INTERPRETATION OF ROCK VARNISH IN AUSTRALIA: CASE STUDIES FROM THE ARID ZONE

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SUMMARY: Rock varnish has a long history of study in Australia. Although Australian varnishes have biological, chemical and morphological similarities to varnishes in other continents, rock varnishes in arid Australia tend to be less stable than in other drylands. Still, with careful sampling, radiocarbon and cation-ratio dating of rock varnish has been used to constrain the age of Henbury Meteor Craters, Northern Territory, and rock engravings in South Australia and New South Wales, as well as to assess the geomorphic surface stability of Ayers Rock, Northern Territory, and the slopes of Pepuarta Bluff in the Olary Province of South Australia.

Rock varnish is recognised today as a dark coating that forms on stable rock surfaces. Its thickness in Australia can range from less than 5 microns to over 200 microns. One of the thickest subaerial varnishes yet observed, about 1.1 mm, was sampled from the Ashburton surface, Northern Territory (cf. Stewart *et al.* 1986). Often called 'desert varnish' because it is most noticeable in drylands, rock varnish can be found in virtually every terrestrial weathering environment. This was observed early in the study of arid Australian varnish (Moulden 1905; Basedow 1914) and stream varnish (Francis 1921). Rock varnish is composed typically of over 50 per cent clay minerals (Potter and Rossman 1977; Raymond *et al.* 1988), about 20-30 per cent manganese and iron oxides (Potter and Rossman 1979) and over 30 other minor and trace elements (Bard 1979; Dorn and Oberlander 1982; Duerden *et al.* 1986; Table 1). The abundance of manganese (Mn) and iron (Fe) in the upper few microns generally controls its appearance. The colour is usually black if Mn is present in similar concentrations relative to iron, or if manganese dominates. If Mn is much less abundant than Fe, the colour becomes orange to dusky-red.

The published study of varnish in Australia started with the observations of Moulden (1905), who identified varnish on 'pebble-covered plains' in central and arid South Australia. A more thorough set of observations was made by Basedow (1914), who was concerned mostly with the age of rock engravings. The development of varnish was believed to reflect the antiquity of the petroglyphs. At the time, the most authoritative works on varnish were by Walther (1891) and Lucas (1905). While accepting Lucas' hypothesis for the origin of varnish by water evaporation, Basedow (1914: 199) believed 'that the excessively fine, floating and suspended material in the desert atmosphere may also take part in the formation.' Basedow's hypothesis on the role of aeolian fallout in composing subaerial rock varnishes was verified much later by Potter and Rossman (1977) and subsequent researchers (for example, Allen 1978; Perry and Adams 1978; Elvidge and Collet 1981; Dorn and Oberlander 1982).

Francis (1921) presented from Queensland some of the first observations in the world of stream-side varnish. Francis, one of the first to propose a biological origin for 'desert varnish', argued that the manganese coatings found along stream channels were from algal activity. Francis also believed that the manganese and iron in the varnish are derived from a source external to the underlying rock; this was verified a half a century later (Potter and Rossman 1977; Allen 1978; Perry and Adams 1978; Dorn and Oberlander 1982; Elvidge and Iverson 1983).

Recent chemical and archaeological work on Australian varnishes has been conducted mostly by Dragovich (1984a, 1984b, 1985, 1986a, 1986b, 1988a, 1988b) and colleagues (Duerden *et al.* 1986). Staley *et al.* (1983) argued for the importance of microcolonial fungi in the development of Australian varnishes. Other research on rock varnish in Australia has consisted of isolated but important observations on environmental associations with varnish (for example, Talbot 1910; McMath *et al.* 1953; Mabbutt 1979; Bourman and Milnes 1985). The purpose of this paper is to present new data on the origin and characteristics of rock varnish in Australia, to review what is understood about rock varnish in Australia, and to assess the use of rock varnish in archaeological and geomorphological research.

STUDY SITES AND METHODS

Sampling was conducted in the central and south-eastern parts of the Australian arid zone, as well as at selected humid locations (Figure 1). Rock varnishes were sampled from a variety of microenvironments: subsurface; ground-line band; surface just above the soil; surface over a metre

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bove the soil and exposed to only subaerial ıllout (preferred microsite for dating work); in nopened rock crevices; on soil peds; on rocks in marine littoral environment; rocks on stream oint bars; and boulders formerly exposed to the ubaerial environment but buried by flood depos-s.

Most of the varnishes analysed here are the lack, manganese-rich variety collected in the arid ɔne. Stream varnish, marine littoral varnish, varish on subaerial surfaces in humid environments or example, the Mount Gambier volcanics), and arnishes from the arid zone that are not Mn-rich ave also been analysed in order to assess the hemical variability of Australian rock varnishes. t sites where varnishes were collected, other aterial in the local environment was also samed: runoff (where available); dust deposited in epressions on rocks; surficial soil; and adjacent egetation.

We have used a wide variety of methods to nderstand the nature of Australian varnish. Chemal analysis of varnish was carried out by proton duced X-ray emission (PIXE) (cf. Cahill *et al.* 984; Duerden *et al.* 1986), electron microprobe f. Dragovich 1988a; Dorn 1989a), and energyspersive analysis of X-rays (EDAX) with a scanng electron microscope (SEM). Structural obsertions were made of varnish surfaces and crossctions by SEM and light microscopy (cf. Dorn 1986, 1990). Age determination of rock varnish was by cation-ratio (Dorn 1983, 1989a) and accelerator-radiocarbon (Dorn *et al.* 1986, 1989) dating methods.

Biological culturing of microorganisms on varnishes was also conducted. Varnishes were scraped with a sterile needle into sterile tubes. The chips were then cultured in the laboratory as described by Dorn and Oberlander (1981, 1982). In addition, undisturbed varnishes were collected and placed in sterile collection tubes for later SEM-EDAX viewing. Possible microbial influences were studied at the following sites in Figure 1: Undoolya Gap near Alice Springs (Northern Territory), Henbury Meteor Craters (Northern Territory), Ayers Rock (Northern Territory) and Oulnina Homestead (South Australia).

CHARACTERISTICS OF AUSTRALIAN VARNISHES

Like rock varnishes elsewhere, the chemistry of Australian varnishes is highly variable. This is true on a micron-scale (Dragovich 1988a), from microsite to microsite in a 100 m² to 10 km² area, and on the scale of a continent. The chemistry of selected varnishes in Australia is compared with varnishes from other sites worldwide (Table 1A, 1B, 1C).

