboriginal rock paintings (MacLeod et al. 1991, MacLeod et al. 1995, MacLeod et al. 1997). The focus of the studies has involved modelling the microenvironmental conditions to enable estimation of the long-term impact of the changes in temperature and relative humidity and how the availability of moisture controls the biological and chemical forces of deterioration. This paper revises interpretation found in the unpublished reports to the grant bodies (MacLeod et al. 1991) in the light of new knowledge reflected in recent reviews on rock art conservation (MacLeod 2000).

Prior to fieldwork being undertaken extensive discussions were initiated both with Gulingi Nanga Aboriginal Corporation Incorporated in Derby and the Junjuwa Community Incorporated in Fitzroy Crossing. Permission to analyse micro-samples of pigments and to collect microenvironmental data at five painting sites in the Napier Range (a limestone Devonian reef) and on the Mitchell Plateau, which was dominated by siliceous sandstone, enabled the basic research design to be defined. The results from the pigment analyses have been previously reported by Ford et al. in 1999.

Equipment

For on-site measurements a Datataker DT 1OOF was used. This model has 23 differential analog input channels, four of which were dedicated to the exclusive use of the humidity sensors. The remaining channels were for thermocouple sensors. The DT100F has a 16K data storage memory, with the capacity to store approximately 7700 data points. The thermocouple sensors used were a type 'K', with an accuracy of ± 0.1°C and the humidity sensors were Vaisala model number HMW 20U, with an accuracy of ± 2%. The three temperature and relative humidity loggers used in the meteorological screen[1] were ACR XT–102 types [2].

The data loggers had internal NiCad batteries which gave an effective field life of up to 12 days, depending on the usage. Backup power was obtained from a solar panel that trickle charged a 'no maintenance' sealed lead-acid battery. Since the frequency of the relative humidity readings are proportional to the current flowing through the cables, (to avoid problems of voltage drop over long distances) the unit in its current configuration had a reasonably heavy power load.

Figure 1a (top). Thermocouple located with chisel pointed branch. Figure 1b (above). Thermocouple and co-located relative humidity sensor.

Relative humidity, temperature and water vapour pressure

Conservators are very familiar with psychrometric charts of temperature and relative humidity that have been traditionally produced by thermohygrographs or more recently by data loggers. Stability of the microenvironment is indicated by relatively small variations in the relative humidity of ± 5% and temperatures of ± 1.5°C. In museums and galleries, millions of dollars of infrastructure is committed to obtaining the international museum environmental conditions of 22 ± 2°C and 50 ± 5% relative humidity in the belief that attaining these conditions will minimise the rate of deterioration of collections. Part of the challenge of modern conservation management practices is to find the balance between energy costs and efficiency, maintaining collections in standard international conditions and finding appropriate microenvironments that enable retention of the original surfaces created by artists and artisans from a previous age (Michalski 2002). Given that much Aboriginal rock art has survived in varying degrees of preservation in the open environment for thousands of years and has been subjected to millennia of extremes in temperature and relative humidity, it is important to understand the inter-related nature of these variables and how they are expressed in terms of the amount of available water vapour. The microenvironment data collected in the West Kimberley was based on data loggers located in a meteorological screen a few hundred metres from the rock shelter and data collected at the painted surfaces, using thermocouples and relative humidity probes temporarily held against the substrate by tensioned wooden poles (MacLeod and Haydock, 2002). Temperature probes and relative humidity sensors were held in place with chisel-pointed branches from local scrub and were taped to the support poles respectively. The tensioned wood provides a firm but non-invasive support (see Figures 1a and 1b).

While it is generally known that the vapour pressure of water at 100°C is 760 mm of Hg it is often assumed that at 0°C the vapour pressure is zero, whereas the vapour pressure is 4.6 mm Hg (Weast 1974). The vapour pressure is in effect a measure of the energy of the water at any given temperature and the relative humidity is simply the fraction, expressed as a percentage, of the amount of water vapour in the air compared with the

1 A meteorological or Stephenson screen (MS) is a white-painted wooden container with a gabled roof and fixed louvers on each side that provides complete shade for the analytical instruments. These devices are used at all the weather bureau stations.

2 The ACR XT–102 dataloggers were loaned to the project from the National Gallery of Australia.

saturated vapour pressure at any given temperature. Over the temperature range of 10°–50°C encountered on the Kimberley rock art sites, the saturated vapour pressure of water can be calculated according to the formula:

$$P_{H20} = 4.5812 \exp((17.269*T)/(T+237.3)) \qquad 1a$$

which was published by Monteith and Unsworth in 1990. This equation provides calculated saturated vapour pressures which agree with the literature in the Handbook of Chemistry and Physics to within a standard deviation of ± 0.008 mm Hg. To convert the logged temperature and relative humidity data into water vapour pressure across the sites and in the environmental screen, the equation can be reformulated into:

$$\log P_{H20} = 0.660979 + 0.43429((17.269*T)/(T+237.3)) \qquad 1b$$

where T is the logged temperature in degrees Celsius and the vapour pressure of water is expressed in mm of mercury (mmHg). Given that there is a logarithmic response of vapour pressure to temperature, the normal diurnal relative humidity changes of 30–50% in an uncontrolled environment is not unexpected.

Analysis of the microenvironment of the rock shelters and the painted surfaces, on the basis of the relative humidity and temperature data, proved to be extraordinarily difficult but use of the absolute humidity (AH) or the vapour pressure (P_{H20}) facilitated interpretation of the changes in site conditions. From plots of the absolute humidity against time it was possible to determine if the site was acting as a 'closed' system (one without internal or external input of moisture) or an 'open' one, where there is a significant change in the amount of water. 'Closed systems' will produce the same vapour pressure of water, i.e. will be isobaric with respect to the vapour pressure of water. Changes can be brought about by drying or moisture-bearing winds or by driving rain. Since the heat capacity of the air is directly related to the amount of moisture that is present in the system, the rates of heating and cooling of the painted surfaces will be affected directly by the temperature and the relative humidity. The amount of air movement also directly affects the flux of water in and out of the painted surfaces, and major effects from direct sunlight impinging on the rocks were also noted.

Previous studies have shown that microbiological activity is very dependent on the water vapour pressure (MacLeod et al. 1995, MacLeod 2005). The rate at which the rock surfaces cool in the night is dependent on the amount of sky that the point can 'see' and the sky view factor (SKV) is the amount of clear sky that can be seen from any particular point on the rock face (Lyons and Haydock 1987, Lyons and Edwards 1982). The night-time radiative cooling of the rock face is controlled by long-wave infra-red radiation. Table 1 shows the calculated SKV for each of the temperature sensor points used in the study, over both the dry season and the wet season. Zero values of the SKV generally relate to microenvironment conditions when the sensor locations are either obscured by features in the rock shelter or by landforms outside the shelter. Incidences of cloud cover will render an SKV as being zero. An SKV value of 1 is given for a point that sees a 360° horizon, or half of a sphere of sky. Similarly if the horizon is 180° the point sees a quarter of a sphere and has an SKV value of 0.5. As the window of view of the sky is reduced, so accordingly is the SKV value (Steyn and Lyons 1985). Generally the greater the SKV, the greater the cooling rate of any specific point, in the absence of sensible and latent heat flux. Sensible heat flux is that change that is effected by wind or air movement, and latent heat flux is that change brought on by the vaporisation or condensation of water, from or to the immediate atmosphere.

Table 1. Sky View Factors (SKV) for temperature sensor points on the Kimberley sites

Sensor	Bilyarra	Barralumma II	Moonooroo	Yalgi
1	0.0372	0.0019	0.0338	0
2	0.0365	0.0106	0	0
3	0.0350	0.0106	0.0392	0
4	0.0396	0.0098	0.0919	0.0001
5	0.0348	0.0117	0.0919	0
6	0.0381	0.0028	0.0377	0.0094
7	0.039*	0.0025	0.0049	0
8	0.0442	0	0.0040	0.0091*
9	0.0284*	0	0.0074	0
10	n.a.	n.a.	n.a.	0
11	n.a.	n.a.	n.a.	0.0041

* temperature sensor had fallen from original location.

The range of SKV values for *Bilyarra* in the Napier Range varies from 0.0284 to 0.0442 while the nearby *Barralumma* II site varies from a very small 0.0019 to a maximum of 0.0117 and this reflects the greater degree of the undercut in the shelter and that some areas of the painted surfaces are very sheltered. The siliceous sandstone site of *Moonooroo* in the Mitchell Plateau region had a much more open nature and this is reflected in the SKV values ranging from 0.0040 to 0.0919 while *Yalgi* is characterised by probes that can see very little amount of clear sky, with values ranging from 0.0001 to 0.0094.

Bilyarra 1990 dry season

The geology of the shelter in which the paintings exist is quite complex and differs from the overall

Figure 2. *Bilyarra* site showing distribution of sensors across the site.

geology of the Napier Range. The shelter has been formed by undercut weathering into a bedding layer that has been described as being a quartzose micaceous calcarenite, which was most likely formed in a high energy beach/tidal environment (Kent 1991). The shelter has a site orientation of 20° (almost NNE) and an overall length of about 120 metres with an overhang width that varies between 5 and 15 metres (see Figure 2). The actual painted area of the site is about 30 metres in length and is sheltered beneath the widest section of the overhang. The constituents of the concretion are largely derived from weathered granitic sources that have been cemented together with calcite. To state that the dry season can be characterised by times of extremely low relative humidity is an understatement when examining the data collected in June 1990 at the *Bilyarra* site.

The temperature and relative humidity data are shown in Figure 3 where values as low as 3 ± 5% RH (very low and very high relative humidity recordings are subject to a relatively greater error than the middle range of data) are associated with moderate temperatures in the range of 15.5°C–33.5°C or some 18°C.

Although the authors were not present at the time of the rain event on 24 June, the response of the sensors in the Stephenson screen (see Figure 4) was rapid and dramatic. Within 24 hours this moisture flux had dissipated and the RH values showed the expected diurnal variations with night-time cooling and daytime heating. The morning of 25 June presented an exception, when there were falling values of relative humidity associated with a period of cooling. It is likely that there was some sensible heat flux associated with this event in the form of a drying wind. The response of the rock surface at temperature sensor TK1 and relative humidity sensor 1 is shown in Figure 5.

When the RH and temperature data from the meteorological screen and a site on the shelter roof are converted to absolute humidity or water vapour pressure, according to equation 1b, the interpretation of the changes in the microenvironment are made much more straightforward (see Figure 6). The extreme desiccation of the local environment at the meteorological screen is reflected in the very low P_{H20} of 1 mm Hg, which rapidly increased at the rate of 8mm Hg.hr^{-1} to 13 mm Hg when the rain event of an isolated shower took place around 2100 hrs on 23 June. After a period of 10 hours the P_{H20}

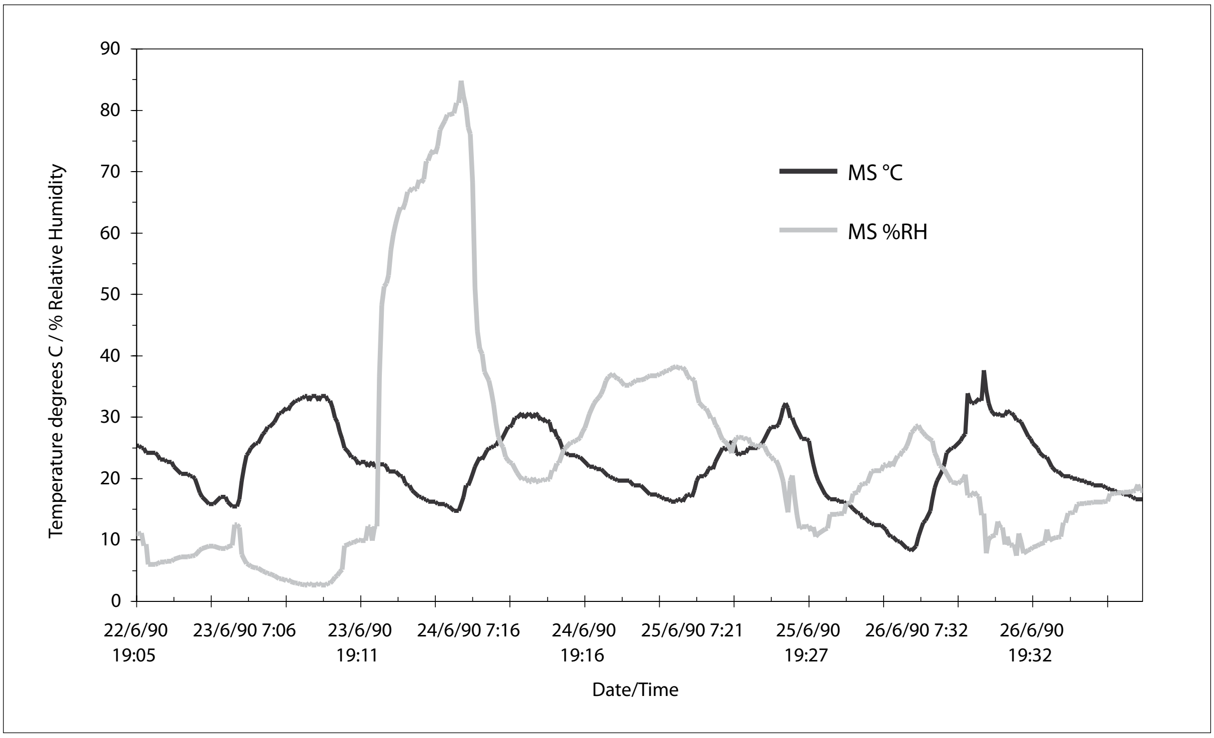

Figure 3. *Bilyarra* 1990 dry season meteorological screen temperature and relative humidity

Figure 4. Stephenson screen at *Bilyarra* site suspended approximately 1 m above ground.

fell rapidly in response to a drying wind and dropped to about 6 mm of Hg for a period of 27 hours before returning to the same very dry values that were initially observed. Following this interval there was a second period of increasing moisture in the meteorological screen. Since the instruments in the screen are protected from direct sunlight only by the nature of the structure in which they are housed, there will be no buffering capacity and the meteorological screen data reflects the rapid changes in moisture that are characterised by the presence of moist and drying winds.

