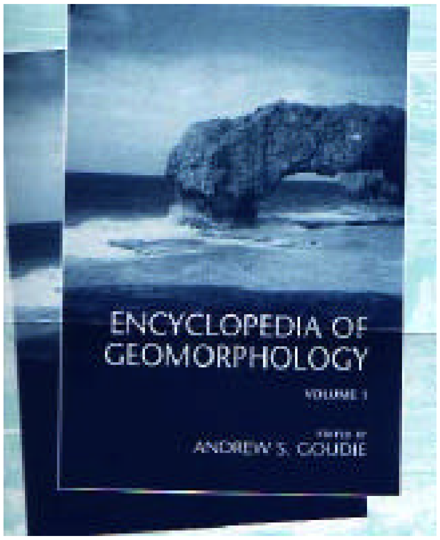
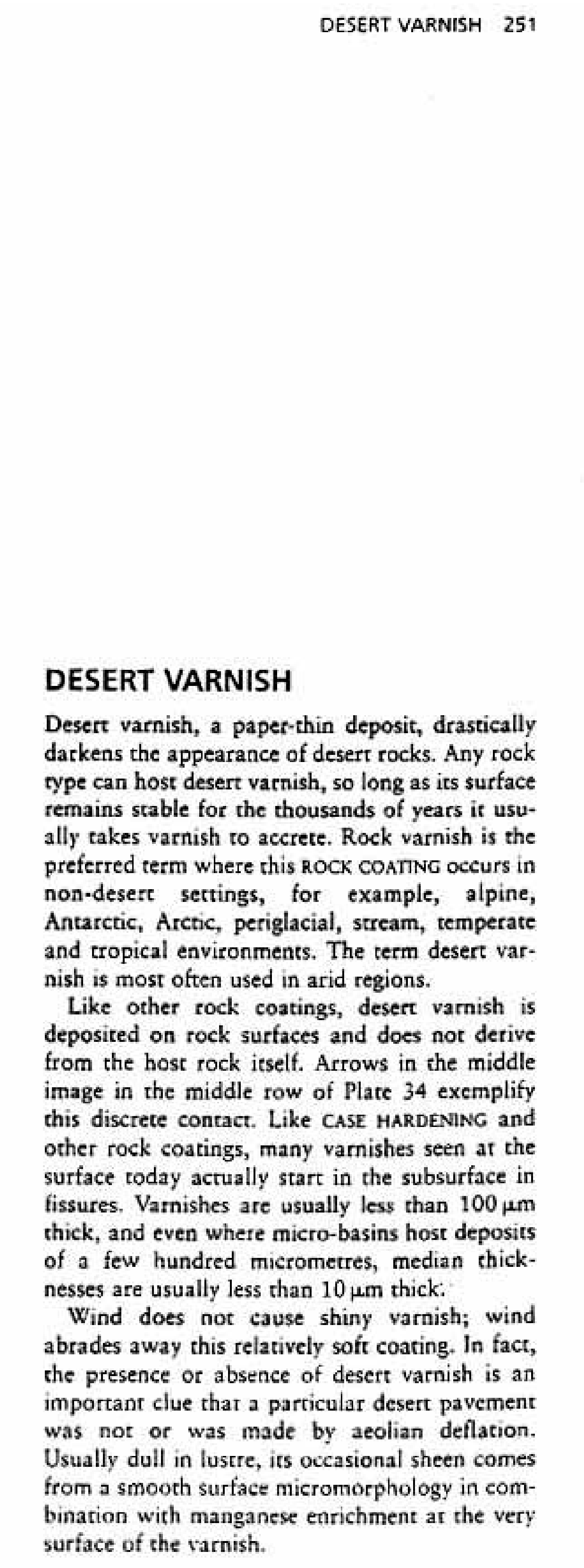


Routledge, London 2004
ISBN 0-415-27298-X (2 volume set)

Dorn, R.I. 2004. Desert varnish, in Encyclopedia of Geomorphology , ed. A.S. Goudie, Routledge: London, 251–254.



DESERT VARNISH

Desert varnish, a paper-thin deposit, drastically darkens the appearance of desert rocks. Any rock type can host desert varnish, so long as its surface remains stable for the thousands of years it usually takes varnish to accrete. Rock varnish is the preferred term where this ROCK COATING occurs in non-desert settings, for example, alpine, Antarctic, Arctic, periglacial, stream, temperate and tropical environments. The term desert varnish is most often used in arid regions.

Like other rock coatings, desert varnish is deposited on rock surfaces and does not derive from the host rock itself. Arrows in the middle image in the middle row of Plate 34 exemplify this discrete contact. Like CASE HARDENING and other rock coatings, many varnishes seen at the surface today actually start in the subsurface in fissures. Varnishes are usually less than 100 μm thick, and even where micro-basins host deposits of a few hundred micrometres, median thicknesses are usually less than 10 μm thick.