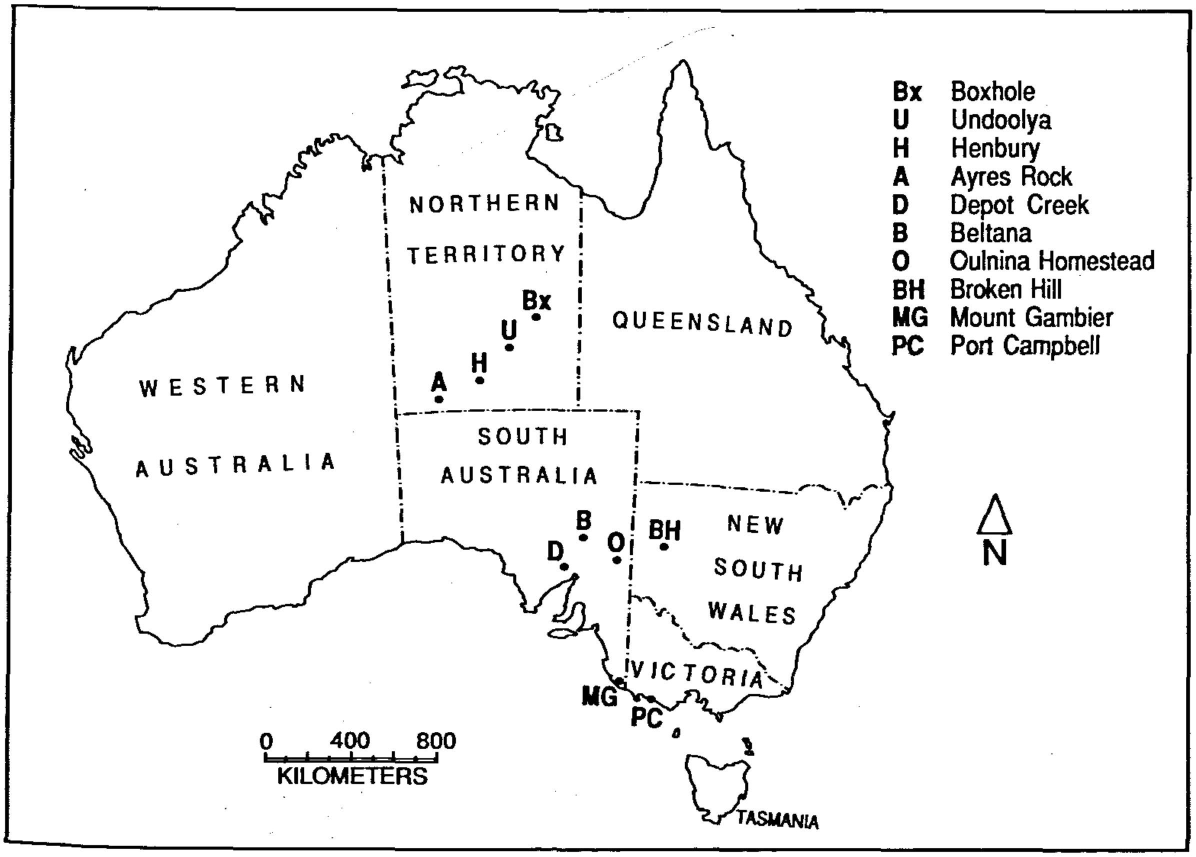

Figure 1: Areas of varnish collection in Australia.

If only subaerial exposures are considered, Australian varnishes appear to have a higher Mn:Fe ratio than varnishes from other deserts. The greater abundance of manganese in varnishes from the Australian arid zone may be explained by water balances of the locations where varnish forms. Oberlander (1979) calculated Thornthwaite's aridity index (Ia) and Oberlander's soil water balance (Ib) for desert stations. When these Ia and Ib values are compared with the Mn:Fe ratios of varnishes collected near the meteorological stations, the least-squares correlation is statistically significant at $p = 0.05$ (Figure 2). When more moisture is available, more manganese is present in the varnish. This is probably because alkalinity of the environment is reduced under conditions of greater moisture effectiveness, and alkalinity inhibits the concentration of manganese (Dorn 1990).

Ayers Rock illustrates the importance of microsite in controlling the concentration of manganese and iron in varnishes. The natural colour of Ayers Rock is almost white. Yet this photogenic landmark is world famous for the interplay of sunrise and sunsets off its orange colouration. This colour is due to the dominance of orange, manganese-poor varnish. The surface of Ayers Rock is in a constant state of weathering and erosion of scales a few centimetres thick. The orange varnish starts to form first in unexposed crevices that are 'preparing' to scale off as they gradually separate from the underlying shell. As will be elaborated in the dating section, some of these 'crack varnishes' started to form within the subsurface during the late Pleistocene about 27,000 yr BP. The chemistry of this orange crack varnish (Table 1C) is similar to ambient levels in the dust, reflecting high levels of Si, Al and Fe with little or no concentration of Mn. Samples of the desert dust that accumulated in five crevices yielded pH values of 7.2, 7.7, 8.3, 8.6 and 9.2. Since alkalinity

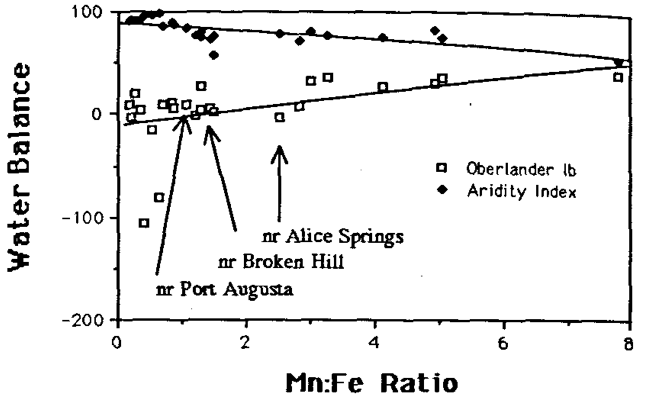

Figure 2: Manganese:iron ratios of varnishes collected near meteorological stations compared with their water balances, from Australian (indicated), western North American, Negev Desert and Atacama Desert sites. Thornthwaite's aridity index and Oberlander's (Ib) water balance are presented in Oberlander (1979) and discussed in the text. As the water balance becomes more moisture effective, the aridity index decreases and Ib increases. The correlations between Mn:Fe and the water balances are significant at $p = 0.05$. These data indicate that as the environment becomes more moisture effective, manganese concentrations increase.

Table 1: Comparison of select varnish chemistries at worldwide sites (1A), with those around Australia (1B), and those at Ayers Rock (1C). Australian sites are shown in Figure 1. Unless stated otherwise, the type of varnish analysed is black in colour and exposed to the subaerial environment. PIXE results are normalised to 100 per cent. Electron microprobe values are in oxide weight per cent; however only the cation is listed. 'bld' indicates below limit of detection; 'na' indicates not analysed.

Table 1A: WORLDWIDE SITES

Elemental abundance	Alibates Nat Monum, Texas, USA	Trail Cyn Fan Death Valley, Calif., USA	Timna, Negev Desert, Israel	Beacon Valley, Victoria Land, Antarctica	Khumbu Till near Lobuche, Nepal	Region near Ingenio, Peru
Method Used	PIXE	PIXE	PIXE	PIXE	PIXE	Microprobe
Li	na	na	na	na	na	na
F	na	na	na	na	na	na
Na	bld	bld	bld	bld	bld	0.35
Mg	0.26	0.14	1.23	bld	0.14	1.97
Al	27.91	23.74	20.93	6.24	24.72	17.22
Si	38.56	39.09	42.36	20.21	38.94	42.14
P	bld	0.49	0.26	bld	0.23	0.57
S	bld	0.7	0.4	bld	0.55	0.92
K	2.53	3.45	2.0	5.72	2.35	2.53
Ca	6.76	4.87	5.29	8.4	4.69	5.73
Ti	2.1	1.52	1.62	bld	1.00	0.78
Mn	10.7	10.87	9.01	2.92	17.33	4.28
Fe	8.9	13.47	14.17	34.11	9.24	11.06
Ni	0.24	0.13	bld	0.36	bld	na
Cu	0.3	0.12	0.36	0.21	bld	na
Zn	0.21	0.27	bld	0.24	bld	na
Rb	bld	bld	0.22	bld	0.13	na
Sr	bld	bld	bld	bld	bld	na
Zr	bld	0.29	0.12	bld	0.14	na
Ba	1.53	0.85	1.4	0.52	0.54	2.48
Pb	bld	bld	0.63	bld	bld	na