When the data on absolute humidity for the rock surface are compared with the data in the meteorological screen, as seen in Figure 6, two features are apparent. There is a rapid drop in P_{H20} from 7 mm Hg to 3 mm Hg over the space of an hour, which then recovers to its former value in a similar time interval. Generally this rapid drop and recovery takes place between 0600 hours and 0900 hours each day and is likely to be associated with the sun moving directly onto a spot near the sensor, which results in localised desiccation, as shown in Figure 6. The fact that the RH also rapidly fell at the same time as the temperature plummeted is consistent with the events being associated with a latent heat flux that sees sunlight hit a surface and result in localised evaporation of water. The other key feature of the rock surface is that it is acting like a 'closed system' with a steady P_{H20} of 8 ± 2 mm Hg vapour pressure. A measure of the buffering capacity of the rock shelter is seen in the afternoon of 25 June when the meteorological screen dropped by 4.4 mm Hg and the surface of the shelter fell by only 2.5 mm and at a much slower rate. The lower rate of change of moisture is largely due to the thermal inertia of the rock surface.

A measure of the reliability of the localised temperature and relative humidity readings on the rock surfaces can be seen in Figure 7, which illustrates the P_{H20} data at surface points as well as at a location within the shelter that was not touching the rock surface but was supported off the ground on a sapling wedged into the shelter envelope. The small gaps between the rock shelter and the surface of the probe were due to instrumental artefacts that could not be corrected.

The data from the RH1 and RH2 sensors is

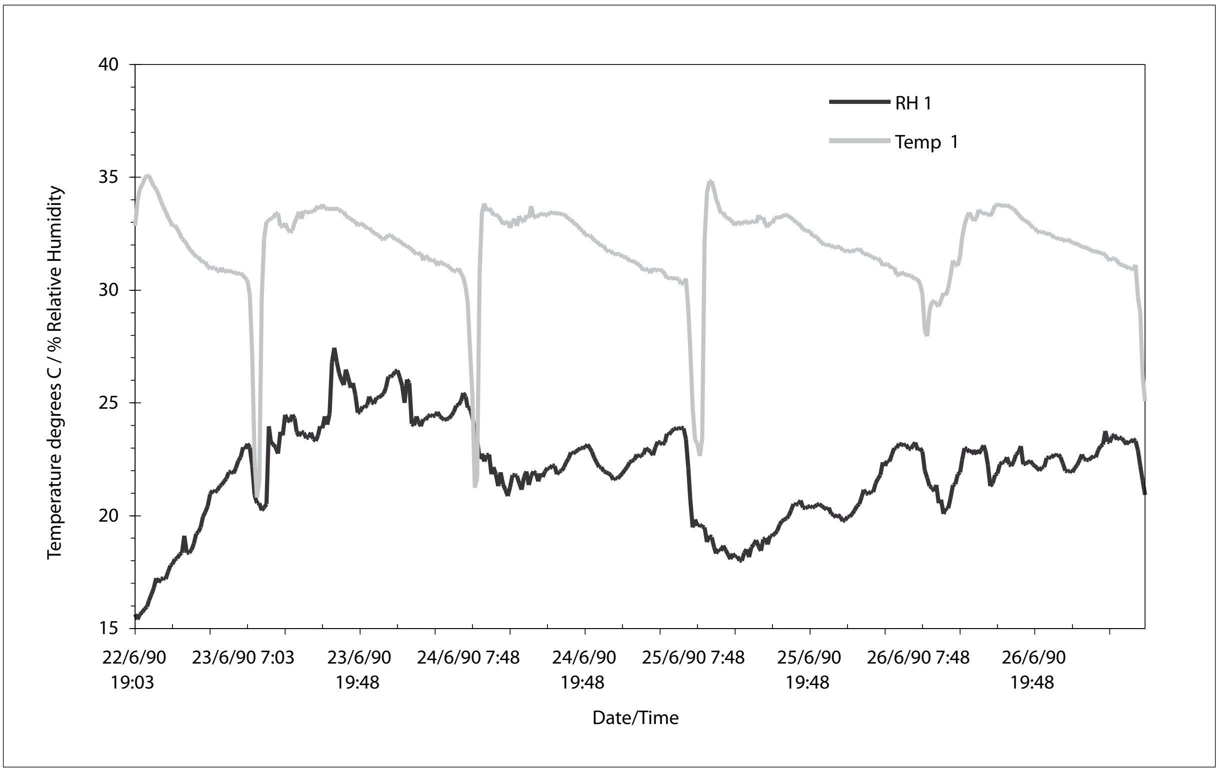

Figure 5. *Bilyarra* 1990 dry season rock temperature (T1) and relative humidity (RH1) vs time.

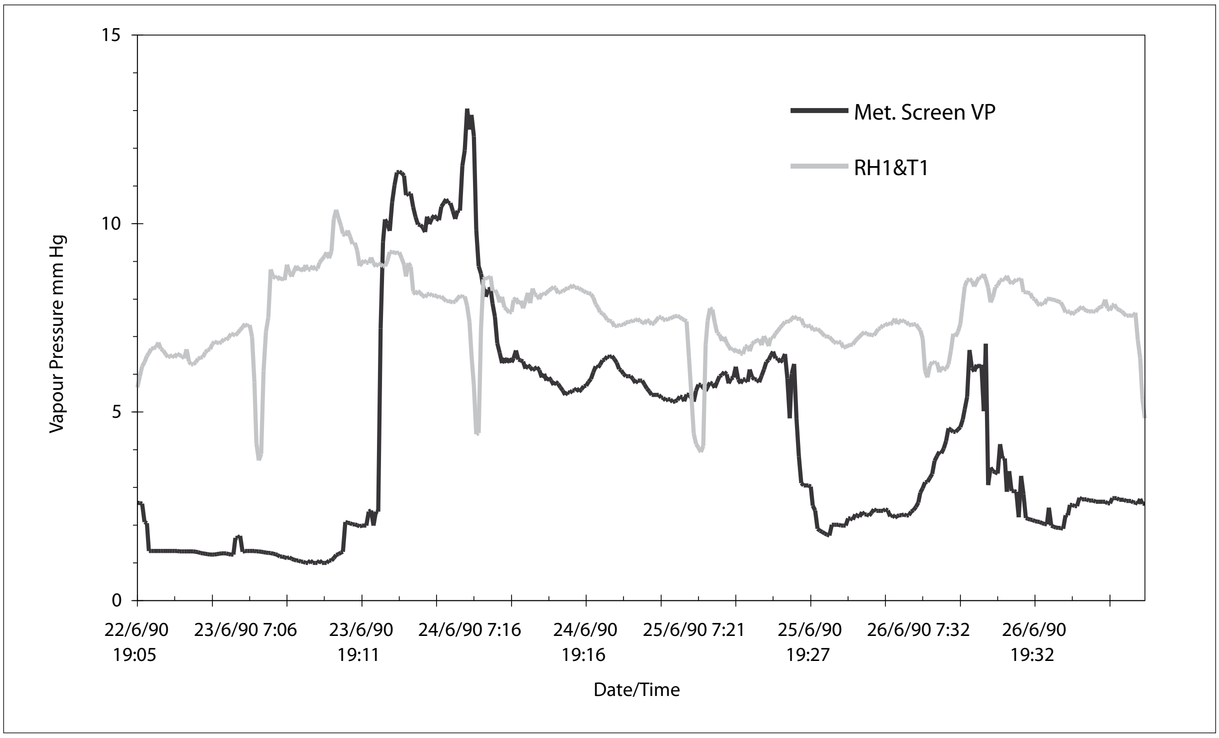

Figure 6. *Bilyarra* 1990 dry season vapour pressure of meteorological screen and rock surface

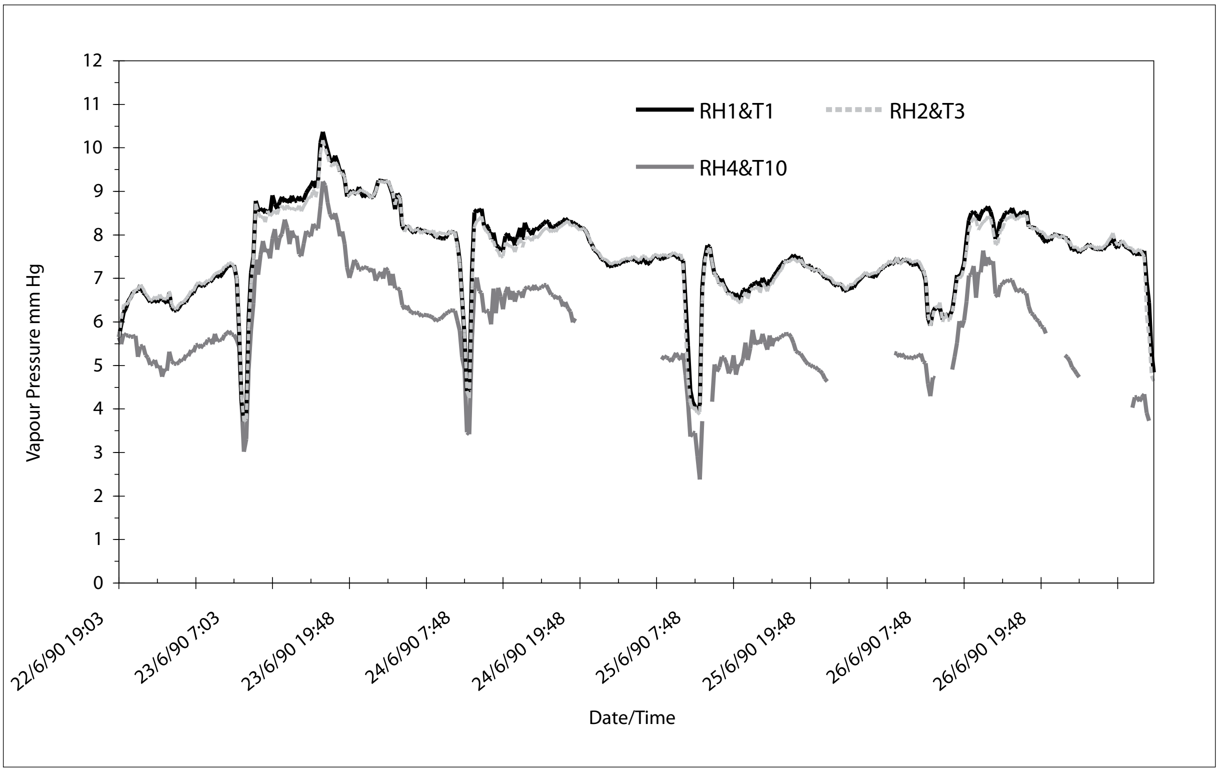

Figure 7. *Bilyarra* 1990 dry season P_{H20} at the rock surface and in the shelter vs. time.

essentially identical and, apart from the previously mentioned rapid drop and rise in P_{H20}, the mean vapour pressure of the rock surfaces is approximately 8 mm Hg, which is roughly 2 mm Hg greater than that found in the open shelter. Given that the *Bilyarra* shelter is made of an ancient Devonian coral reef, it is not unexpected that this surface exerts a buffering capacity and the micro-porous nature of the rock will tend to retain or give out moisture as the local environment changes. Just as the meteorological screen temperatures were very responsive to changes in the micro-environment, the T10 ambient temperature sensor cooled on 26 June after 1800 hours at the rate of $-0.510 \pm 0.007°$ C.hr^{-1}, which is much greater than the rock surface probes T5 at -0.103 ± 0.003 °C.hr^{-}

