Preprint of a paper which appeared in *The Victorian Naturalist*, 121(1): 14-22, 2004

Solution Pipes or Petrified Forests?

Drifting sands and drifting opinions!

Ken G. Grimes

PO Box 362, Hamilton, Vic 3300. ken-grimes@h140.aone.net.au

Abstract

Two alternative interpretations exist for the pipes and other features of the so-called 'Petrified Forest' at Cape Duquesne, west of Bridgewater Bay, Victoria. The early tree-mould hypothesis of Boutakoff (1963), which is still advocated by the new interpretation signs at the site, is rejected in favour of more recent suggestions that interpret the features as solution pipes formed by focussed vertical water flow through the porous calcareous sands (aeolianites). The focussing of the flow may be spontaneous and associated with patchy cementation of the hardpan of the soil, or it may be guided by other factors such as concentrated stem-flow beneath trees, or along taproots, or the pooling of water in hollows in exposed hardpans.

Introduction

The 'Petrified Forest' at Cape Duquesne, in the Bridgewater Bay area 20 km west of Portland, is a particularly good example of the many exposures of vertical pipes in calcareous dune sands which are seen in coastal areas of western Victoria, South Australia and Western Australia (Fig. 1). Similar features also occur in other parts of the world (e.g. Southern Africa, the Caribbean and Bermuda - see reference list) where the host sand is known as calcarenite or aeolianite.

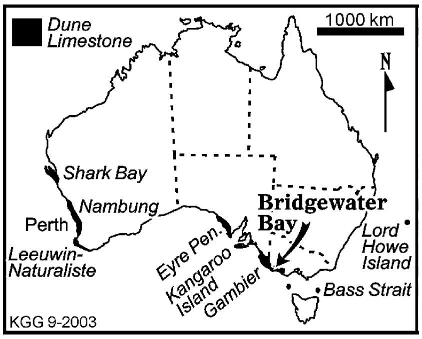


Figure 1: Dune limestone areas in Australia.

Typically the pipes in the Gambier–Portland region are 0.2 to 0.5 m across, but can exceed 1.0 m. The exposed part is usually 1-3 m high (with the top removed by erosion and the base hidden below the surface). In a few places we see them up to 20 m deep. They can occur as isolated individuals, widely spaced sets (e.g. 5-10 m spacing) or in dense fields (as at the 'Petrified Forest') with spacings closer than 1 metre (Fig. 2; Appendix 1). They form smooth vertical cylinders which may narrow downward towards a rounded base ('cigar shaped' is a common description) or terminate abruptly in a hemisphere (Fig. 3). They commonly, but not always, have a calcareous cemented rim around them that is a few centimetres thick. These rims may have concentric layers, and some have traces of thin calcareous root structures (rhizomorphs) and calcareous veins embedded in them (as does the surrounding sand). The exposed pipes tend to be empty, or are filled with a red or pale brown soil (silty sand). Occasionally the fill contains concentric calcareous laminae. The pipes are commonly, but not always, associated with an old soil horizon— either descending from it (Fig. 4), or cutting through a calcified band that could be a sub-soil hardpan. Occasionally, as noted by Boutakoff (1963), the pipes may bottom in a palaeosoil.

Solution pipes are subsoil karst features comprising vertical cylindrical pipes attributed to solution by downward percolating water. They can occur in hard crystalline limestones, where they generally follow vertical joints, but are a distinctive feature of soft limestones; e.g. the chalk of Europe or the Australian aeolian calcarenites (Jennings 1985). Some authors distinguish 'soil pipes' from 'solution pipes' by restricting the former term to soil-filled pipes and the latter to empty pipes. Here I will use the term 'solution pipe' for both types.

Figure 2: Stereopair of the main cluster of pipes at "The Petrified Forest", Victoria.