Table 1B: AUSTRALIAN SITES

Elemental Abundance	Depot Creek near Port August, SA	Undoolya Gap near Alice Springs, NT	Ejecta Blanket Henbury Crater #4, NT	Pepuarta Bluff near Mannahill Olary Prov. SA	Near Broken Hill NSW	Near Broken Hill NSW	Humid varnish Mt. Gambier SA	Marine crust near Port Campbell Victoria	Stream varnish near Port Campbell Victoria	Dark red varnish near Broken Hill NSW	Dark, iron-rich varnish west of Port Augusta, SA
Method Used	PIXE	PIXE	PIXE	PIXE	PIXE	Microprobe	PIXE	PIXE	PIXE	Microprobe	Microprobe
Li	na	na	na	na	104 (ug/g)	na	na	na	na	na	na
F	na	na	na	na	590 (ug/g)	na	na	na	na	na	na
Na	bld	bld	bld	bld	0.21	0.17	bld	bld	bld	1.14	0.06
Mg	bld	0.59	0.36	0.44	0.74	2.87	1.42	2.78	bld	1.27	0.44
Al	18.10	20.40	29.00	18.03	10.9	17.05	22.68	2.47	6.23	25.92	0.46
Si	32.62	25.79	37.46	27.05	30.3	38.13	41.95	15.23	13.72	35.06	3.14
P	0.34	bld	bld	bld	0.6	0.46	0.24	0.72	bld	2.56	0.18
S	bld	bld	bld	bld	na	0.09	bld	bld	bld	0.24	0.06
K	3.75	2.59	2.66	2.76	2.05	2.83	3.06	1.43	1.37	1.54	0.01
Ca	5.33	2.39	3.38	2.70	0.39	3.28	1.59	3.58	2.00	0.44	0.27
Ti	1.22	0.86	0.73	1.21	0.37	0.95	0.45	0.72	0.84	1.3	0.02
Mn	20.29	31.92	14.50	25.76	3.8	12.51	18.14	30.46	47.48	5.5	0.06
Fe	16.73	12.77	10.88	20.61	4.71	9.64	10.21	41.21	26.38	17.85	88.90
Ni	bld	0.33	0.24	bld	145 (ug/g)	na	bld	0.54	0.42	na	na
Cu	0.42	0.57	bld	0.80	73 (ug/g)	na	0.26	0.14	0.40	na	na
Zn	bld	0.20	bld	bld	499 (ug/g)	na	bld	0.36	0.20	na	na
Rb	0.23	bld	bld	bld	87 (ug/g)	na	bld	bld	bld	na	na
Sr	bld	bld	bld	bld	232 (ug/g)	na	bld	bld	bld	na	na
Zr	0.31	0.17	0.48	0.26	143 (ug/g)	na	bld	bld	bld	na	na
Ba	0.67	0.54	0.30	0.39	0.48	1.65	bld	0.36	0.95	na	na
Pb	bld	0.89	bld	bld	570 (ug/g)	na	bld	bld	bld	na	na

Table 1C: SITES AT AYERS ROCK

Elemental abundance	Black surface varnish on fracture	Black water streak varnish w/o organics	Black water streak varnish with lichens	Orange crack varnish, not exposed at surface	Orange varnish exposed at surface	Black crack varnish, not exposed at surface	Surface black varnish, on layer of orange varnish	Layer of orange varnish beneath black surface varnish
Method	PIXE	PIXE	PIXE	PIXE	PIXE	PIXE	Microprobe	Microprobe
Li	na	na	na	na	na	na	na	na
F	na	na	na	na	na	na	na	na
Na	na	bld	bld	bld	bld	bld	na	na
Mg	1.36	1.01	5.03	1.15	1.44	1.58	1.48	0.72
Al	28.46	22.34	22.87	29.18	29.84	28.77	20.21	17.5
Si	37.63	19.4	18.07	34.31	35.9	35.69	38.99	31.63
P	bld	bld	bld	bld	bld	bld	na	na
S	bld	bld	bld	bld	bld	bld	na	na
K	1.68	1.35	4.88	1.33	1.38	2.11	2.09	0.84
Ca	1.25	1.67	1.05	1.25	1.31	1.45	4.88	5.76
Ti	1.07	0.91	2.2	0.9	1.45	1.19	0.86	0.77
Mn	7.52	36.79	22.07	1.21	2.01	11.91	15.74	0.27
Fe	20.15	14.41	22.74	30.04	25.82	16.57	10.3	28.55
Ni	bld	bld	bld	bld	bld	bld	na	na
Cu	0.15	0.2	bld	bld	0.15	bld	0.23	0.06
Zn	0.23	0.38	bld	bld	0.28	bld	na	na
Rb	bld	bld	bld	bld	bld	bld	na	na
Sr	bld	bld	bld	bld	bld	bld	na	na
Zr	bld	bld	bld	bld	bld	bld	na	na
Ba	0.49	1.55	1.09	0.62	0.43	0.73	0.51	1.22
Pb	bld	bld	bld	bld	bld	bld	na	na

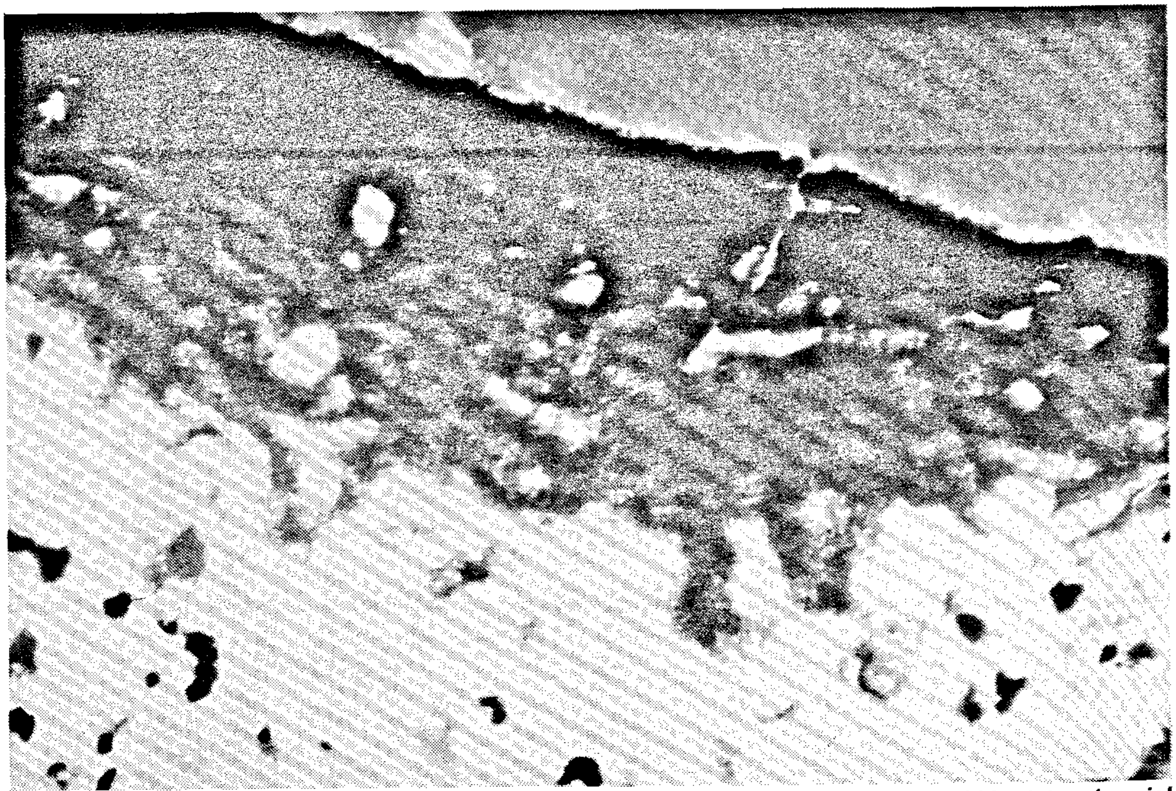

***Plate 1:** Thin section of rock varnish from Ayers Rock. The darker surface layer is of Mn-rich subaerial varnish accreted on an orange (Mn-poor, Fe-rich) varnish originally deposited in a crevice. In order to enhance the contrast between the layers of black (Mn-rich) and orange (Mn-poor) varnish, the texture of the underlying rock was washed out in the photographic printing. Still, the irregular subsurface boundary between the orange varnish and the rock can be detected. The total thickness of the varnish is about 80 microns.*

inhibits the oxidation of manganese by varnish-forming microorganisms (Dorn and Oberlander 1981, 1982), and alkalinity would also inhibit the concentration of manganese (Dorn 1984, 1990) if it occurred by a purely abiotic mode of manganese enhancement (cf. Smith and Whalley 1988), it is not surprising that the varnish colour is orange from an abundance of iron, but not manganese.