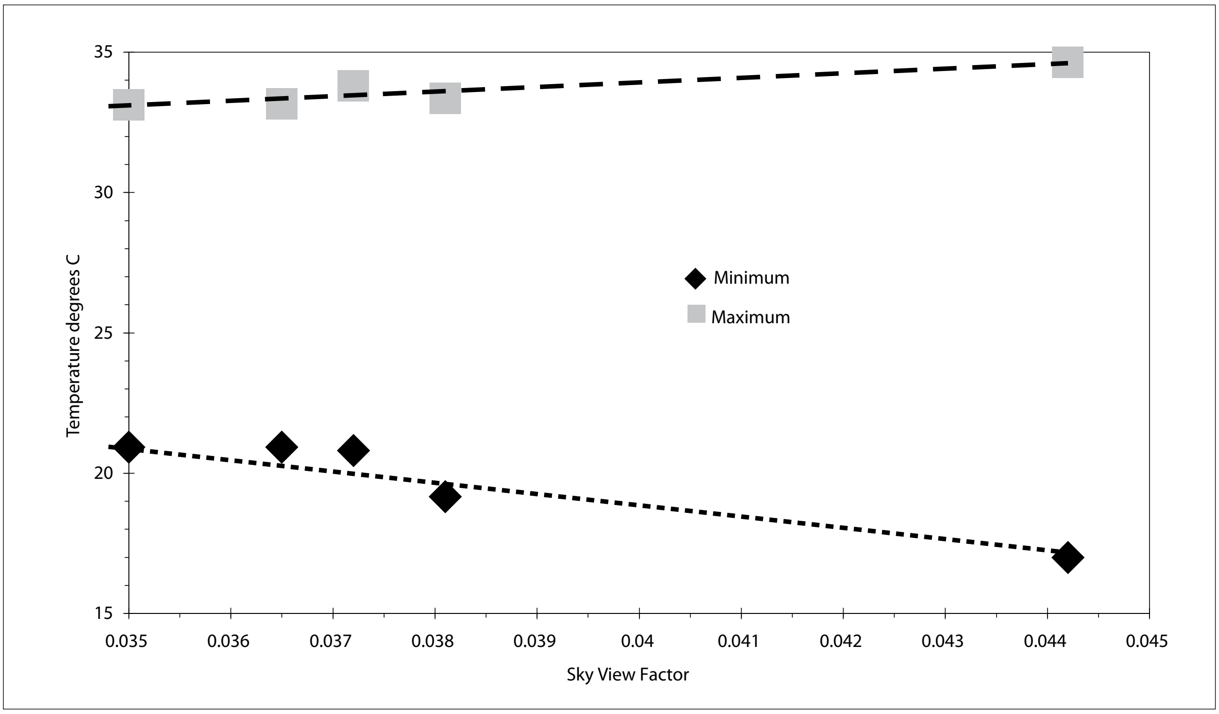

Figure 8. *Bilyarra* maximum and minimum temperatures as a function of the Sky View Factor

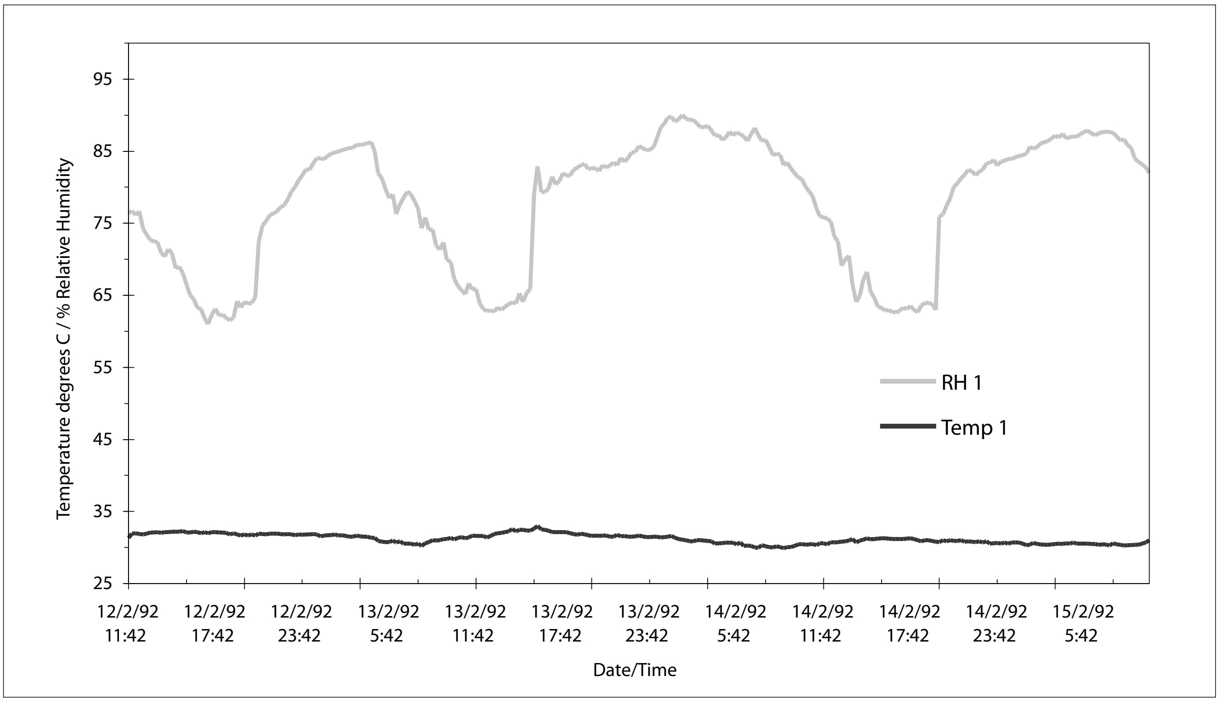

Figure 9. Relative humidity (RH1) and temperature (T1) at *Bilyarra* during February 1992

^{1} and T2 at $-0.187 \pm 0.004°$ C.hr^{-1}. The different cooling rates correspond to differences in the SKV values of the measurement points (see Table 1) with those sites having the greater SKV value cooling at a faster rate.

Sky View Factor

When the average minimum and maximum rock face temperatures for each sensor are plotted against the Sky View Factor (SKV) the best fit is obtained with a linear regression, which supports the supposition that the rates of cooling is related to the SKV of that measurement point. The relationship between the SKV and the mean maximum temperatures is given by equation 2, which has an R^2 value of 0.8808 for the five sensors.

$$^{dry\ Bilyarra}T_{maximum} = 27.4 + 163\ SKV \qquad 2$$

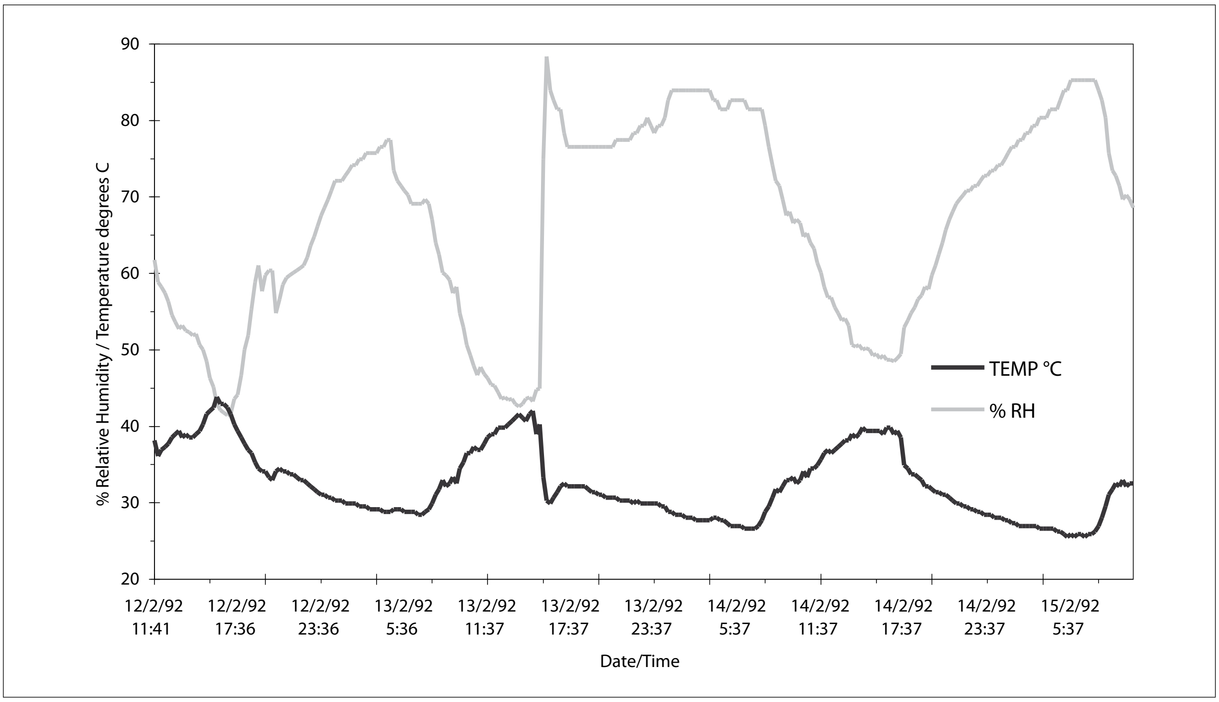

Figure 10. *Bilyarra* wet season 1992, temperature and relative humidity in meteorological screen

The corresponding equation for the mean minimum temperatures is given by equation 3, which has an R^2 value of 0.8167:

$$^{dry\ Bilyarra}T_{minimum} = 34.9 - 402\ SKV \qquad 3$$

The negative exponent for the SKV factor associated with the minima equation simply means that the larger the SKV, the lower the mean minimum temperature, as shown in Figure 8. The good degree of correlation between the dry season data for *Bilyarra* is consistent with long-wave radiation providing cooling on cloudless nights. The slope for the maxima is 2.5 times less sensitive to the SKV data than that for minima and this is a possible reflection that heating can come from direct sunlight and from radiated heat absorbed by other parts of the site. The first three days at *Bilyarra* showed similar ranges of maximum and minimum temperatures of 13.1 ± 0.6°C, but only 5.9°C on Day 4, when there was significant cloud cover. Although the cloud cover did not affect the maximum temperatures, the presence of the cloud on the evening of Day 4 resulted in the minimum being 27.8°C compared with a mean of 20.8 ± 1.1°C for the previous three days.

The corresponding relative humidity data showed that the environment was relatively constant with mean values of 25.4 ± 0.5% RH_{max} and 19.4 ±0.2% RH_{min} and these values did not seem to be influenced by the amount of cloud cover that came in on day four.

Bilyarra 1992 wet season

The main difference between the dry and the wet season is the range of temperatures on the rock surfaces with a mean maximum of 32.6 ± 0.6°C and a mean minimum of 30.7 ± 0.3 °C. The dry season ranged from a mean maximum of 33.9 ± 0.5°C to a mean minimum of 22.5 ± 3.6°C. The principal reason for the much lower temperature range in the wet is due to the higher heat capacity of moist air. The wet season at *Bilyarra* had a mean relative humidity maximum of 85.8 ± 1.0% RH and a mean minimum of 69.5 ± 1.7% RH. This is shown in Figure 9 where the temperature is relatively constant while the relative humidity changes as moist fronts move in and out of the site. The impact of monsoonal rain on the microenvironment in the meteorological screen is shown in Figure 10, where the relative humidity increased from 45% to 88.4% in half an hour on 13 February 1992. It should be also noted that the RH values increased the previous day as a thundercloud rolled in but no rain event took place. The normal diurnal build-up of moisture and the collapse of the system following the drying winds is seen more directly in the P_{H2O} plot of the meteorological data in Figure 11, which shows that the site is an 'open' system, since there are periods where there is a net influx and a net output of moisture.

The difference in the inherent hygroscopicity of the Napier Range limestone is seen through the rock surfaces only changing by 8 mm Hg compared with the meteorological screen, which changed by 10 mm Hg during the period of measurements. The rock surface generally had a 'time delay' of six to eight hours after a

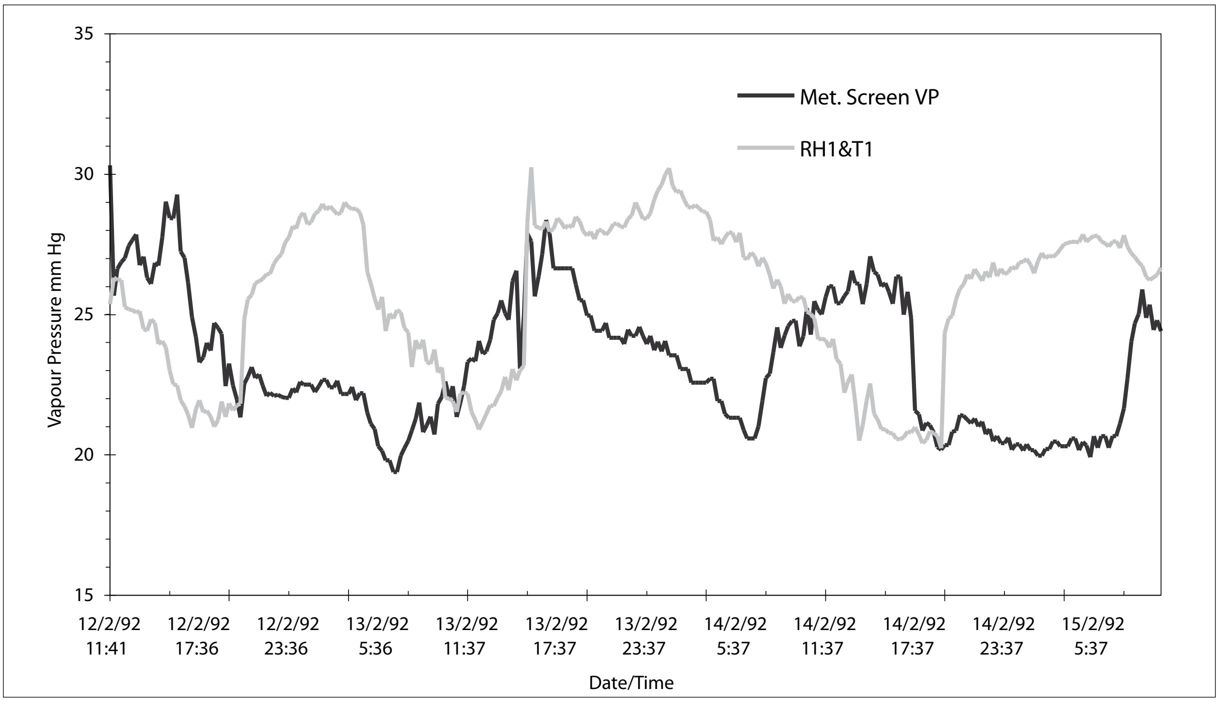

Figure 11. Bilyarra wet season plots for the meteorological and the rock surface.

rain event, before there was an increase in the P_{H2O} at the surface which may be due to slow mixing between the shelter and the atmosphere.