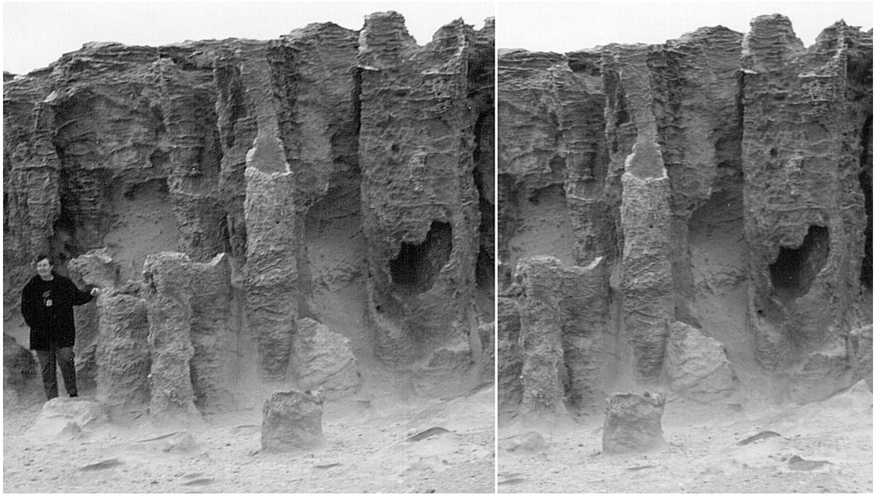


Figure 3: Stereopair of a pipe with rounded base at "The Petrified Forest", about 30 m west of the main group shown in Figure 2. Scale-bar is 10 cm.

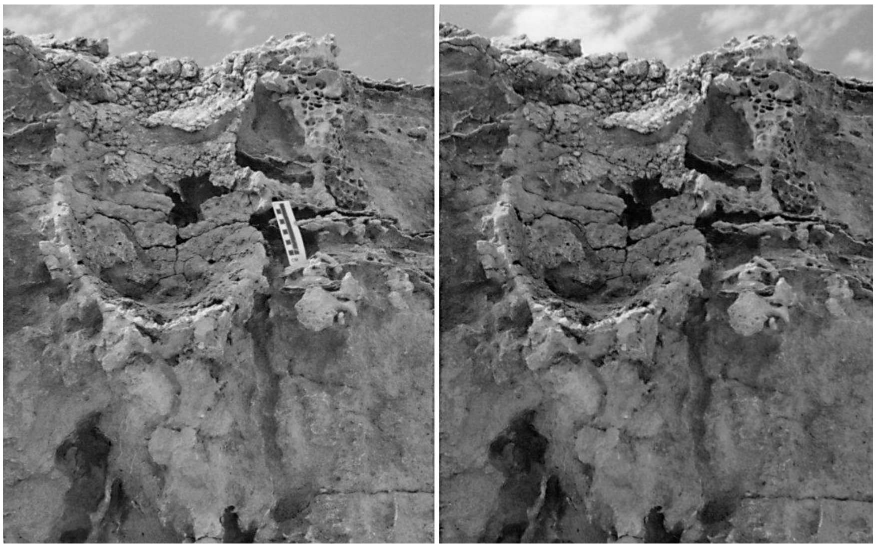


Figure 4: Red paleosoil and soil-filled pipes beneath a younger sand dune exposed in a cliff at Canunda National Park, South Australia.

Associated with the pipes are *rhizomorphs*, which are hard calcified root structures. They are common in the calcareous dunes of the region and have an obvious branching root structure. These form from carbonate that has been precipitated around the root - which may be identifiable as a thin hollow core if that has not been infilled by younger cement. Thus they are much thicker than the original root, examples occur up to 100 mm thick but are generally less than 20mm.

A petrified forest?