After the overlying scale spalls or opens enough to wash away the alkaline desert dust, the orange crack varnish is effectively exposed to the near-neutral subaerial environment and a coating of manganese-rich black varnish forms. Plate 1 illustrates black subaerial varnish formed on an orange crack varnish. Electron microprobe analyses of the underlying orange crack and overlying black subaerial varnish layers are presented in Table 1C. The scaling of the surface of Ayers Rock, therefore, controls its colour. In places that are more unstable, orange crack varnish dominates. On surfaces that are more stable or where crevices have opened enough to wash away the desert dust, black varnish has had time to develop.

The appearance of Ayers Rock is also affected by places where dark 'water streaks' have formed. The streaks consist of two different types of manganese-rich black varnish: with lichens and cyanobacteria and without these organisms. Where varnish grows with lichens (cf. Dorn and Oberlander 1982; Dragovich 1986b) or cyanobacteria, its development is patchy, reflecting a balance of rapid formation and rapid erosion. Where varnish grows in water streaks without competing microorganisms like lichens, the development of varnish is less patchy; it is also much thicker than normal subaerial and crack varnishes at c. 5-50 microns, reaching over 0.5 mm in places. The chemistry of the different varnishes are contrasted in Table 1C: orange crack and surface; black crack and surface; black water streak with lichens; and black water streak without lichens. This variability reflects different environmental controls on varnish development.

Plate 2: Cross-section of varnish collected from Pepuarta Bluff, Oulnina Homestead, South Australia. The parallel lamellate structure indicates abundant clay minerals. Note the distinct morphological break between the underlying rock and the varnish. Width of SEM image is about 40 microns.

While manganese and iron have received the most attention in varnish research, Si and Al make up the bulk of Australian varnishes (Table 1B, 1C). Although no clay mineralogical work has been conducted on Australian varnishes, the proportion of Al and Si is similar to varnishes in the US deserts that are known to be dominated by clays. Evidence for the importance of clays is also found in the structure of Australian varnishes as observed by SEM. The structure of varnish in Plate 2 is strongly suggestive of the dominance of clay minerals. Still, exceptions do occur, such as the iron-dominated coating in Table 1B, from west of Port Augusta.

Whatever is falling out of the atmosphere has a probability of being incorporated into subaerial varnishes. This includes organic matter, such as pieces of pollen grains or organics adsorbed to clay minerals. Minor elements of Australian varnishes are usually K, Ca, Ti, P, Ba, and Na. Trace elements include Li, F, S, Cl, Ni, Cu, Zn, Rb, Sr and Pb. With more sensitive analytical techniques such as neutron activation, we would anticipate the list would grow to over 30, as in some US varnishes (cf. Bard 1979).

The origin of Australian rock varnishes is only examined here for the arid zone. The origin of the clay poses no problem. Most have agreed that airborne dust of local or regional origin provides the clay minerals in varnishes (Potter and Rossman 1977; Dorn and Oberlander 1982; Elvidge and Iverson 1983; Raymond *et al.* 1988) and likely the bulk of the minor and trace elements in the varnish. Many trace elements such as Cu, Zn, Co, U, Th and Pb are scavenged by manganese and iron oxides (Dorn and Oberlander 1982).

The key to the origin of varnish is the mechanism(s) by which manganese and iron are enhanced one to three orders of magnitude above concentrations in adjacent rocks and soils. Although in some dispute (Smith and Whalley 1988), three different research groups (Krumbein 1969; Krumbein and Jens 1981 — Dorn and Oberlander 1981, 1982 — Taylor-George *et al.* 1983; Palmer *et al.* 1985) have concluded that the most reasonable mechanism for manganese concentration is biological. Iron, on the other hand, could be enhanced by either physico-chemical or biological mechanisms. A purely physico-chemical mechanism for the enhancement of manganese is unlikely (Krumbein and Jens 1981; Dorn and Oberlander 1982; Dorn 1989b).

Methods used in microbial culturing of Australian varnishes are described by Dorn and Oberlander (1981, 1982). Although not as systematic as the work in western North America, this study yielded clear evidence of manganese- and iron-enhancing bacteria growing on rock varnishes at all sites discussed in the study sites and methods section. *Pedomicrobium, Metallogenium* (or *Arthrobacter,* cf. Palmer *et al.* 1985), and eight other unidentified manganese-oxidising bacteria were cultured. These developed over a period of two to eight weeks. Manganese-enhancing bacteria were also observed *in situ* on samples collected in the field and placed in a sterile vial until examination with SEM and EDAX (Plate 3a and 3b). Although identification is not possible based on morphology observed by SEM, the general morphologies seen ranged from those resembling *Metallogenium* and *Pedomicrobium* budding bacteria (cf. Dorn and Oberlander 1982), as well as the cocciforms in Plate 3a. Antecedent rainfall occurred within three months of the collection of all samples, so it was not possible to determine if prolonged drought would influence the presence and type of manganese-oxidising microorganisms on the surface of varnishes in Australia.

One of the most noticeable aspects of the biology of Australian varnishes is the development of microcolonial fungi (Staley *et al.* 1982). In studying varnishes from a large number of sites in arid Australia, Staley *et al.* (1983) found an abundance of microcolonial fungi (MCF). We concur. An important issue here is the role of the MCF in concentrating manganese and iron. Most of the observations made under SEM suggest MCF in Australia are largely destructive of varnish, probably due to the secretion of organic acids (Plate 4a). Some MCF are buried by newly accreted varnish (Plate 4b). There was little evidence presented by Staley *et al.* (1983), and little evidence found here to indicate that microcolonial fungi concentrate manganese or iron in varnish. The vast majority of MCF appear to be agents of varnish destruction, while some are simply adventitious.

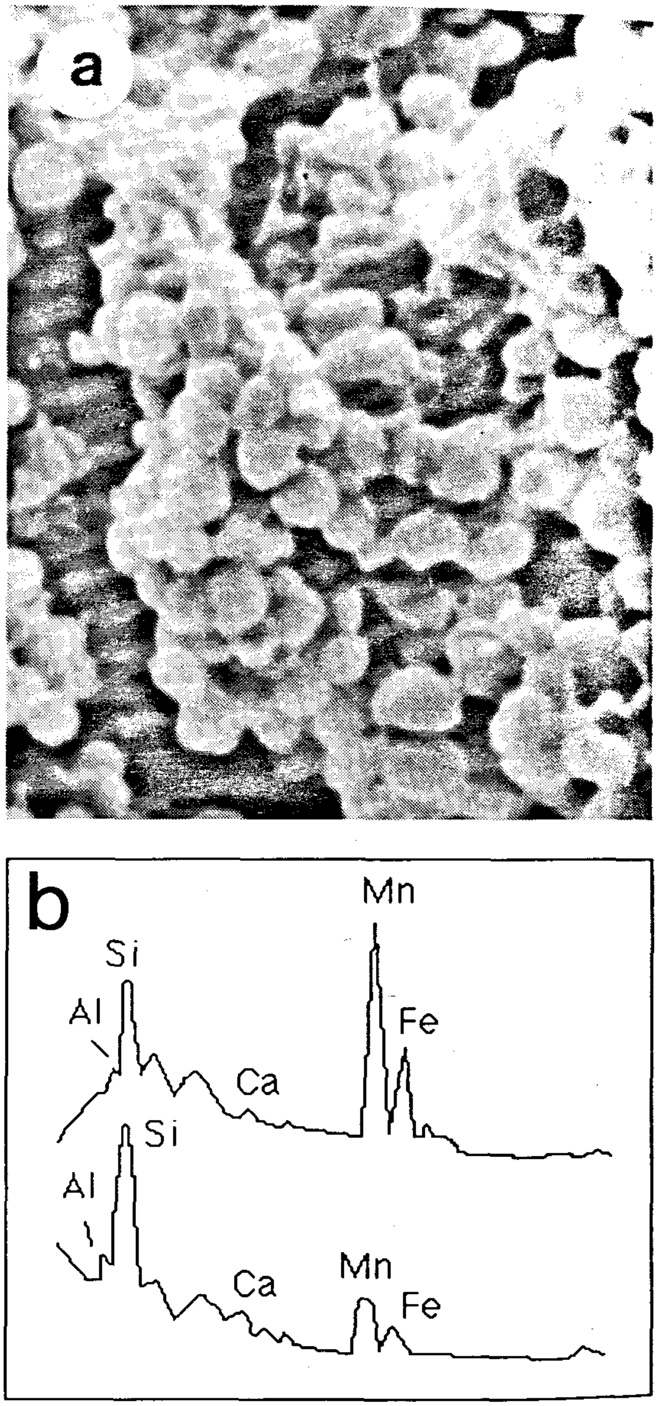

Plate 3: *Mn-concentrating bacteria observed* in situ *from Wilkatana, South Australia.*
a. Cocci bacteria growing on the surface of the varnish. Some of the cells are being coated with new varnish in the upper part of the image. Width of image about 10 microns.
b. Two EDAX signatures of the varnish in plate 3a. The signature that is greatly enriched in manganese and iron was taken by a spot chemical analysis from the bacteria. The signature that contains more Si and Al was of a less focused spot, incorporating X-rays generated from the varnish surrounding the bacteria.