A comparison of the P_{H2O} plots for all four temperatures and relative humidity probes shows that there is essentially uniform behaviour across the length and breadth of the rock art shelter. Typical diurnal variations see the absolute humidity increase from 21 mm to 31 mm Hg as moist fronts arrive and periodic rain events take place, before the drying winds move in and remove heat from the rock surfaces through a combination of sensible and latent heat fluxes. The sensors at T6 recorded a night-time (after 11 pm) cooling rate of -0.192 ± 0.005 °C.hr^{-1} and -0.103 ± 0.009 °C.hr^{-1} for T9, which is in accordance with T6 having a much larger SKV than T9. When the mean maxima and minima are plotted as a function of the SKV, similar linear responses to those observed in the dry season were obtained, but the slopes of the lines were less steep owing to the increased buffering capacity of the moist air. The relationship between the SKV and the mean maximum temperatures at Bilyarra in the wet season is given by equation 4, which has an R^2 value of 0.8075 for the four data sets.

$$^{\text{wet Bilyarra}}T_{\text{maximum}} = 28.7 + 29\ \text{SKV} \qquad 4$$

The corresponding equation for the mean minimum temperatures is given by equation 5, which has an R^2 value of 0.8983 for the six data points

$$^{\text{wet Bilyarra}}T_{\text{minimum}} = 33.1 - 64\ \text{SKV} \qquad 5$$

The ratio of the slope of the dry season to the wet season for the cooling equations is 6 : 3, which is the same as the inverse ratio of 6 : 2 obtained for a comparison of the mean water vapour pressures in the dry and wet season. This direct correspondence supports the supposition that the amount of water vapour (11.1 mm Hg wet and 1.8 mm Hg dry season) has a direct bearing on the rate of cooling of the rock surfaces.

'Barralumma II' 1990 dry season

The site exhibits typical karst weathering features, with solution weathering leading to the formation of large caverns in the upper and rear surfaces, which have been richly painted. The surface texture and profile may be described as coarse and highly irregular; as a result the site has an inherently greater hygroscopicity than *Bilyarra*. The northern side opens out onto the plains while the area in front of the site is bounded by limestone on the eastern and western sides. The site is situated at ground level within an overhang about 25 m long, 5 m wide and 2.5 m high at the dripline. The data recorded in the meteorological screen for 1–7 July 1990 is illustrated in Figure 12, which shows a fine example of a 'closed system' with massive diurnal variations of relative humidity as the temperature cycles, with very little net input of moisture from the external environment.

A comparison of the P_{H20} plots for the meteorological screen and the rock surface shows that the porosity of the parent rock exerts a moderating influence on the amount of moisture in the local environment. The meteorological screen P_{H20} had a mean value of

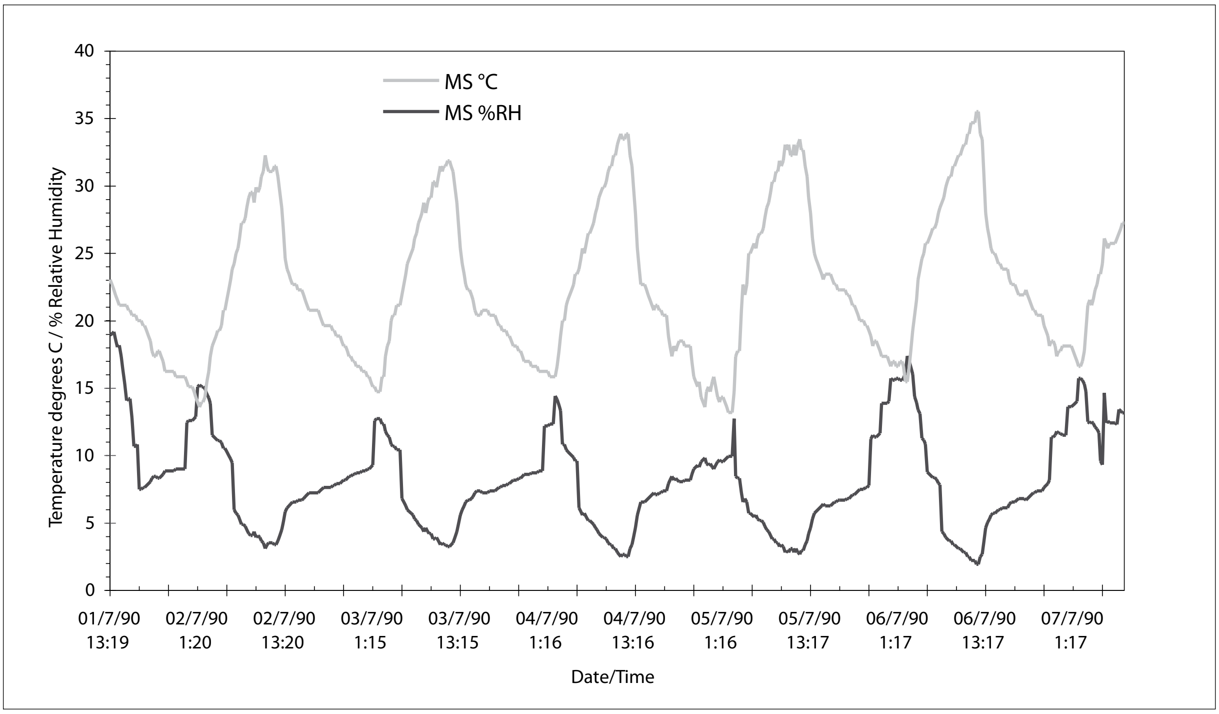

Figure 12. *Barralumma II* dry season temperature and relative humidity data for the meteorological screen.

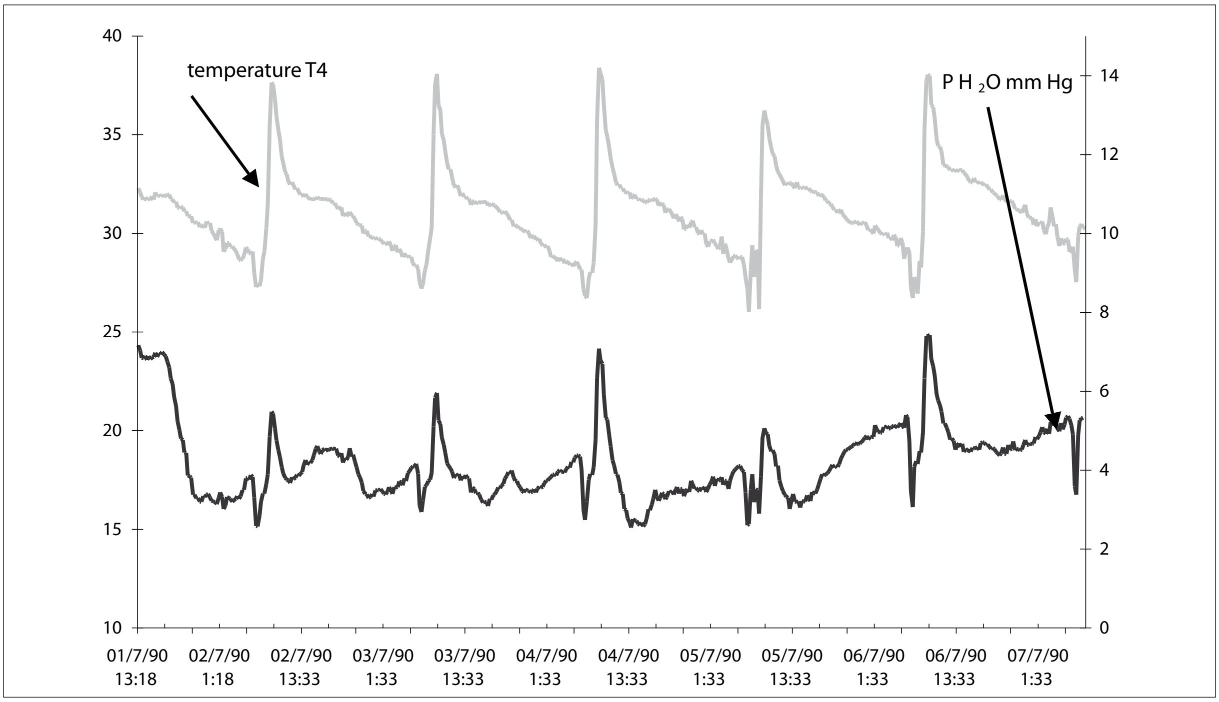

Figure 13. *Barralumma II* dry season P_{H2O} and temperatures on rock surface vs time.

2 ± 1mm Hg while the rock shelter where the painted images were located had a mean value of approximately 4.2 ± 1 mm Hg. Variations in absolute humidity were due to sensible heat flux associated with localised heating, causing some turbulent mixing of the air. The mean values of the relative humidity daily maxima and minima were 15.8 ± 0.9 and 9.2 ± 0.5 mm Hg respectively, while the corresponding temperature values were 37.2 ± 0.8 and 25.5 ± 0.4°C. The more open nature of the shelter resulted in there being a less distinct relationship between the minimum temperatures on the apparent sky view factors. There was, however, a high degree of correlation between the SKV values and the maximum temperatures with equation 6, which has an R^2 value of 0.9486, describing the relationship between the mean maxima and the SKV:

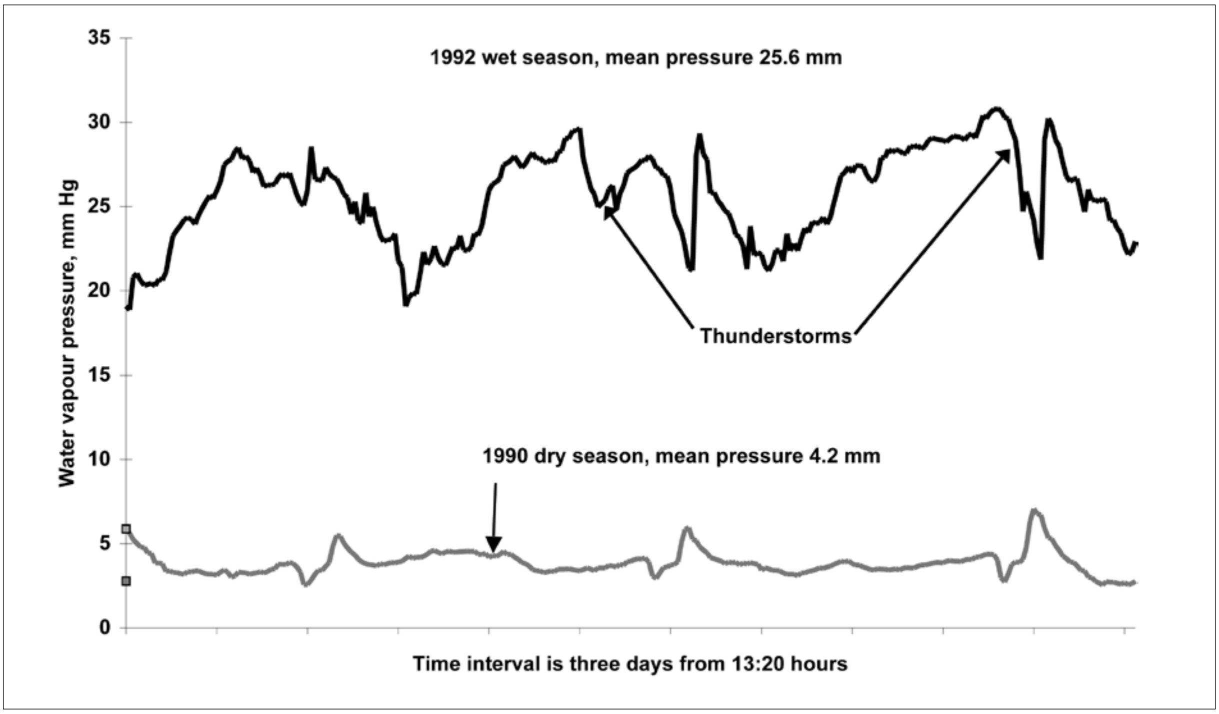

Figure 14. *Barralumma II* comparison of P_{H2O} for wet and dry seasons.