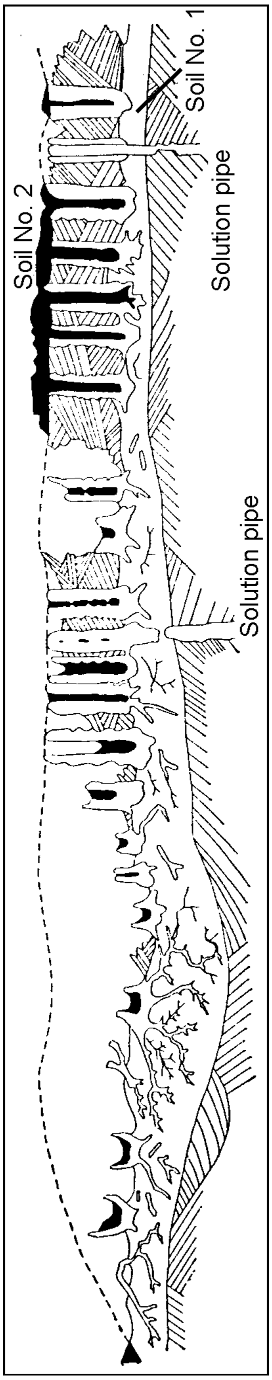


Figure 5: Boutakoff's figure 17 shows many features of the "Petrified Forest" correctly but grossly exaggerates the thickness and extent of root development at the base of the pipes. Black is soil fillings.

In 1963, N. Boutakoff interpreted the pipes in the Portland region as having formed where an advancing dune had engulfed a forest of trees. Boutakoff argued that after the sand had been cemented into a soft rock, and the trunks had rotted away, the pipes were left as open holes which were locally filled by later soil that developed on the surface of the engulfing dune. He rejected the alternative hypothesis that these were solution pipes (which had been argued by Woods (1862) and others); but he did allow that occasional deeper solution pipes occurred as solutional modifications of the tree moulds. Calcified traces of what are recognisably old roots (rhizomorphs) occur together with the pipes and were cited in support of his hypothesis. Boutakoff claimed to have seen 'unmistakable rooted tree stumps' and bark, logs and other 'woody structures'. He illustrated his argument with an imaginative diagram (his figure 17, which is reproduced here as Fig. 5) that unfortunately shows large roots spreading out from the base of the 'trunks' which do not appear in the real outcrop!

Boutakoff has overstated his case: these features are either capable of alternative interpretations or cannot now be found in the area.

Boutakoff's interpretation is attractive at first sight, and his diagram is deceptively beguiling. It has been referred to on numerous occasions in the local literature (e.g. Bird 1993) and appears, unchallenged, on interpretative signs recently erected in the area by Parks Victoria. However, his 1963 interpretation was rapidly challenged. Blackburn *et al.* (1965), described numerous areas of pipes just across the border, in South Australia, and referred to Boutakoff's site (and others) as having 'indisputable solution pipes'. Jennings (1968) favoured solution as the main process, and commented that 'secretion round the roots of vegetation growing down into the sand' seemed more likely than burial of a forest. Coetzee (1975) also argued against Boutakoff's concept from a study of similar features in southern Africa. There was initially some support from workers in Bermuda (cited by Boutakoff), where the pipes were regarded as moulds of palmetto stumps; but recent work has discredited this (Herwitz 1993). Palm trunks do have a rounded basal form more akin to the shape of the pipes than other trees, but no native palms are found in the Portland region.

Boutakoff(1963) quoted an extract from Darwin (1845) which describes calcified 'roots and branches' (but not trunks) at King George Sound in Western Australia. Fairbridge (1954: 68-69) discussed that and other early reports on the Coastal Limestone of Western Australia, and agreed that the smaller branching bodies are formed from roots (i.e. they are rhizomorphs), but he then went on to say 'The most important correction that must be made concerns the larger "cylindrical bodies". These are now recognised as karst solution pipes or sink holes'. A more detailed discussion of the alternative solutional origin of the Western Australian pipes appears in Fairbridge (1950).

The 'tree mould' hypothesis has a number of problems, which I will expand on below:

- The spacing of the pipes (less than 0.5 m in places) seems too dense for a typical forest with trunks the size of these pipes.
- Where seen, the base of the pipes is a rounded hemisphere—nowhere are there thick-rooted tree structures such as those shown in Boutakoff's figure.

- Boutakoff(1963) claimed his pipes were based ('rooted') in a palaeosoil layer and extended upward from it. This is unusual; usually the pipes are seen descending to varying depths below an old soil or unconformity.
- The cross-bedding of the dune sand shows no disruption where it passes the 'trunks'.
- Some pipes are up to 20 m deep (or high!), and are all unbranched vertical cylinders.
- The pipes are not restricted to dunes, they also occur in beach and marine calcarenites.