The same factor, namely greater effective moisture in the Australian drylands than in many other deserts (cf. Oberlander 1979), promotes a higher concentration of manganese in Australian varnishes. Greater moisture promotes the development of manganese- and iron-concentrating bacteria, but greater moisture also promotes the development of microcolonial fungi, lichens, cyanobacteria and other organisms that compete for space on rock surfaces. These organisms also secrete acids that chemically erode varnish (Dorn and Oberlander 1982; Dragovich 1986b). In a model of varnish growth (Figure 3) much of the Austra-

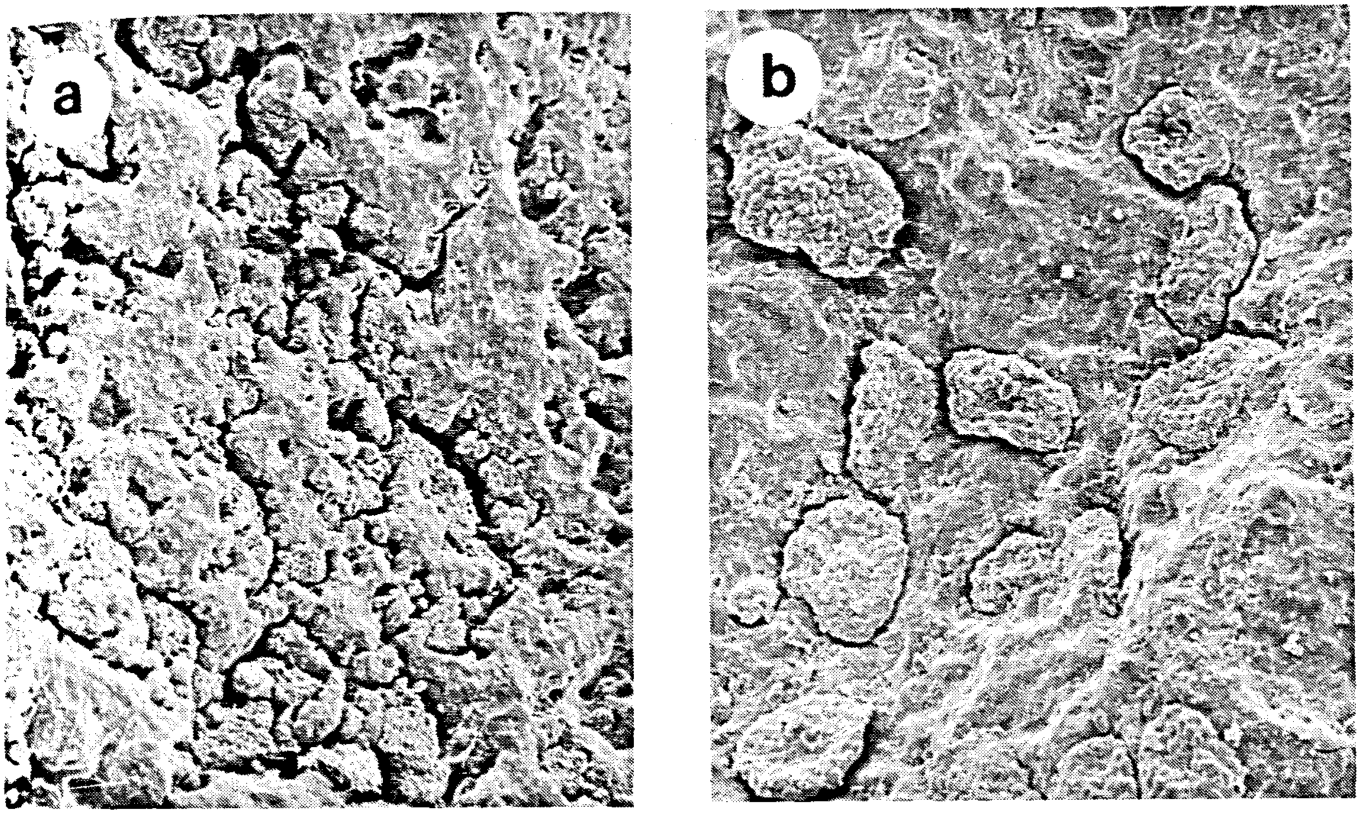

Plate 4: *Microcolonial fungi from the arid zone of Australia.*
a. Field of several hundred square microns dominated by microcolonial fungi eroding varnish, collected from near Jessie and Emily Gap, near Alice Springs, Northern Territory. Width of image about 400 microns.
b. Higher magnification view of typical microcolonial fungi, collected from subaerial orange varnish, Ayers Rock. Some are being coated by newer varnish. Other microcolonial fungi are eroding pits into the varnish. None of these microcolonial fungi tested with EDAX concentrate Mn or Fe. Width of image about 150 microns.