Wind does not cause shiny varnish; wind abrades away this relatively soft coating. In fact, the presence or absence of desert varnish is an important clue that a particular desert pavement was not or was made by aeolian deflation. Usually dull in lustre, its occasional sheen comes from a smooth surface micromorphology in combination with manganese enrichment at the very surface of the varnish.

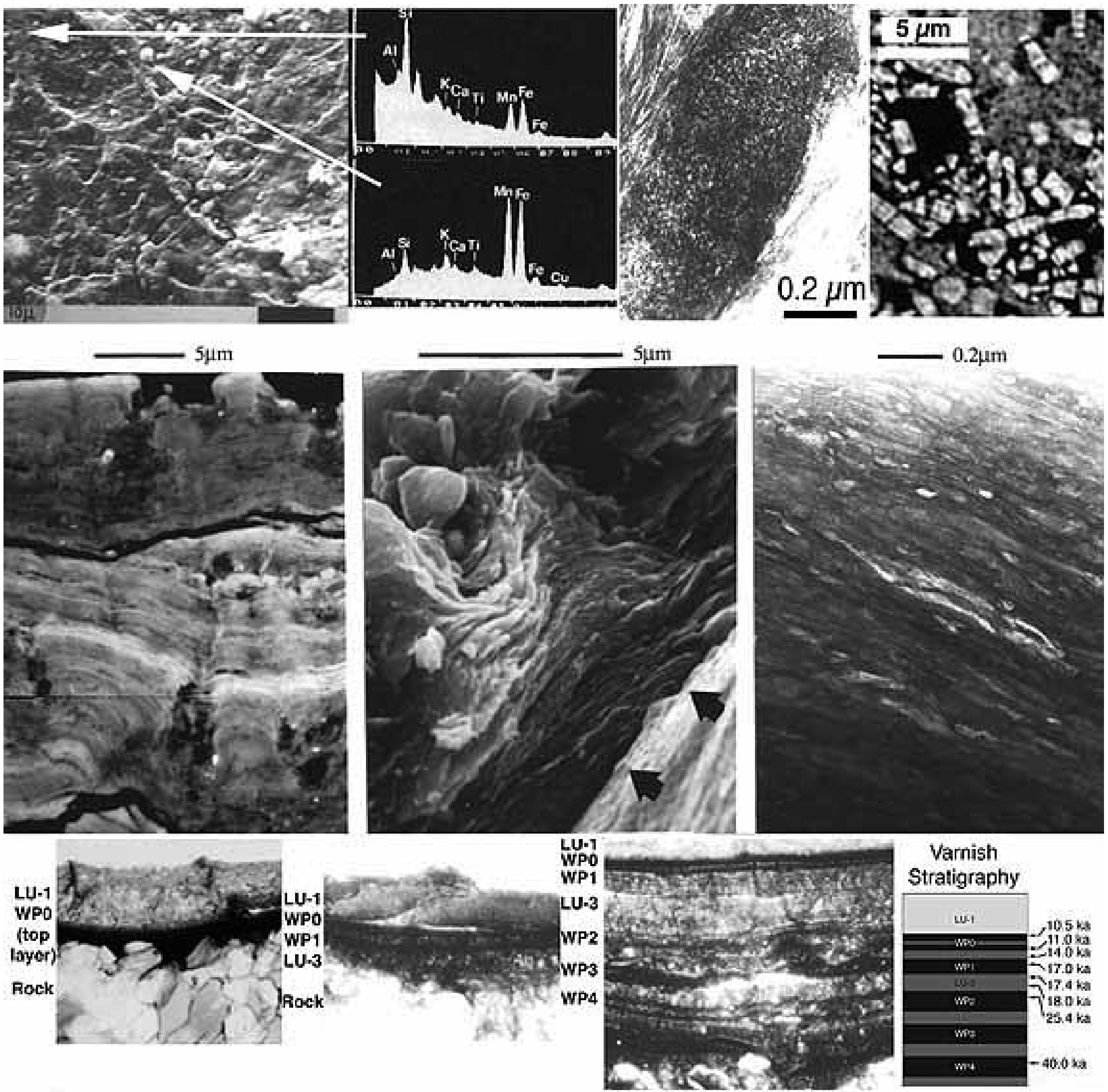


Plate 34 Microscopic views of desert varnish from arid environments. Top row: microscopic evidence for bacterial origin of rock varnish from left to right: secondary electron image of Negev Desert budding bacteria where the bacteria greatly enhanced manganese and iron; transmission electron image of manganese encrusting a bacterial form; and backscattered electron image of bacteria revealed by acid etching. Middle row: layering of desert varnish shown in backscattered (left), secondary (middle), and high resolution transmission electron microscope (right) images. Bottom row: calibration of microlaminations seen in optical microscopic views of ultra-thin sections, where black layers in the varnish represent wet periods that have been calibrated by Tanzhuo Liu's research (Liu *et al.* 2000). The thin sections from left to right show progressively older varnishes with progressively more complex layers from Death Valley, California

Clay minerals are the major ingredient of desert varnish, typically comprising more than half and sometimes as much as 90 per cent. The clay minerals impose the layered structure seen in the middle row of Plate 34. Clays are deposited as dust on rock surfaces, and are then cemented to the host rock by hydroxides and oxides (Potter and Rossman 1979) of manganese (birnessite) and iron (goethite and hematite). Manganese and iron make up about a third of varnish, with typically less than 5 per cent of varnish composed of other components.