Size and spacing:

At the 'Petrified Forest' site, and elsewhere, the spacing of the pipes (locally less than 0.5 m, see Appendix 1) seems too close for a typical forest with trunks the size of these pipes, whose inside diameters are typically 0.2 to 0.5m (Appendix 1). In a comparable area in Puerto Rico, Lundberg and Taggart (1995) report cases of overlapping pipes, where younger pipes intersect older ones—though there are no good examples of this in our area. McNamara (1995) argued that the pinnacles at Nambung, WA, were remnant cemented areas left between coalescing solution pipes.

The close spacing seen in the 'Petrified Forest' could only occur with dense stands of small-diameter trees such as paperbarks or ti-trees. The Parks Victoria interpretation sign suggests 'Moonah', *Melaleuca lanceolata*, but that species usually has a mallee-like habit of multiple diverging stems which is unlike the individual vertical pipes. Boutakoff recognised this problem of size, and argued for the development of a series of calcareous layerings around smaller trunks which makes them seem bigger. None the less, the observed rims average only 5cm thick, and the hollow centre within the cemented rim (Appendix 1) seems still larger than is compatible with the density of the 'trunks'. Also, if one accepts Boutakoff's suggestion of massive 'thickening' of the original trunk size by cement rims, then one must consider also Jennings' (1968) suggestion that calcification around taproots growing down into the sediment is a more likely explanation of the pipes than burial of a forest—though Jennings favoured solution as the primary process.

Lack of solid basal roots:

The bases of the pipes are seldom seen at the 'Petrified Forest', but where we do see them (there and elsewhere) they end in a rounded hemisphere (Figs. 3 and 7). Nowhere have we found thick-rooted tree structures such as those shown in Boutakoff's figure 17 (Fig. 5). His photographs (plates XIV-3 and 6) of a supposed stump with roots show small rhizomorphs running away from a pipe, but even without allowing for the exaggerated thickness of such calcareous overgrowths, these seem too small to support a trunk of that size. Small calcified roots (rhizomorphs) do occur, but are at all depths, not just at the base of the pipe.

Downward or upward development?

Boutakoff claimed his pipes were based ('rooted') in a palaeosoil layer and extended upward from it. When observing the surface outcrops, as distinct from the cliff cross-sections, one frequently gets the impression that the pipes are ending just below the surface. This is because of the concave layered filling of partly cemented red soil and is misleading. Where seen in a good cross section (cliff or quarry) the pipes descend to variable depths, but have a uniform upper termination at the present surface or at an old unconformity surface which may have an associated palaeosoil (Fig. 4). Where pipes are seen to bottom uniformly in a basal soil (as in some parts of the 'Petrified Forest'), that could be explained by reduced permeability and solubility of the soil material inhibiting further downward solution.

Lack of disruption to the dune bedding:

The cross-bedding of the dune sand shows no disruption where it passes the 'trunks'— there are no eddies or hollows on the lee side. This is not a strong argument, as Boutakoff argued that his calcareous growth layers extended out into the dune bedding and so would have destroyed any such distortions.

Some very deep pipes occur:

The pipes at the 'Petrified Forest' are only short (1– 3 m), but similar pipes elsewhere in the region can be up to 20 m deep (e.g. in Brown Snake Cave, described below). These deep pipes are simple vertical unbranched cylinders - not tree-like. Boutakoff regarded these isolated long pipes as 'secondary' solution pipes formed by modification of his tree moulds.

Host sands are not all dunes:

The pipes are a characteristic feature of dune limestones, but are not restricted to dunes. Similar pipes occur in beach sands associated with the dunes, and in the mid Tertiary marine Gambier Limestone - though the latter do not occur in the dense fields described by Boutakoff and so one cannot be sure that the genesis is identical. An example of solution pipes in marine limestone is seen in Brown Snake Cave (5U-14) at Naracoorte. This cave is in soft, sandy, Tertiary marine limestone with a thin capping of dune limestone. It is entered via a 15 m deep solution pipe that opens into the ceiling of a large chamber. This vertical pipe is perfectly cylindrical and about 0.6 m wide (apart from a constriction where it passes through a better-cemented band just above the ceiling of the chamber). Within the cave chamber there are 10 other blocked pipes in an area about 60 m long, each with a conical soil cone below it indicating a connection with the surface. For a map of this cave see figure 13 in Grimes *et al.* (1995).