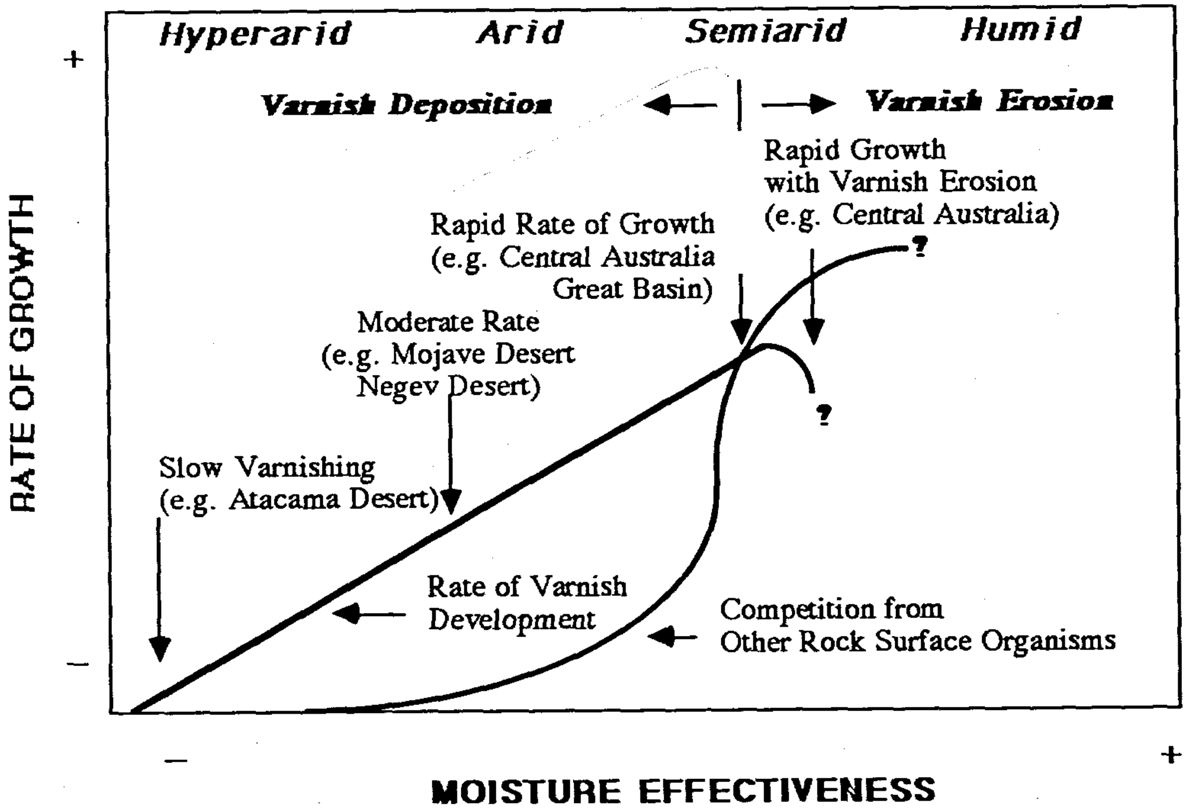

Figure 3: Theoretical model of varnish growth highlighting Australian varnish, as compared to warm drylands such as the Sonoran Desert, Mojave Desert and the Great Basin in North America, as well as Negev Desert and Atamaca Desert varnishes. Competition from rock surface organisms can completely inhibit the development of Australian varnish when the environment becomes too moist.

lian arid zone appears to be right around the peak of growth, and also very close to partial or complete varnish erosion. Whether varnish forms or erodes in Australia appears to be more influenced by biogeography than by inorganic geochemistry.

The micromorphology of rock varnishes in Australia was found to be mostly lamellate (Plate 5a), both at the surface and in cross-section (Plate 5b). Botryoidal varnish was observed on the Mount Gambier volcanics (Figure 5c), but only in patches elsewhere (Figure 5d). Botryoidal varnishes form when the accretion of manganese and iron around microbial nucleation points is greater than the deposition of clays. Lamellate varnishes form when the accretion of clays overwhelm the oxides (Dorn 1986). We anticipated finding much more botryoidal varnish, because a water balance similar to that found in much of arid Australia (cf. Oberlander 1979) would be associated with botryoidal varnish in North American drylands (Dorn 1986). This might be explained by the high frequency of dust storms in the areas of arid Australia where varnish was collected (McTainsh and Pitblado 1987). An alternative explanation might be found in a different mineralogy of the clays in Australian varnishes. North American and Israeli varnishes are dominated by mixed-layer illite-montmorillonite clays. The mineralogy of the clays in Australian varnishes is not known and could very well influence the micromorphology. Another explanation might involve differences in the microbial community concentrating the manganese and iron, and whether the enhancement tends to occur at nucleation centres, hence favouring the development of varnish botryoids. While the microbial communities of the Australian sites sampled seemed to be similar to the North American sites, the length of sampling and density of sampling sites was not comparable to the North American study (cf. Dorn and Oberlander 1981, 1982).

DATING GEOMORPHIC SURFACES

Dating the onset of rock varnish accretion provides a minimum-limiting exposure age for the underlying rock surface. There are two types of geomorphic applications of dating varnish. The first use is in providing a surface exposure age for a landform, if the varnish started to form soon after deposition or erosion ceased. The second use is in providing a time for when the very surface of the landform was last altered by weathering or small erosional/depositional modifications.

For a varnish date to reflect the true age of the landform requires a condition of no erosion for the microsite where varnish was sampled. Also, the varnish itself must form continuously as a synsedimentary deposit. This can be assessed by SEM or thin-section analysis (Dorn 1990). Uninterrupted deposition is frequently not the case in Australia. Thin-section analysis by SEM and light microscopy often revealed erosion by microcolonial fungi, lichens, and cyanobacteria (see also Dragovich 1986b). An age determination for an eroded varnish, whether it be by the cation-ratio or radiocarbon method, would represent a composite of the original varnish and any varnish that had refilled eroded pockets. It is especially critical that Australian samples be thoroughly screened before they are radiocarbon or cation-ratio dated, because the Australian drylands examined for this study appear to experience active biogeochemical erosion of varnish in all but the most xeric sites.

Henbury Meteor Craters in Australia provide an excellent laboratory to assess the use of varnish in providing a surface exposure age. There are constructional ejecta surfaces that reflect the timing of meteor impact. Henbury craters have age control from the cosmogenic ^{14}C content of the meteorite, indicating a maximum age of less than 4700 radiocarbon yr BP (Milton 1968). The varnish at Henbury craters also appears to be relatively free of the destructive influence of microcolonial fungi. Two accelerator mass spectrometry (AMS) ^{14}C ages for organic matter extracted from the bottom $\leq$ 10% of the varnish are 3420 ± 90 (Beta 22213; ETH 3199) and 3770 ± 85 (Beta 26690; ETH 4293). The oldest analysis more closely reflects the timing of impact, as varnish radiocarbon dates are minimum ages (Dorn *et al.* 1989). If the oldest age is corrected for a lag time between the exposure of the ejecta blanket and the accretion of the bottom layer of the varnish, calibrated to be about 10 ± 5% for semiarid sites of known age (Dorn *et al.* 1989), the best estimate for the age of the ejecta blanket is about 4150 ± 650 yr BP.

The ejecta blankets of the different Henbury craters vary in their degree of preservation. Some are heavily eroded by gullying. Others are fairly pristine in appearance, although pavement modification (cf. Mabbutt 1979) has undoubtedly occurred. The rills on the ejecta blanket of Henbury crater #4 (Milton 1968) were measured; the vertical lowering of the rills averages about 14 ± 3 cm/1000 years. We do not feel this can be extrapolated to the whole ejecta blanket, because some solution undoubtedly occurs on the ungullied ejecta and aeolian deposition is also likely. Still, this figure indicates that rill erosion has taken place in the late Holocene; it provides one long-term estimate for erosion of unconsolidated slopes in the region.

Ejecta from Boxhole meteor impact crater (Figure 1) were also sampled. However, the cover of vegetation is substantially greater at Boxhole. Varnish was collected from 17 different parts of the ejecta blanket. In the laboratory, microcolonial fungi were found eroding varnishes from every sample. An accelerator radiocarbon date of 1230 ± 110 (Beta 2216; ETH 3202) was from the basal layer of varnish from Boxhole. The true age of the