$^{dry\ Barralumma\ II}T_{maximum} = 35.7 + 206\ SKV$ 6

The slope of equation 6 is similar to that of *Bilyarra* in the same season and the more open structure of the *Barralumma II* site is reflected in the higher intercept value of the maximum and minimum temperature values at a zero value of the sky view factor. The R^2 value for the mean minimum temperatures was only 0.3831 and this is too low to produce comparative data.

The geology of the shelter is reflected in the temperature and P_{H20} graphs shown in Figure 13, which illustrates that the rapid increases in temperature are directly reflected in an increased absolute humidity against the rock surface. It is likely that this phenomenon reflects the impact of sunlight on the release of moisture from the rock surface. The inherent hygroscopicity of the rock is reflected in the way the cooling curves change with the absolute humidity. Nine surface temperature probes had cooling rates that are described by equation 7,

$\delta T/\delta t = -0.041 + 0.600\ \delta P_{H20}/\delta t$ 7

The value of the rate of cooling $\delta T/\delta t$ is in °C.hr^{-1} and the rate of change of water vapour pressure $\delta P_{H20}/\delta t$ is in mm Hg.hr^{-1}. The physical manifestation of the cooling rate equation 7 is that if the local area climate changes from having an influx of moist air to 'drying winds' then the rate of cooling of the rock surface will increase. The temperature probe that was not touching the rock surfaces had a constant cooling rate of –1.808 ± 0.048°C for the entire period of observation. Adsorption of water vapour caused the steady cooling of –0. 45°C.hr^{-1} over three nights for sensor T8 to decrease to the point where there was a night-time heating rate equivalent to 0.129 °C.hr^{-1}. In the presence of a moisture front, adsorption of water onto the rock surface causes the temperature to increase during the night rather than exhibit its normal night-time cooling.

'Barralumma II' 1992 wet season

The meteorological screen (MS) data for the wet season was recorded over the period 15–18 February 1992. The RH varied from 45% to 100% while temperatures ranged from 22°C to 40°C over the period, with sudden changes in temperature being associated with early morning heavy showers. The wet season rock surface data from the *Barralumma II* site was analysed in the same fashion as the dry season data and this confirmed that the cooling curves generally exhibited linear decrease of temperature with increasing time and that the rates of change were dependent on the rate of change of the P_{H20} in terms of the net flux of moisture into and out of the rock surfaces. On 15 and 16 February 1992, the night-time cooling rate for T4 was –0.278 ± 0.010 °C.hr^{-1} while T2 gave –0.244 ± 0.008 °C.hr^{-1}. Owing to the higher ambient absolute humidity of 25.6 mm Hg in the wet, compared with only 4.2 mm Hg in the dry season (see Figure 14), the average rate of change of P_{H2O} with time was –0.0135 mm Hg.hr^{-1} compared with 0.600 for the dry season. The lowered sensitivity of the cooling rates to the changing absolute humidity is a reflection of the inherently 'saturated'

Figure 15. Moonooroo site A during the dry season

nature of the rock surfaces with regard to its desire to absorb or desorb moisture.

Inspection of Figure 14 shows how the P_{H20} increases during the build up of moisture prior to a rain event, and the subsequent air movement and drying winds associated with the rapid cooling of the landscape reduce the absolute humidity, and the cycle begins again. With the increased amount of cloud in the evenings, which totally changes the rate at which the rock surfaces cool, the correlation of the mean maximum and minimum temperatures with the SKV data is poor. The mean maximum temperature in the wet season was 33.4 ± 0.7°C which was 3.8°C cooler than in the dry season while the minimum value at 27.6 ± 0.8°C was 2.0°C warmer than in the dry season, reflecting the slower cooling rates due to the higher ambient P_{H20} . The wet season mean maximum relative humidity was 86.9%, some 71.1% greater than in the dry season. The corresponding minima were 52.3 ± 2.4% for the wet compared with the desiccating dry season value of 9.2 ± 0.5% relative humidity.

Mitchell Plateau siliceous sandstone sites *'Moonooroo' 1990 dry season*

Moonooroo consists of an outcrop of low-lying quartzite boulders scattered in piles over about a hectare, near the King Edward River. The river has a major impact on the ambient relative humidity values, which are much higher than the typically desiccated values at *Bilyarra* and *Barralumma* II in the Napier Ranges. The paintings (Sites A, B and C) are scattered throughout the outcrop, usually in shelters that were formed by block weathering. Two sites are on either sides of a 5 m high, 12 m long and 6 m wide rock. The site orientations are: 345° (Site A approx. NNW); 30° (Site B approx. NNE); and a small separate frieze (Site C) had an orientation of 340° (approx. NNW)—see Figure 15.

The dry season data for *Moonooroo* was gathered on 26–29 July 1990 and day one recorded in the meteorological screen exhibited typical 'closed' system conditions, with the RH cycling between about 25% and about 90% each day as the temperature ranged from 12–30°C. Previous research by MacLeod et al. (1994) indicates that this extreme daily change of RH would place considerable stress on the huntite pigments at the site. However, when the relative humidity and temperature data are converted to P_{H20} , as shown in Figure 16, the apparent stress on the pigments is seen to be much less severe than previously indicated.

The meteorological screen P_{H2O} plot shows a steady value over the first day until an evening wind brought moisture, which then gradually dissipates to re-establish the microenvironment one day later. The P_{H2O} data for the rock surface, RH2 and T3, exhibited much more rapid changes and the changes in absolute humidity had much greater amplitude than in the screen, which is sheltered from direct sunlight.

The 10 mm Hg fall in P_{H20} between 0700 and 0900 hours on the first day probably reflects the impact of sunlight on the adjacent rock surface, leading to evaporation of surface moisture, and the latent heat flux causing the temperature sensor T3 to plummet as seen in Figure 17.

This cycle of events is repeated on Day 2 and Day 3. On the second day, the rock surface moisture-time profile mimics the meteorological screen microenvironment but with a swing from 19 mm to 4 mm compared with 8.5 mm to 17.0 mm of Hg in the screen. In order to understand the complex nature of the *Moonooroo* site, it is useful to review the way in which the temperature changes across the site(s), as illustrated in Figure 17. The sub-site A is under a small rock overhang and has higher P_{H2O} values than the more exposed sub-site B. During the morning heating period all the sensors had essentially the same rate of heating but at night-time the effect of the SKV was apparent with T6, T8 on sub-site B and T9 at sub-site C having the same cooling rate of –0.371 ±0.005 $°C.hr^{-1}$ while T3 and T5 at A cooled at –0.533 ± 0.013 $°C.hr^{-1}$. The 18°C minimum at T3 is due to the latent

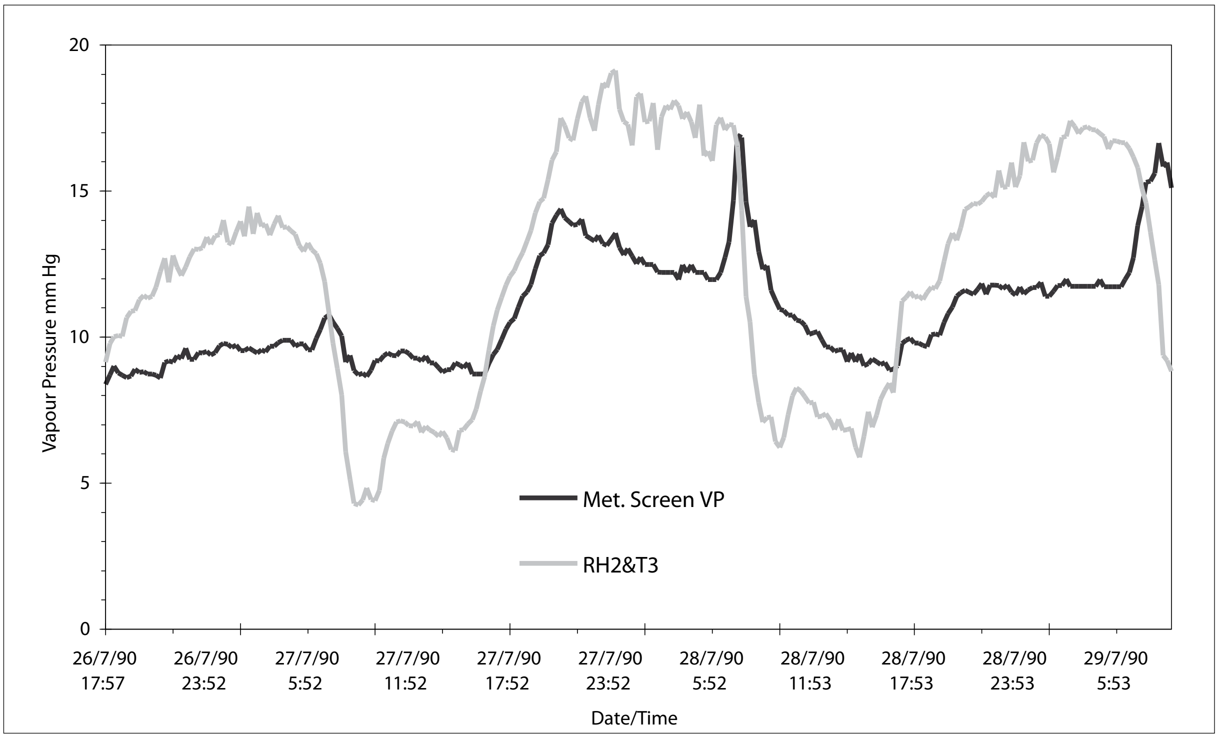

Figure 16. *Moonooroo* site P_{H2O} for the meteorological screen and rock surface in the dry season.

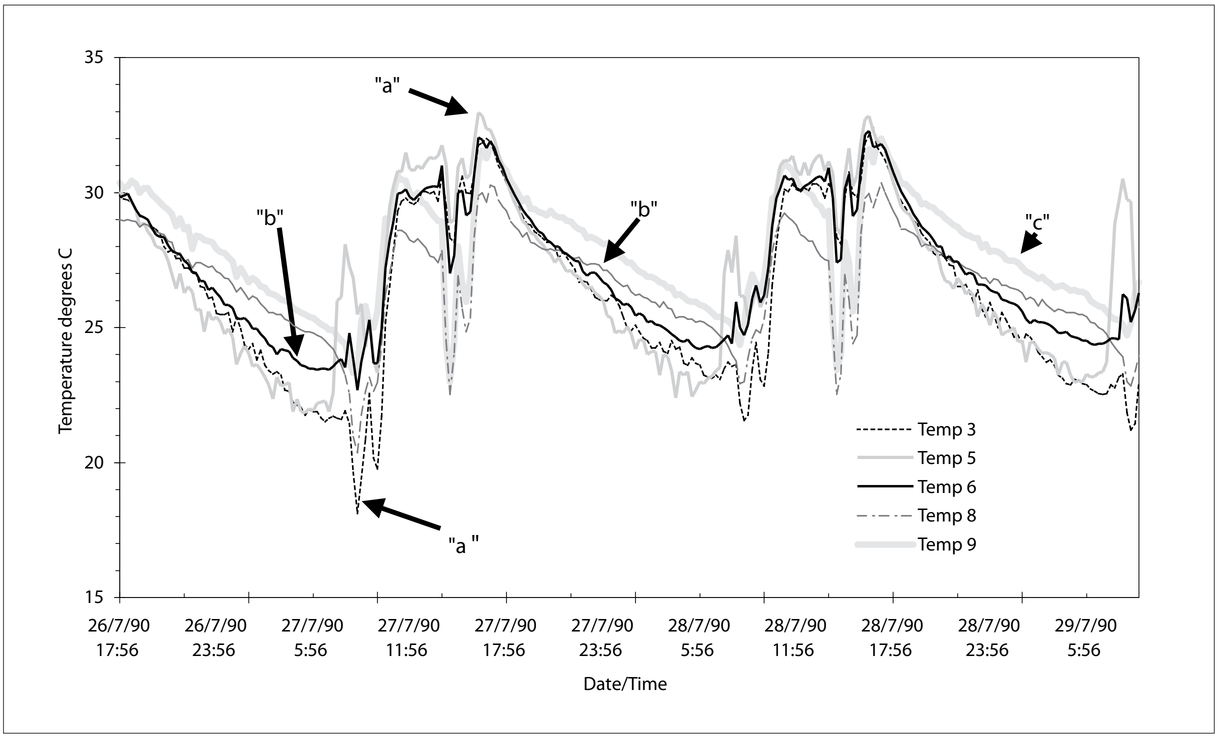

Figure 17. *Moonooroo* dry season 1990 temperature profiles for the main sub-sites A, B and C.