Or Solution Pipes?

A recent review of solution pipes is given by Lundberg and Taggart (1995), who advocate 'dissolution pipe' as being a more correct term. They note that dissolution by focussed downward vertical flow of under-saturated rain or soil water through the porous sediment can explain all the features of the pipes: the uniform, vertical cylindrical form, the dense clustering in places, and the cemented rims (where dissolved material is re-precipitated at the edges of the pipe). The associated rhizomorphs are simply formed around roots that have penetrated the sands from above, possibly following the soil-filled pipes by preference and radiating out from them. As the pipes are developing downward from the surface or from a soil cover the infilling material will progressively fill them as they deepen.

But why is the downward water flow focussed into the pipes rather than travelling evenly throughout the uniformly porous sand? In hard limestone, pipes usually form where flow is concentrated along the intersections of joints or steeply dipping bedding planes. But in soft sandy limestone there are no vertical joints, and the initial inter-granular porosity is uniform apart from occasional horizontal hard-bands—the dune cross-bedding seems to have little effect on flow directions. Three methods of concentrating the flow have been suggested by Lundberg and Taggart (1995), drawing on earlier authors: surface hollows, roots and stem-flow; to those I will add a fourth: patches of higher porosity in the developing soil hard pan (Fig. 6).

In passing, it is worth noting that similar vertical pipes occur in the giant podsols that develop on the quartz sand dunes of the Queensland coast (Thompson and Bowman 1984). These have a deep leached A2 horizon over a humic-rich B horizon, with pipes of the leached A2 from a few centimetres to nearly half a metre wide penetrating several metres down into the enriched B horizon. I have also seen analogous, soil-filled, pipes formed in ferruginous duricrusts associated with deep-weathering profiles in tropical Australia. In both cases, focussing of downward water flow seems to be involved.

Stem-flow is the process whereby the leaves of a tree intersect rain, and direct it down the branches so that it is concentrated at the base of the trunk. The concentrated inflow would cause localised solution and pipe development (Fig. 6-a). Herwitz (1993) measured stem flow under a variety of trees in Bermuda and showed that it could generate significant concentrations of water with increased acidity and noted that multiple generations of trees could produce the dense spacing of pipes which is observed in places.

Figure 6: Alternative ways to focus downward flow and generate solution pipes. Note, the alternatives are not mutually exclusive, they could all contribute in different settings.