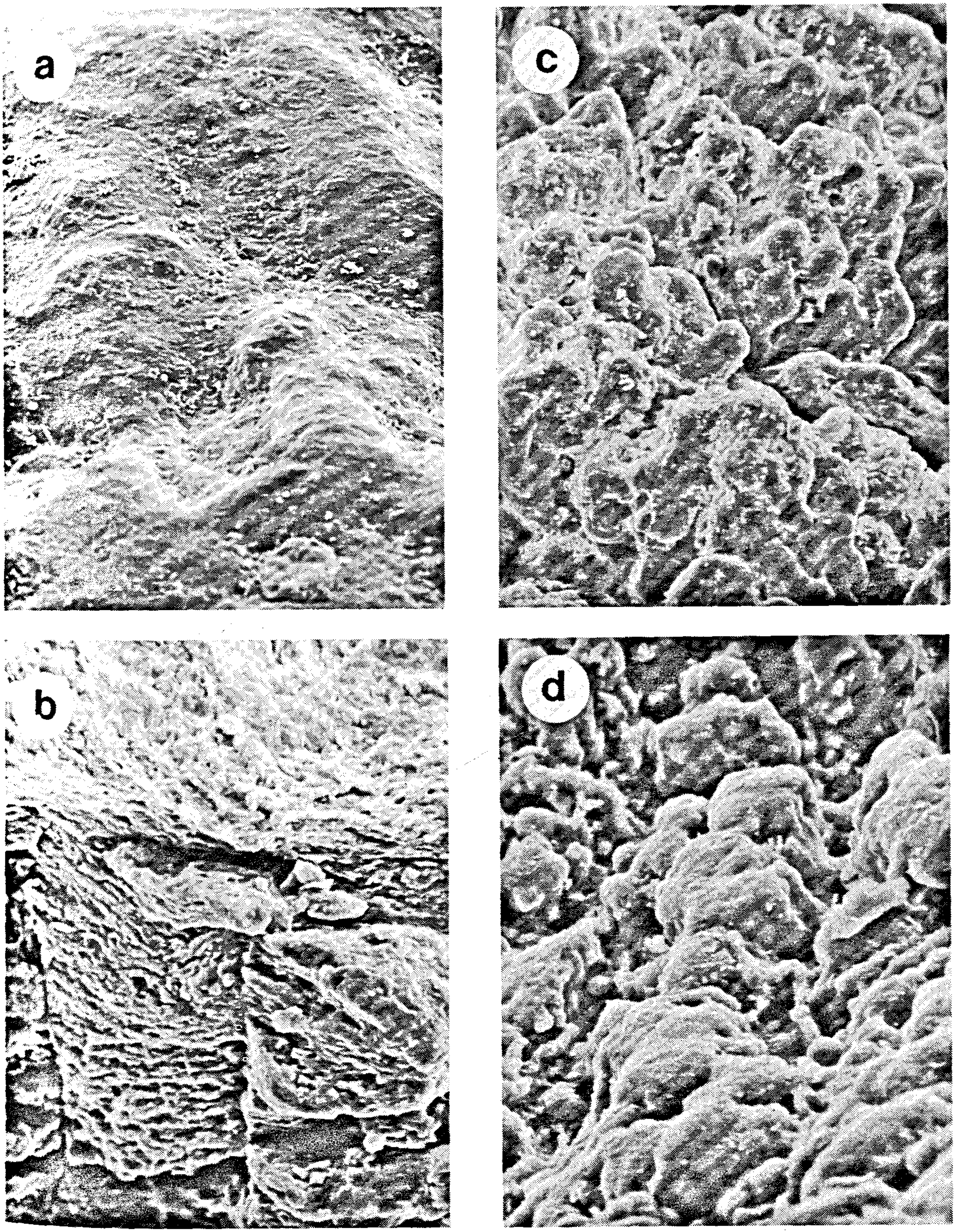

Plate 5: *SEM micrographs of varnish micromorphology from selected sites in Figure 1.*
a. Typical lamellate surface varnish from Beltana, South Australia.
b. Cross-section of the surface varnish from Beltana (Plate 5a). Note the lamellate structure of the varnish.
c. Botryoidal varnish from Mount Gambier (cf. Sheard 1978), South Australia, collected from the 'Devil's Punchbowl'.
d. Patch of semi-botryoidal varnish from Depot Creek, South Australia. Botryoidal structures are being coated by lamellate varnish. Most of the rock varnish was lamellate, but areas on the largest clasts on the alluvial fan had areas similar to this micrograph. Widths of images are about 100, 30, 140 and 60 microns, respectively.

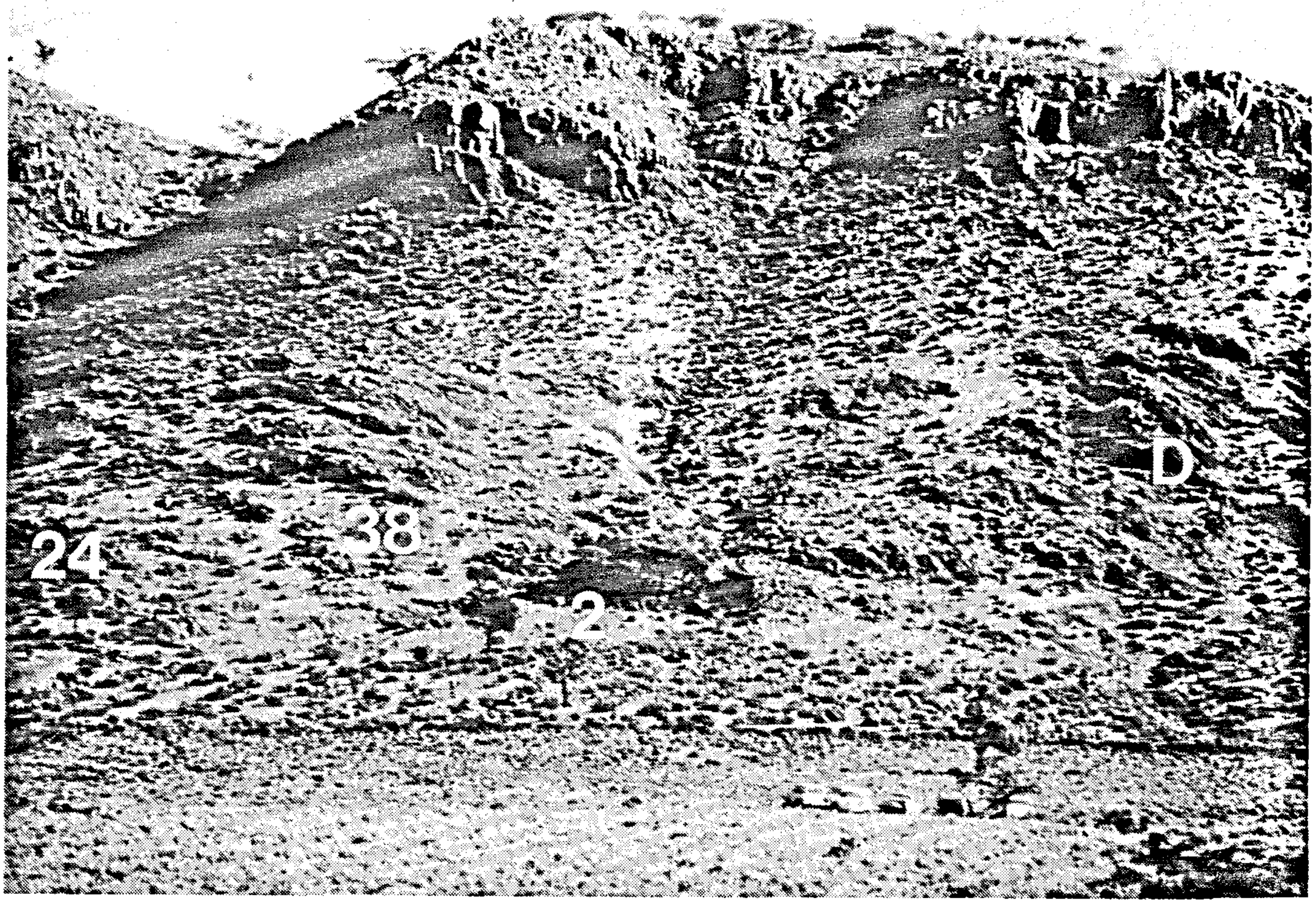

Plate 6: Pepuarta Bluff on Oulnina Homestead, near Mannahill in South Australia. The numbers refer to the accelerator radiocarbon dates (in thousands of years) obtained from the hillslope surfaces discussed in the text. 'D' refers to a varnish sample that was radiocarbon 'dead' at older than 38,000 yr BP. Scale is provided by cars in the foreground. The dates are corrected for the lag effect discussed in the text.

crater is probably slightly older than Henbury (Shoemaker and Shoemaker 1988). The young radiocarbon date is probably due to the post-impact erosion of varnish. This instance highlights the need for careful evaluation before the sample is accelerator radiocarbon dated.

Slopes of Pepuarta Bluff in the Oulnina homestead near Mannahill, Olary Province of arid South Australia (Figure 1; Plate 6), were sampled for AMS ^{14}C dating of varnish. Pepuarta Bluff is composed of Pepuarta tillite with varying degrees of jointing. Three finite dates are reported in Dorn *et al.* (1988): 2120 ± 150; 21,550 ± 240; and 34,590 ± 560 yr BP. In addition, a radiocarbon 'dead' sample at > 38,000 yr BP was also collected from this slope. The locations of these samples are indicated on Plate 6. The youngest sample, collected from the small alluvial fan, was particularly difficult to collect and analyse because of the abundance of lichen on the fan. Still, we feel this date is reliable, because the varnishes analysed for the date did not indicate a lichen problem on the surface or in thin sections.