heat flux as water evaporates from the surface in the morning sun at the same time that the sun strikes the sensor T5 and causes the temperature to rapidly climb from 21°C to 28°C in one hour. The direct impact of sunlight and the latent heat flux means that the minimum values for temperature are not reflective of the SKV at the sensor points. When the sensors directly affected by the latent heat flux of the impinging sunlight are removed from consideration, the minimum temperatures for *Moonooroo* in the dry season exhibited similar relationships to that of the Napier Range sites, with an R^2 value of 0.9495 for equation 8:

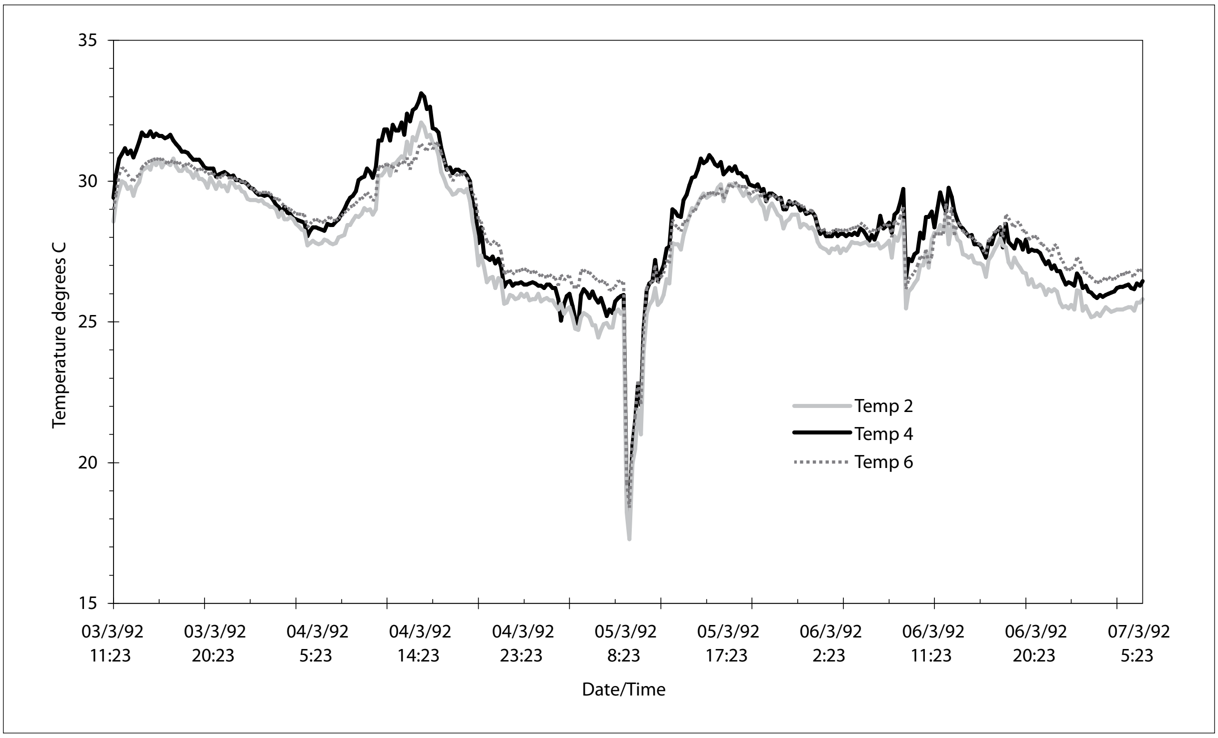

Figure 18. *Moonooroo* wet season temperatures at the rock surfaces.

$^{\text{dry Moonooroo}}T_{\text{“a \&b” minimum}} = 21.5 - 150\ \text{SKV}$ 8

The maximum temperature at sub-site A gave a very good correlation with the SKV of the probes, when the latent heat effects observed at T3 were removed from consideration. The R^2 value for the maximum temperatures at sub-site A was 0.9772 and the relationship is defined by equation 9:

$^{\text{dry Moonooroo}}T_{\text{“a” maximum}} = 32.2 + 16\ \text{SKV}$ 9

The mean temperatures of the sub-site A thermocouples T1–3 was 26.2 ± 3.3 °C while sub-site B surface probes T4–6 had a corresponding value of 27.2 ± 0.3°C. The mean temperature data reflects the difference in the amount of shelter of the sub-sites. Relative humidity values are also reflective of the degree of shelter with the mean 52 ± 21% for sub-site A and 45 ± 15% for sub-site B. The influence of the SKV on sub-site B had the same slope but a lower intercept value of 31.3 ± 0.3°C and an R^2 value of 0.9495 for the three sets of thermocouples.

'Moonooroo' 1992 wet season

The wet season cooling rates of the rock shelters were lower than during the dry season and the rates were in direct proportion to the SKV with T4, with a sky view factor of 0.0919, cooled at - 0.240 ± 0.006 $°C.hr^{-1}$ while T6, with a sky view factor of 0.0377, cooled at −0.183 ± 0.006 $°C.hr^{-1}$, as seen in Figure 18.

Figure 19. Temperature and relative humidity sensor close to rock fissure at *Moonooroo*.

The sharp drop in the temperature of 8°C in an hour on the morning of March 5, 2002 is likely to be due to the direct impact of sunlight and the associated induced latent heat flux of evaporating moisture from the surface (see Figure 18 and site details in Figure 19).

The corresponding P_{H20} plot shows a sudden drop in the amount of moisture present on the rock surface. Microenvironmental data for *Moonooroo* in the wet season showed that the mean relative humidity over the sub-sites was 88.8 ± 1.0% at a mean temperature of 28.2 ± 0.4 °C which can be characterised as thermally very stable, owing to the high heat capacity of the surrounding moist air.

The mean minimum temperatures of 16.6 ± 0.6°C were found to be insensitive to the SKV, owing to the significant amount of cloud cover, while the mean maximum temperature of 32.1 ± 0.6°C showed the expected positive dependence on the SKV. Equation 10

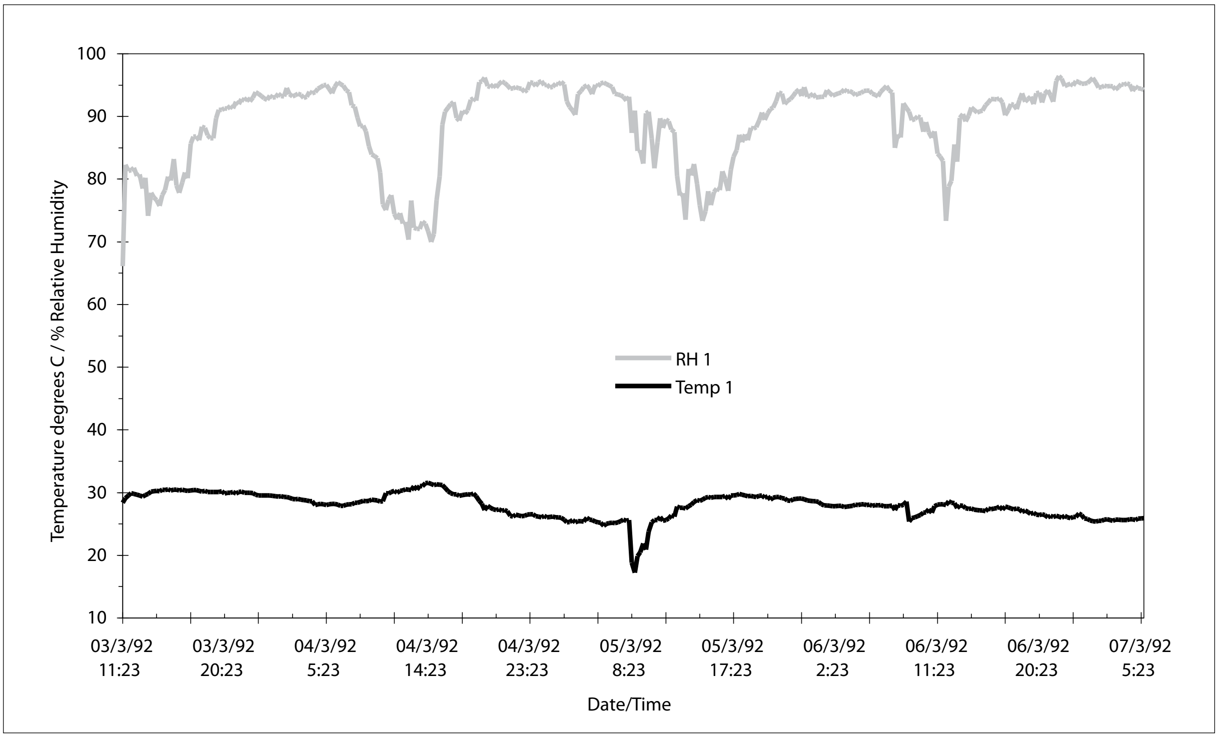

Figure 20. *Moonooroo* in the 1992 wet season with daily monsoonal rain.

shows the site has a moderate R^2 value of 0.8266 and the slope of 26 ± 8 is within experimental error the same as for the dry season maxima.

$$^{\text{wet Moonooroo}}T_{\text{maximum}} = 30.7 + 26\ \text{SKV} \qquad 10$$

There is a time lag of approximately eight hours between the maximum values of the P_{H20} observed in the meteorological screen and when it manifests itself on the rock surface at sub-site B with RH 4 and T6 probes. On three successive days there was an increased absolute humidity in the site owing to the arrival of the monsoonal rain showers, which is illustrated in Figure 20. The temperature on 5 March was due to nearby sunlight causing evaporation of moisture, i.e. it is a latent heat flux phenomenon.

Differences in the degree of protection afforded by rock overhangs at the sub-sites are reflected in the P_{H2O} plots which show that sub-site A has higher moisture content than sub-site B readings are generally 1 mm Hg lower than for the site with the small overhang.

'Yalgi' 1990 dry season

The *Yalgi* shelter, formed by block weathering, is located at the base of an outcrop adjacent to a low sandstone cliff running parallel to a large creek. There are numerous fissures located on the ceiling and rear wall, which, in conjunction with water, play an active role in the preservation of the paintings through the formation of protective silica skins (Watchman, 1990). The orientation

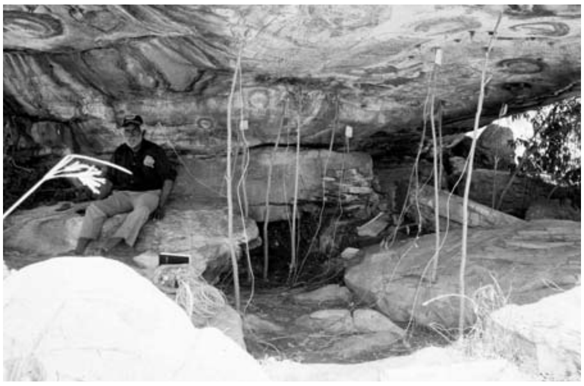

Figure 21. *Yalgi* site showing Wandjina images and location of sensors

of the site is 30° (approx. NNW) and the painted part of the shelter measures 4 m wide, 7 m long and 1.5 to 2.5 m high (see Figure 21). The topography of this region is rugged. *Eucalyptus spp.* and tall grasses, interspersed with a few unidentified evergreen and deciduous trees, dominate the open woodland on the higher sides on the drainage system. The presence of a seepage point within the shelter and the presence of the nearby creek have a most dramatic effect on the microenvironment, which makes *Yalgi* very different from *Moonooroo* and the Napier range sites of *Bilyarra* and *Barralumma II*. The data for *Yalgi* were recorded between 30 July and 2 August 1990.