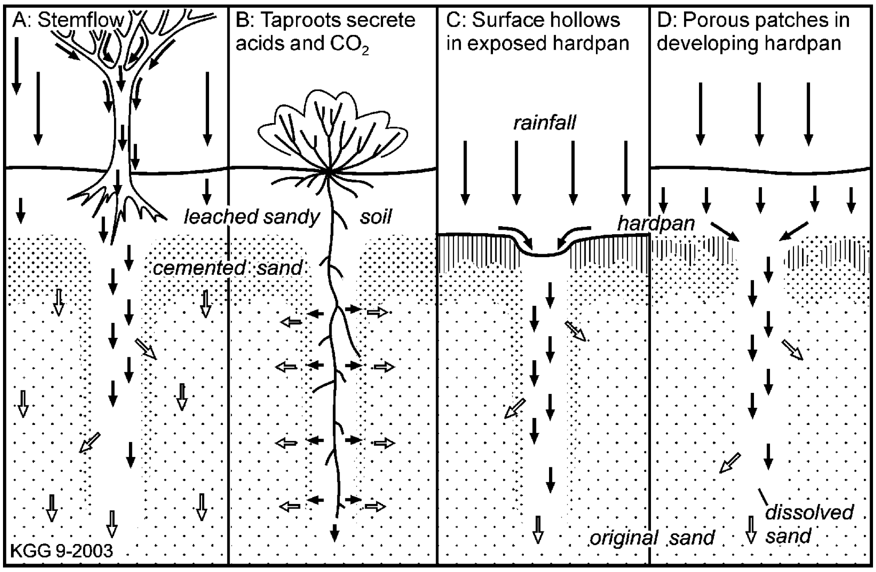
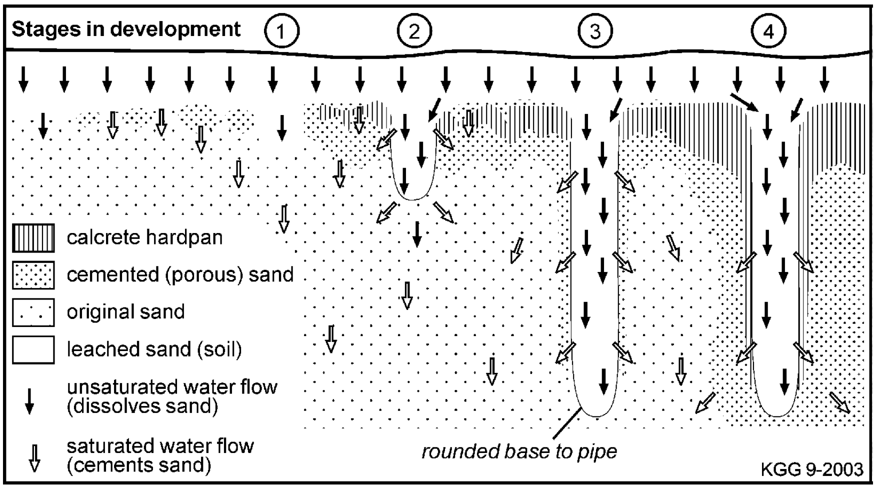


Figure 7: How a solution pipe deepens and develops a rim.



The influence of **tree roots** was suggested by Jennings (1968) and later by Bird (1970). Roots generate organic acids and raised CO_2 levels that enhance solution in their vicinity (Fig. 6-b). A vertical taproot could therefore form an initial thin pipe which would enhance water flow and enlarge with time. This is a self-perpetuating process as a pipe, with soil fill, would be a preferred place for continuing root growth and organic activity.

Surface hollows were suggested by Coetzee (1975) and others (Fig. 6-c). If hollows exist (on a partly indurated surface, or on the top of the soil hardpan) then water will accumulate in these and the base of the hollows will be lowered by solution at a faster rate than the surrounding higher areas—the process becomes self-perpetuating.

A possible fourth process involves **uneven cementation of the hardpan**. Rain dissolves carbonate grains as it penetrates the sandy soil, and some of this is re-precipitated lower down to form a hardpan or calcrete band near the base of the soil. In the initial stages this band would not develop evenly (Fig. 6-d). The early-cemented areas would tend to deflect flow laterally to places which retained more of their original porosity and concentrated inflow would occur there, inhibiting further cementation, and allowing solution pipes to form below.

In all four cases, once the inflow is concentrated at a point, solution will progressively deepen a vertical pipe beneath the focal point. Lateral movement of saturated water out of the pipe would form the cemented rim (Fig. 7).

Discussion

Boutakoff himself admitted that some of the pipes were solutional in origin, but argued that most were tree moulds. I argue the opposite: most are solutional and while it is possible that a forest could be buried and rot away to leave moulds resembling the pipes, this would probably be a rare event and there is no unambiguous evidence for it at the 'Petrified Forest'.

The focussed solution process seems a better hypothesis for general interpretation of both isolated pipes, and the dense fields of pipes which are a distinctive feature of dune limestones throughout the world. Note that the four alternative modes of focussing water flow discussed above are not presented as mutually exclusive hypothesises—all could act, either together or separately, according to the local situation in any area.

Rhizomorphs are common in dune sands and form around small roots growing through the sand. Such roots would preferentially follow the organic-rich soils that fill the solution pipes and branch out from them. Thus, rhizomorphs could be called petrified roots, but the pipes are not petrified trunks.