These varnish radiocarbon dates are minimum-limiting ages for the stability of the surfaces sampled. They indicate in a general sense that geomorphic processes have been irregular in the retreat of Pepuarta Bluff. The source area for the small fan in Plate 6 has undergone active erosion in the late-Holocene; a channel has incised into the head of the fan something after the 2120 ± 150 yr BP date on varnish on the abandoned fan segment. The other samples are from more stable positions on the cuesta, indicating that tens of thousands of years have passed while these positions on the cuesta have seen very little modification. This should not be surprising. Relatively great surficial stability is possible adjacent to relatively unstable sites, due to differences in jointing, bedding, facies and lithology. What is significant is that it is now possible to determine quantitatively how long surfaces have remained stable, opening up a new set of questions on the nature of hillslope evolution and allowing Quaternary hillslope processes to be related to landforms on the piedmont.

AMS ^{14}C dating of the basal layer of varnish, outlined by Dorn *et al.* (1989), provides a technique to obtain surface exposure ages for the weathering of landforms, such as Ayers Rock. For example, a sample of orange varnish was collected for AMS radiocarbon dating from a slope of 32° on the west face of Ayers Rock. It initially formed in a crevice and was exposed when the overlying scales (about 3 cm thick) were broken off during sampling. The radiocarbon age of organic matter in the basal layer (< 10%) of the orange varnish is 27,100 ± 410 yr BP (Beta 19893; ETH 2809). The interpretation is that the orange varnish started to form in the crevice before 27,000 radiocarbon years ago. This analysis indicates that the processes of scaling at Ayers Rock can operate over tens of thousands of years. Using this one sample that may not be representative, Ayers Rock is scaling back at that location at a rate greater than 1 cm/10^4 yr. A more thorough sampling grid including radiocarbon dates on orange varnishes on scales at different depths would be needed to establish what are representative rates of erosion.

THE ANTIQUITY OF ROCK ENGRAVINGS

Many Aboriginal rock engravings in Australia are completely or partially coated with varnish, or occur on surfaces which themselves have some varnish cover. Although the presence of adjacent non-varnished and varnished engravings on the same rock exposure points to a difference in engraving ages (Basedow 1914), such qualitative assessments provide relative ages at best.

A minimum engraving age can be established by dating materials overlying engraved surfaces. Initial attempts to date rock engravings near Broken Hill, NSW, sought to utilise datable materials other than varnish. Some calcium carbonate was found superimposed on a thin layer of varnish, and radiocarbon dating of the carbonate yielded ages of 10,250 ± 170 yr BP (Beta 13803) and 10,410 ± 170 yr BP (Beta 13804). Other subsoil carbonate coatings which had formed directly over engravings were younger; carbonate over one varnished engraving had an age of 2680 ± 380 yr BP (SUA 2099) and over a non-varnished engraving at 45 cm below the soil surface at 3530 ± 210 yr BP (SUA 2100) (Dragovich 1988b). As this site forms part of an Aboriginal heritage area, speculative excavation in search of carbonate-coated varnishes is not possible. An age of 17,000 years has been proposed for carbonate-bearing aeolian deposits found at Fowlers Gap to the north (Chartres 1982), so datable carbonate coatings older than 10,000 years could occur at the site near Broken Hill.

Since most rock engravings are not coated by carbonate, only the varnish itself is left to date. The most accurate method of placing a numerical age on the varnish would involve AMS radiocarbon dating of the varnish itself (Dorn *et al.* 1989). Unfortunately, this method normally requires larger quantities of varnish than is typically present within engravings. Further, the collection of varnish for radiocarbon dating would involve major alterations to the appearance of heritage items.

Cation-ratio dating of rock varnish, as it is practised here, by removing the varnish from the rock surface (Dorn 1983, 1989a; Tanzhuo and Yuming *in press)* does not suffer from either limitation. Varnish needs to be scraped from only a few square millimetres of surface. This does not significantly alter the appearance of the petroglyph; the sampling would be noticed in most cases only upon examination with a hand lens. Other approaches to cation-ratio dating involve the non-destructive *in situ* analysis by PIXE (Pineda *et al.* 1988) and destructive *in situ* analysis by EDAX attached to an SEM (Glazovskiy 1985; Harrington and Whitney 1987). Still, the accuracy of cation-ratio dating is less than radiocarbon dating. Cation-ratio dating is based on the calibration of the ratio (K+Ca)/Ti of varnishes with the established ages for the exposure of geomorphological surfaces. Conventional radiocarbon dates for the ages of geomorphological surfaces could be used as a calibration, or AMS radiocarbon dating of rock varnish if conventional ages are not available near the archaeological site.

Cation-ratio dating was used to assign preliminary minimum-limiting ages to 24 rock engravings in the Olary Province of South Australia (Dorn *et al.* 1988; Nobbs and Dorn 1988). Varnish cation ratios on these engravings were assigned calibrated ages based on only three AMS radiocarbon dates on varnish and a historical date for a rock engraving. The varnishes on the Aboriginal engravings ranged in calibrated ages from about 1400 to 31,500 yr BP. The underlying engravings are assumed to be only slightly older than the varnishes, since varnish starts to form on an exposed surface after about 100 years in this region based on observations of historical petroglyphs. One of the conclusions of this study is that what is now recognised as a similar 'style' of tracks, lines, dots, circles, grooves and designs has remained quite similar for about 30,000 years. The work of Dorn *et al.* (1988) and Nobbs and Dorn (1988) supports Smith's (1987) results of human occupation in central Australia by 22,000 years ago. These results are also consistent with the more recent findings of Cosgrove (1989) that humans occupied Tasmania by about 30,800 yr BP.

Future work on the dating of Australian rock engravings will probably depend on AMS radiocarbon dating of rock varnish to calibrate varnish cation ratios. This is because organic material suitable for conventional radiocarbon dating is rarely available to date desert landforms. Although tested in North America and Hawaii (Dorn *et al.* 1989), AMS ^{14}C dating of varnish has not been compared with conventional radiocarbon dates in Australia. An important future task will be to obtain

AMS radiocarbon dates on varnishes buried by calcium carbonate coatings where both the organic and inorganic fractions of the coatings can be radiocarbon dated.

CONCLUSION

Rock varnish in Australia is superficially similar to varnishes in other deserts of the world. It is black, typically enriched in manganese by microbial activity, and is external to the underlying rock. It appears to have a trace and minor element chemistry also similar to varnishes elsewhere. The chemistry appears to be highly variable on micrometre, metre, and kilometre scales. However, there appear to be some substantial differences. The varnish in Australian drylands is much more susceptible to erosion than in other deserts. Rock surface organisms like lichens and microcolonial fungi appear to be more abundant in Australia than in the drylands of North America, Israel, Peru-Chile and Antarctica. While most of the varnishes appear to be composed of a similar amount of clays, over 50 per cent by Si and Al chemistry, the mineralogy could differ perhaps reflecting the mineralogy of ambient aeolian clays. The micromorphology of Australian varnishes is mostly limited to lamellate, whereas varnishes elsewhere tend to form botryoidal structures more readily in less dusty sites.

Rock varnish in Australia has great potential as an archaeological and geomorphological research tool. This has been demonstrated at selected sites in the Northern Territory and South Australia. To fully utilise this potential, considerably more basic research on the nature of varnish in Australia will be required. Data gathered for this study are from a few sites scattered over a small portion of the arid zone. It is very likely that new varnish phenomena await discovery at other sites. We have literally and figuratively barely scratched the surface of the problem of interpreting rock varnish in Australia. Exploration is desperately needed on topics such as environmental gradients from winter to summer rain, of the interaction of cycles in the aeolian system and possible cycles in varnish, and of microchemical interactions at the micron level (cf. Dragovich 1988a; Krinsley and Anderson 1989). Rock varnish studies will never provide the instant fix of a radiocarbon date on charcoal in a stratigraphic deposit, but we do believe varnish in Australia has a demonstrated potential to justify its further exploration.

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