The mystery of desert varnish surrounds how to explain the great abundance of manganese, the element that gives varnish its dark brown to black colour. The elemental abundance of manganese in varnish is 50 to 300 times the concentrations found in dust that falls on rock surfaces. Put another way, ratios of manganese to iron are about 1:40 to 1:60 in surrounding soils and dust, but are about 1:1 in varnish.

In the past century, there have been two competing models to explain manganese enrichment. The first was a chemical process favoured by geochemists, whereby naturally acidic rain dissolves manganese in the rock or dust (but not the iron). Then, manganese oxidizes upon exposure to a slightly higher pH. The competing model was a microbial process, whereby bacteria precipitate manganese (Drake *et al.* 1993).

Although bacteria have been cultured from varnish and have made 'artificial varnish' in the laboratory (Dorn 1998), the typically slow rate of varnish growth (on average, about a micrometre per thousand years) makes it very difficult to have confidence that bacteria cultured today in the laboratory make varnish. In fact, the type of gram-positive bacteria most easily cultured from desert varnish today have not yet been identified within varnish layers. To make the matter more difficult, 'biomolecular fossils', such as amino acids generated by these bacteria, exist in both desert varnish and unvarnished weathering materials. Thus, most convincing evidence for a bacterial mechanism is actually seeing manganese enhancement *in situ*. In the upper row of Plate 34, budding bacteria can be seen concentrating manganese and iron.

New high resolution transmission electron microscope evidence (Krinsley 1998) reveals that these chemical and biological models are not truly in competition, but work in tandem. Varnish formation can be explained by a four-step process. Step 1 is the enhancement of varnish (and to a lesser extent iron) by bacteria; the top row in Plate 34 shows manganese-rich sheaths of bacteria. Step 2 is the chemical dissolution of the bacterial sheaths, whereby manganese and iron are broken down into nanometre-sized granules. Step 3 is chemical transport of manganese and iron into clay minerals. Step 4 is the precipitation of unit cells of manganese and iron inside clay minerals. Potter and Rossman (1979) noted that the hexagonal arrangement of oxygens in clay mineral layers form a template for crystallization of the manganese mineral birnessite seen in desert varnish.

Krinsley (1998) shows high resolution imagery revealing all steps in this polygenetic process whereby clay minerals and oxides are co-dependent in varnish formation. Clay provides the overall structure and template for oxide precipitation, while bacteria simply provide a ready source of manganese (and iron) cement. Varnish formation all takes place within a few micrometres of the bacterial source, where the manganese and iron are redistributed with hygroscopic water – all inside layers like those seen in the middle row of Plate 34.

Environmental changes play an important role in the development of desert varnish. Where lichens start to grow, for example, biological acids destroy desert varnish by dissolving the manganese and iron oxides. Where rocks come to exist in a desert pavement, a ground-line band of very thin and shiny varnish forms a circle around a desert pavement clast. But where varnish grows on the tops of boulders less influenced by local environmental changes, regional climatic change plays an important role in varnish formation.

In these boulder-top varnishes wetter climates favour bacterial enhancement, yielding layers that are particularly rich in manganese. Drier climates with more alkaline dust produce layers that are not as rich in manganese. The bottom row in Plate 34 shows desert varnishes from Death Valley, California, where growth of these layers has been calibrated using a combination of numerical dating methods (Liu *et al.* 2000; Zhou *et al.* 2000). Progressively older varnishes show progressively more complex layers. Varnish microlaminations provide archaeologists and geomorphologists with a powerful tool, because they reveal both climatic change and a time signal.

Some of the most interesting aspects of desert varnish surround its minor and trace constituents. Lead, for example, is greatly enhanced in the uppermost micron of the varnish from twentieth-century air pollution. The carbon that is trapped within and underneath varnish shows some potential as a means of radiocarbon dating varnish, but the history of the carbon is usually too complicated to make this technique useful. Mobile trace elements decline progressively over time, as they are leached by hygroscopic and capillary water (Krinsley 1998). Varnish also traps foreign material crushed into rock engravings as a part of religious ceremonies (Whitley *et al.* 1999). New experimental studies of trace isotopes such as ^{7}Be, δ^{13}C and δ^{17}O show potential to reveal new insights into this ubiquitous weathering phenomenon. Some planetary scientists believe that desert varnish exists on Mars, and that Martian varnish might preserve active organisms or at least biological fossils such as those seen in the top row of Plate 34.

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SEE ALSO: rock coating

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