The clearest indication of the connection between the local climate at the meteorological screen and the rock shelter (RH3, T6) is seen in the plot of the P_{H20} for both locations. Figure 22 shows two 'envelopes' of increasing, plateaued and decreasing moisture which are followed by

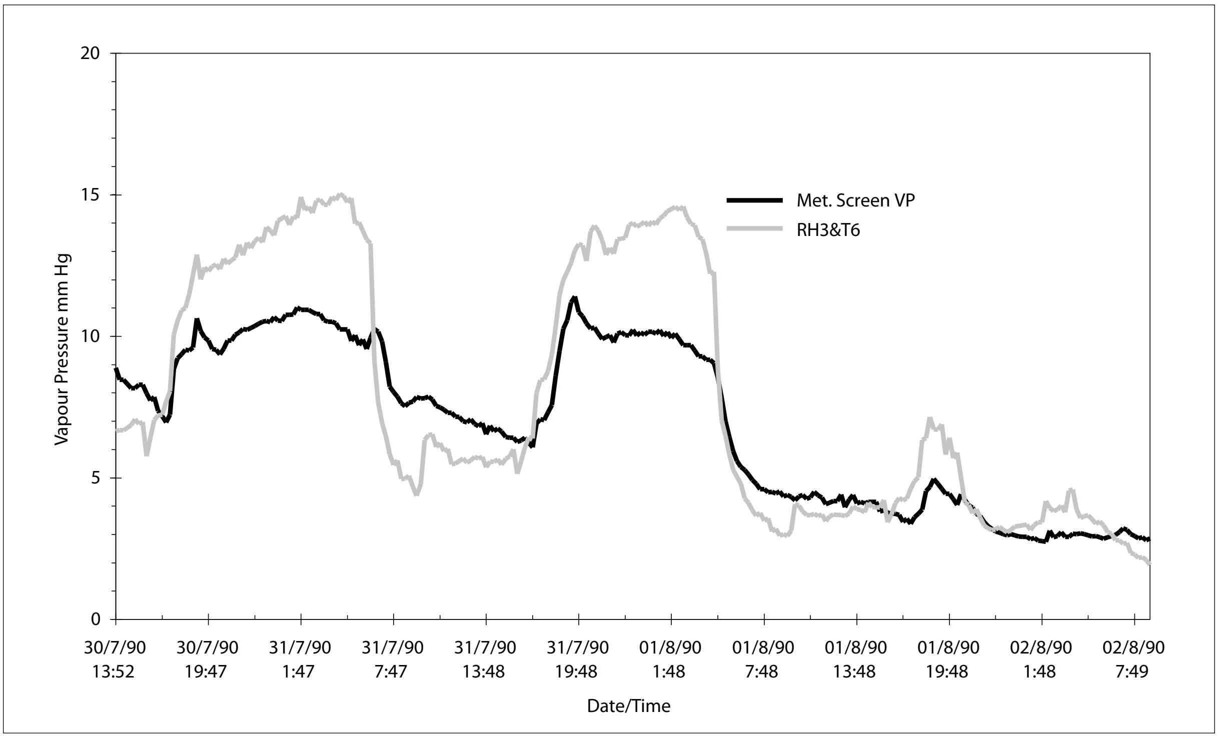

Figure 22. *Yalgi* 1990 dry season P_{H2O} for the meteorological screen and the shelter.

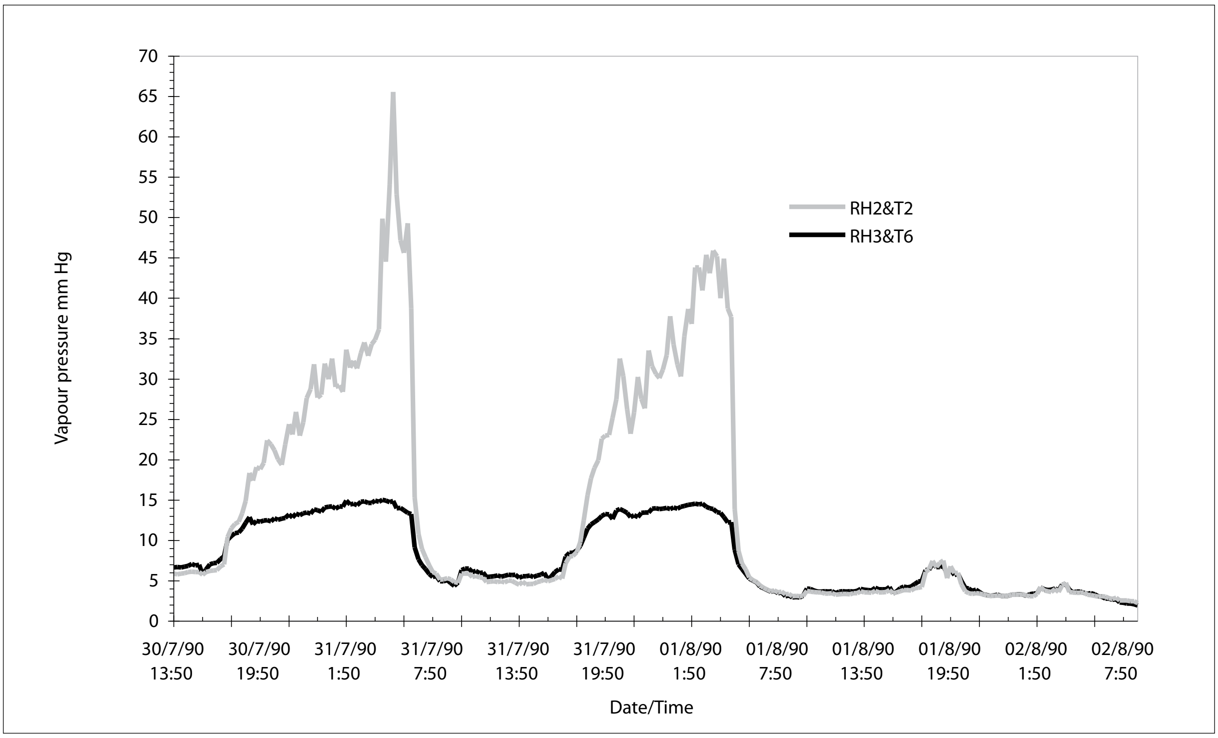

Figure 23. *Yalgi* 1990 dry season P_{H2O} for probe T2 adjacent to water seepage

a period of desiccation when the mean vapour pressure fell to around 7 mm Hg, which is characteristic of the dry season in the West Kimberley. Although the mean relative humidity was 24.7%, the range varied by approximately 60% in any one day, as moisture from the river was mobilised and brought by sensible heat flux to the rock surface. Owing to the local winds, the absolute humidity of the rock surface and meteorological screen were of a similar magnitude and proportionality.

The higher P_{H20} at the rock surface measured by RH3, T6 is due to the surfaces of the aged rock being more porous and inherently hygroscopic than the sterile

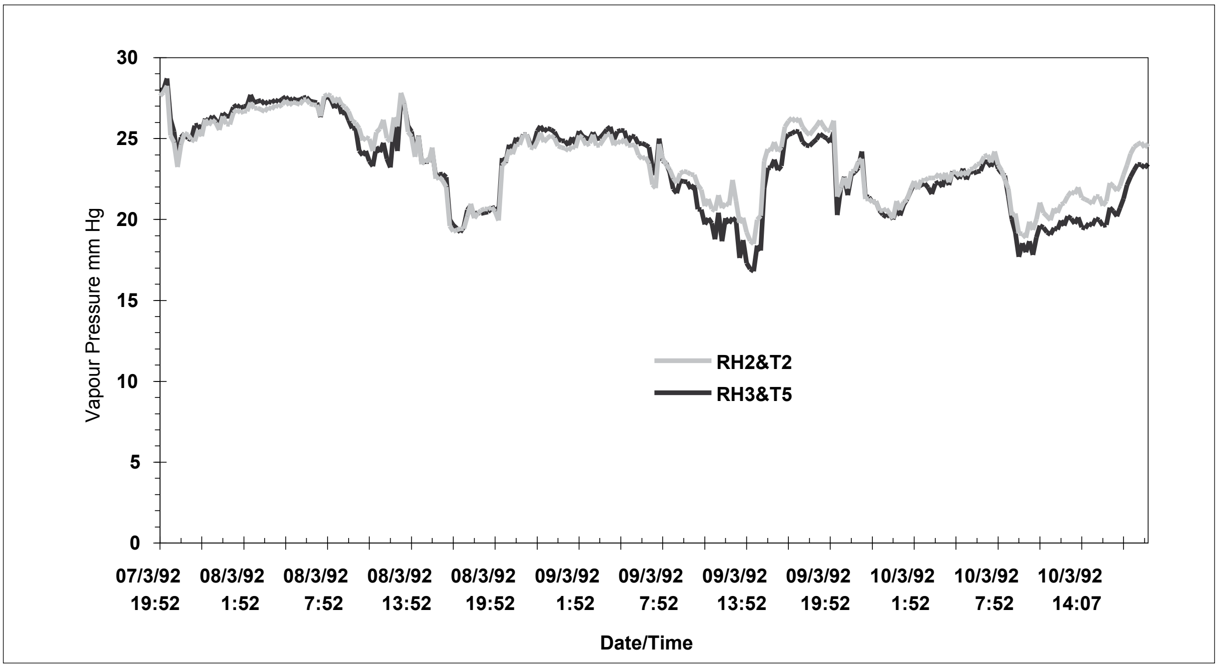

Figure 24. *Yalgi* in the 1992 wet season; P_{H20} in mm Hg vs time for T2 and T5 sensors.

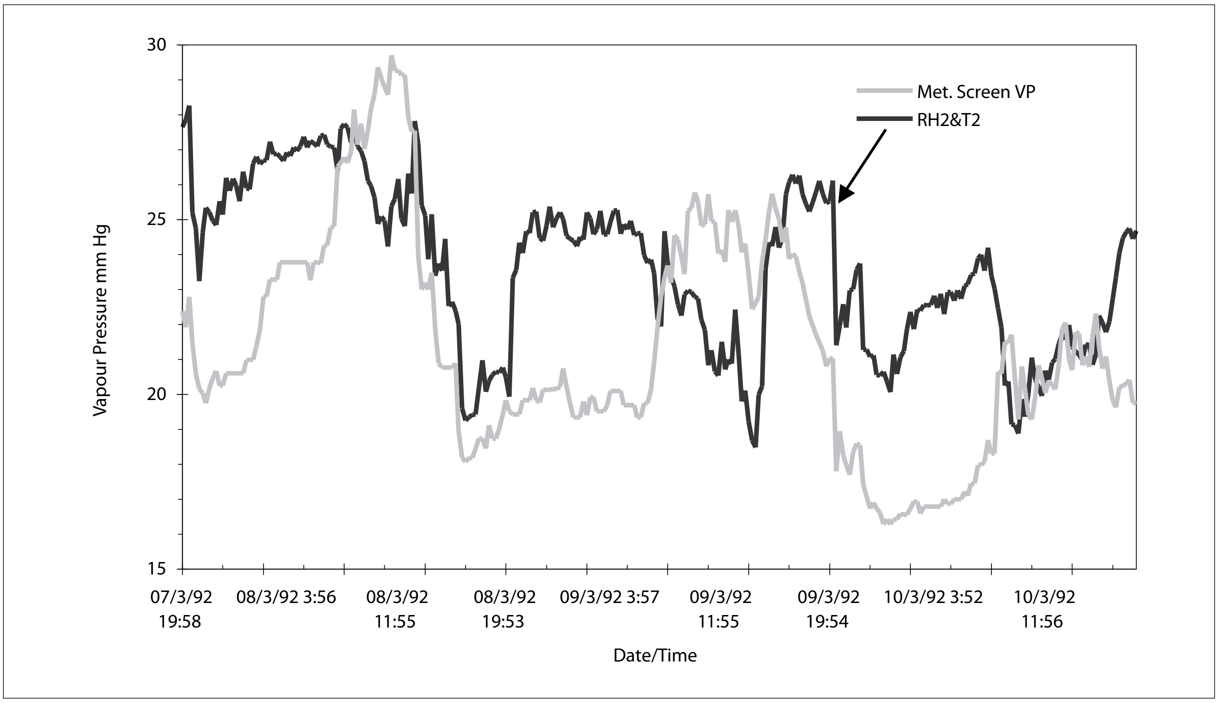

Figure 25. *Yalgi* wet season P_{H20} data from the meteorological screen and shelter seepage point.

metal sensors housed inside the meteorological screen.

The increased moisture at T2 is due to night-time water seepage, with maximum absolute humidity of 66 mm and 45 mm on the 31 July and 1 August respectively. By the following night the source of the seepage had dried up and the high moisture content had been reduced to normal levels by the arrival of a desiccating southerly wind that came from the desert areas. In contrast to the more open nature of *Moonooroo*, there is significant lowering of the swings in relative humidity at *Yalgi*, with a 70% RH diurnal change in the meteorological screen to only 30% on the site in areas away from the water seepage. Similarly the meteorological screen had a temperature range from 10°–35°C compared with 20°–30°C for the shelter.

Analysis of the night-time cooling intervals at *Yalgi* show

Figure 26. *Yalgi* site with water seepage near Wandjina image.

that all the measurement points cool at similar rates but have different maximum day time values, which causes the separation of the temperature-time plots. The differences are due to varying heat capacities of the underlying parent rock and the effects of sensible heat fluxes during the day. The cooling rate of – 0.385 ± 0.014 °C.hr^{-1} at T4 and –0.396 ± 0.010 °C.hr^{-1} at T9 are statistically indistinguishable from each other and are similar to the dry season data at *Moonooroo*, which shares a similar geology. Both sensors have a SKV of zero. There was insufficient data on the mean maxima and minima to establish any systematic relationship between the sky view factor and the turning points in the temperature-time plots.

'Yalgi' 1992 wet season

The relative humidity recorded in the shelter and in the meteorological screen was typical of the wet season, in that there were periods of increasing relative humidity associated with the incoming thunderstorms. Figure 24 shows that within the confines of the rock shelter there was good internal coherence in the microenvironment, with no real difference between the readings of T2 and T5, with average P_{H20} at around 24 mm Hg which is the same as at *Moonooroo* in the wet.

The data in Figure 24 is characterised by a gradual fall in P_{H20} over a period of five to six hours in the morning before the arrival of the afternoon thunderstorms which restore the P_{H20} back to the plateau level. The normal daily drying and rehydration cycles are best illustrated by Day 2, i.e. on 9 March 1992. The remarkable microenvironmental stability of the *Yalgi* site in the wet season is reflected in the mean value of the mean of the 11 temperature sensors, which was 29.4 ± 0.3°C, while the corresponding value for relative humidity was 80.9 ± 1.2 % RH for the four probes over the four days of measurements. The temperatures had a low mean range of 3.2 ± 0.3°C with mean maxima of 30.9°C and minima of 27.6°C, which should lead to less physical stress on the pigments attached to the rock surface. An increased understanding of the general nature of the microenvironment in the shelter is obtained by comparing the P_{H20} shelter data with that from the meteorological screen, as seen in Figure 25.

The P_{H20} at the water seepage point inside the shelter (RH2, T2) is about 4–5% RH higher than the corresponding data from the meteorological screen. On Day 1 the rock surface exhibits greater stability of absolute humidity, owing to its thermal inertia but as the day heats up the time and rate of fall in P_{H20} of the two sets of data is indistinguishable (see Figure 26). The rapid increase in P_{H20} for the seepage point on 8 March is likely to be associated with localised contribution from the rock. Just as the dry season saw this moisture source suddenly 'turn off' the sudden drop and increase in P_{H20} on Day 2 is likely to be due to a localised drying wind, which when gone, allows the site to re-establish its equilibrium.

Although the amount of cloud cover affected the cooling rates for the site there was a reasonable correlation of the minimum temperatures with the SKV since the R^2 value was 0.8705 for the *Yalgi* minima, given by equation 11:

$$^{\text{wet Yalgi}}T_{\text{minimum}} = 28.4 - 100\ \text{SKV} \qquad 11$$

The night-time cooling rates at *Yalgi* in the wet season were lower than in the dry season, as is expected on the basis of the increased heat capacity of the water vapour surrounding the rock surfaces. Sensors T1 and T9 cooled at the rate of –0.081 ± 0.016 °C.hr^{-1} and –0.233 ± 0.023 °C.hr^{-1} respectively and since both points had a zero SKV the different cooling rates relate to their relative positions at the rear and towards the front of the shelter, since the sensors were responding to different thermal masses of the surrounding rock.

Effects of rock type on cooling rates

The variable nature of the rates of cooling and heating at rock surfaces has been shown to be due to the concomitant changes in the absolute humidity or P_{H20} prevailing at the time. The only time when night-time heating was observed was on the porous calcarenite rock of the *Barralumma II* site in the Napier Ranges. The siliceous sandstone of the Mitchell Plateau had insufficient porosity to act as a 'sponge' for the moist air. Discussion of the cooling rates, as observed through the minimum temperatures recorded at the different sensors on the four rock art sites, has shown that in the absence of significant cloud cover, the rate of cooling is strongly dependent on the SKV. During the wet season the amount of cloud cover can dramatically alter the amount of open sky available for cooling, thus a cooling rate of $-0.75\ °C.hr^{-1}$ at T9 at Bilyarra fell to only $-0.3\ °C.hr^{-1}$ in the presence of cloud cover. *Barralumma II* experienced the greatest changes during the dry season where the impact of moisture fronts has the potential to alter the way in which the rock surfaces respond to changes in the microenvironment. A net increase of 0.94 mm Hg/day was able to change the T8 cooling rate from $-0.45\ °C.hr^{-1}$ to a heating rate of $+\ 0.129\ °C.hr^{-1}$.

When the slope of the temperature maxima and minima as a function of SKV, i.e. $\delta T/\delta SKV$ are compared there appear to be systematic differences between the wet and dry seasons that are related to the underlying geology of the sites. Thus in the dry season the Napier Range calcareous sites have an average slope of 185 for the T_{max} plots, while the siliceous sites in the Mitchell Plateau have much lower values of 60. This indicates that the greater porosity of the underlying rock makes the sites more sensitive to the sky view factor when the sites are warming up. In the same way the average slopes of the T_{min} plots against the SKV are –500 for the Napier Range sites and –165 for the Mitchell Plateau. Within experimental error the ratios of the heating and cooling rates in the dry season are the same at 3 : 0 which indicates that the porous ancient Devonian coral reef is three times more sensitive to the SKV for heating and cooling than the siliceous sandstone.

Since the rate of cooling is more directly dependent on long-wave emission of energy from the site it is only natural that the slope of the plots is much greater for the cooling rather than the heating curves. It has already been noted that the range of temperatures in the wet season is much less than in the dry, owing to the increased heat capacity of the moist air and so it is to be expected that the wet season ratios will be less sensitive to the sky view factor. The Napier Range sites had average slopes of +100 for T_{max} and –200 for T_{min} while the less porous Mitchell Plateau sites had slopes of +40 for T_{max} and –100 for the minimum temperature. Within experimental error, the wet season rates are twice as sensitive for heating and cooling as are the sandstone sites.

Correlation of microenvironment with condition of painted images

The *Bilyarra* site is both visually and geologically complex as the site consists of a mosaic of botryoidal accretions; active and inactive calcite flows; exfoliated and exfoliating sections and an unstable inter-bedded layer. The rock surface is prone to laminar exfoliation, which periodically removes large sections carrying art with them. The eastern side of the shelter demonstrates the highest density and worst cases of laminar exfoliation and the relative humidity and temperature probes confirmed that this area was subjected to greater P_{H20} variation than the western end of the site, which had painted images in much better condition. It is possible that the multiple layers of repainting makes the most recent images subject to relatively rapid loss owing to the fact that the pigments are bonded to a mixture of other degraded pigments and the parent rock. In some areas the highest points of the rock shelter appear to be more extensively covered with pigment but this may simply be a reflection of the lower sky view of the area, which will result in less extreme rates of heating and cooling and lead to a disproportionate chance of survival. In the same way the paint on the lowest points of the surface has remained relatively intact. The inherent chemical reactivity of pigments such as calcite $CaCO_3$ and huntite $Mg_3Ca(CO_3)_4$ may in part be masked by their compatibility with the calcareous substrate. Similarly the grey-white silicate pigment of sericite-illite $K_{1.1.5}Al_4(Si,Al)_8O_{20}(OH)_4$ and the off-white gypsum $CaSO_4.2H_2O$ are chemically stable while the apparent cream pigment of whewellite $CaC_2O_4.2H_2O$ is likely to be an alteration product of the huntite. Detailed descriptions of the pigments on the West Kimberley sites have been previously reported (Ford et al. 1999).

The *Barralumma II* site is located within an area of back-reef Devonian limestone and the geology exhibits typical karst weathering features. Ferruginous bedding planes dominate the shelter and the surface texture and profile is coarse and highly irregular. The site lies on the northern outside edge of the Napier Range looking northwards towards the King Leopold ranges, with the area in front of the site bounded by limestone on the eastern and western side. The northern side opens out onto the plains. The site is situated at ground level within an overhang about 25 m long, 5 m deep and 2.5 m high at the dripline. The paintings are predominantly placed over much of the ceiling area, though some are on the back wall. Apart from the absence of illite as a pigment, the original minerals and their alteration products, in the form of calcium oxalates, were very similar to that found at *Bilyarra*. There are some discrete areas of considerable exfoliation within the shelter where the ceiling surface has delaminated in both large and small quantities. These areas do not affect the preservation of the paintings.

The site at *Barralumma II* was the subject of a major repainting exercise in 1987 but this activity did not hide the presence of multiple layers of repainting as generations of elders practiced the law associated with the site. Some whewellite accretions are accumulating on the surfaces of older pigments. There are a few groundwater seepage zones in the shelter, but neither these nor rainwater pose any immediate threat to the paintings. During the wet season there was a significant increase in the amount of algal growth on drip lines and mould colonies on damp patches of the surfaces.

Moonooroo and *Yalgi*, situated on or near the Mitchell Plateau, both consist of originally clear quartz sandstone that has been subjected to a fairly intense metamorphism such that the individual sand grains have been deformed and forced together. Void spaces are negligible, hence the very low porosity, and there has been some secondary silica (overgrowths) further cementing the grains together. Traces of iron normally present in the parent rock display some secondary silicification on the weathered surface, which is often associated with secondary iron staining. Weathering is generally in the form of granular disintegration on the upward-facing surfaces and sheet exfoliation, leading to the leaching of silica. At *Moonooroo* the surface profiles for the sites A and B are smooth, whereas the substrate for the sub-site C is predominantly coarse and irregular. Despite the fair condition of the paintings in sub-sites A and B, there are some major problems with the long-term preservation of the pigments. Huntite is the predominant pigment used for Wandjina paintings (Mowaljarlai 1988, Clarke 1976) as well as some kaolinite. There was one instance where the aluminium phosphate mineral taranakite, $K_3Al_6H_6(P0_4)_8.18H_20$, was present as a major component in a sample taken from the silica build up that covered part of the images. Quartz and amorphous silica are the dominant mineral species that were intermixed with other pigments such as the red goethite, γ-FeO.OH and the transformation product whewellite.

The shelter at *Yalgi* has been formed by block weathering and consists of an outcrop located adjacent to a low sandstone cliff which runs parallel to a large creek. There are numerous fissures located on the ceiling and rear wall that have produced a matrix of botryoidal accretions and areas of smooth and irregular surface profiles. The paintings are situated on the back of the ceiling and the back wall. The most poorly preserved paintings are located on the rear wall and on the adjacent ceiling area, where the deterioration has been caused by salt and water seepage through nearby fissures in the rock. There was considerable loss of the white pigments huntite and calcite associated with Wandjina eyes and evidence of spalling as well as figure-cutting that lead to a complete loss of detail of the paintings, leaving a 'background' red pigment, with residual white and yellow pigments. The adhesion of the charcoal pigments to the underlying white material is characteristically poor and again this is why there is major loss of the 'eyes' of the Wandjinas. The microenvironmental data indicated that *Yalgi* had the highest P_{H20} values of the four sites in both seasons and this is reflected in the large number of botryoidal concretions as well as the di-hydrated calcium oxalate, weddellite $CaC_20_4.2H_20$, which was found in two pigment samples.

Conclusion

While some data on the nature of microclimates in shelters and the survival of painted surfaces has been published (see for example Dragovich 1981), little has been reported on the complex nature of the sites and painted surfaces in the Kimberley region of Western Australia. The analysis of the microclimate data collected over the 1990 dry season and the 1992 wet season in the West Kimberley rock painting sites in the Napier Ranges and in the Mitchell Plateau has yielded significant information regarding the nature of the processes controlling the deterioration of the images. The hydration and dehydration of a site and of specific points within a site has been shown to be sensitive to the rates at which the points heat and cool. The cooling rates are controlled by the long-wave emission of heat energy and as such the rates are dependent on the amount of sky which can be viewed from this point. Thus, in the absence of other competing phenomena, the sky view factor (SKV) will control the rate at which the heat dissipates from the rock surface. The complexities associated with trying to interpret the temperature and relative humidity data plots has been made simpler through the use of plots of water vapour pressure as a function of time. In a 'closed system' the vapour pressure of water is constant and in these situations the rate of night-time cooling can be regarded as a baseline parameter, which varies according to the SKV and to the substrate. Variations in the cooling rates of specific reference points within a site have been found to be dependent on the rate at which the water vapour pressure falls. Increased rates of loss of the water vapour pressure result in greater night-time cooling rates. It is interesting to note that the converse is also true—that the cooling rates are reduced when moisture, as measured by the rate at which the water vapour pressure is increasing, is entering the system. In cases of zero SKV, night-time heating can occur as the adsorbed water gives off heat as a result of the chemisorption of water by the rock surface.

Specific differences in the hydration profiles of various parts of images on some sites have been shown to correlate with differences in apparent state of preservation of the pigments. Moisture emanating from fissures within the rock substrate has been shown to provide a significant increase in available water for hydration/dehydration cycles during the dry season. Traditional thought has indicated that little deterioration occurs in the dry season and that the wet season brings about the most significant change in deterioration of the images. Our measurements have shown that even in the dry season there are very significant changes in the amount of moisture in the rock.

The massive temperature spikes associated with some of the sites are indicators of rapid increases in the local amount of air movement and with this comes the heat loss due to the desorption of the water that is in the surface layers of the rock and the images. Evidence of the association of absorption of water from moisture laden air with changes from night-time cooling to night-time heating has been able to explain why the simple model based on no sensible heat flux cannot adequately explain the diurnal temperature profiles on the rock surfaces (MacLeod and Haydock 2002).

Acknowledgments

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Author biographies

Ian MacLeod has worked for the Western Australian Museum for 30 years in a variety of roles involving conservation of collection items, shipwreck and rock art sites. He inherited a rock art survey grant to review the pioneering work of John Clarke and teamed up with Philip Haydock who was then an Environmental Science student at Murdoch University. They have worked collaboratively for more than 20 years.

Phillip Haydock was trained in micrometeorology by Professor Tom Lyons at Murdoch University and graduated in rock art conservation during the Getty-sponsored course at the University of Canberra along with Bruce Ford. He has worked extensively on sites throughout Western Australia and the Northern Territory and is now focused on assisting Aboriginal communities in managing their land and cultural resources.