So, while 'Petrified Forest' provides a picturesque name for the features at Cape Duquesne, the name should be kept in quotes, and not confused with the real process by which these features were formed. The recently erected interpretation signs are incorrect.

Acknowledgements

My colleague, Susan White, has contributed to many discussions on the nature of these and other features of the calcareous dunes. I also thank my wife, Janeen Samuel, for assistance in the field. Andy Spate and two anonymous referees helped by pulling me up on some excessive statements and by providing copies of additional reports discussing the local geology.

References

Bird ECF (1970) Shore potholes at Diamond Bay, Victoria. *The Victorian Naturalist.* **87,** 312-318.

Bird ECF (1993) *The Coast of Victoria.* (Melbourne University Press, Melbourne).

Blackburn G, Bond RD and Clarke ARP (1965) Soil development associated with stranded beach ridges in South-east Australia. *CSIRO Australia Soil Publication* **22,** 1-65.

Boutakoff N (1963) The geology and geomorphology of the Portland area. *Geological Survey of Victoria, Memoir* **22**. 117 pp.

Coetzee F (1975) Solution pipes in coastal aeolianites of Zululand and Moçambique. *Transactions of the Geological Society of South Africa* **78,** 323-333.

Darwin C (1845) *Journal of researches into the natural history and geology of the countries visited during the voyage of H.M.S. Beagle around the world*. London.

Fairbridge RW (1950) The geology and geomorphology of Point Peron, Western Australia. *Journal of the Royal Society of Western Australia* **34,** 35-73.

Fairbridge RW (1954) Quaternary eustatic data for Western Australia and adjacent states. *Proceedings of the Pan Indian Ocean Science Congress, Perth (1954)* Section F, 64-84.

Grimes KG, Hamilton-Smith E and Spate AP (1995) *South East Karst Province of South Australia.* (Report by Australian Caves & Karst Management Association to the South Australian National Parks and Wildlife Service. 110 pp.)

Herwitz SR (1993) Stemflow influences on the formation of solution pipes in Bermuda eolianite. *Geomorphology* **6,** 253-271.

Jennings JN (1968) Syngenetic Karst in Australia. In *Contributions to the study of karst,* pp 41-110. Ed. PW Williams and JN Jennings, Australian National University, Department of Geography Publication G/5(1968).

Jennings JN (1985) *Karst Geomorphology.* (Blackwell, Oxford)

Swan ARH and Sandilands M (1995) *Introduction to Geological Data Analysis*. Blackwell Science, Oxford.

Lundberg J and Taggart BE (1995) Dissolution pipes in northern Puerto Rico: an exhumed paleokarst. *Carbonates and Evaporites* **10,** 171-183.

McNamara KJ (1995) *Pinnacles,* rev ed. (Western Australian Museum, Perth)

Thompson CH and Bowman GM (1984) Subaerial denudation and weathering of vegetated coastal dunes in eastern Queensland. In *Coastal Geomorphology in Australia,* pp. 263-290. Ed BG Thom (Academic Press, Sydney)

Webster CL (1996) The intrigue of the questions about the Bridgewater "Fossil Forest", Victoria, Australia. *Origins* **23,** 50-60.

Woods JET (1862) *Geological Observations in South Australia*. (Longman, Roberts and Green, London)

Appendix 1: Morphometric analysis of solution pipes

The Petrified Forest, this study

A 5 x 5m quadrat was set up near the track to the 'Petrified forest', just before the first good three-dimensional exposure. This contained 53 pipes, giving a density of 2.12 pipes/m^2. For each pipe within the quadrat, or crossing the north and east boundary, the following were measured: Inside diameter, outside diameter, thickness of cemented rim, distance to nearest neighbour (centre to centre), direction to nearest neighbour. Where the pipes were noticeably elongate both the length and width were measured; there were three of these, with elongation ratios between 1.6 and 2.6. Three composite pipes occurred, two pairs and one triplet. For one pair, the rim of the larger pipe was slightly superimposed on the smaller, suggesting that it formed later. For the other two, the members shared a common rim and were connected by open necks. For these composite units, the widths etc. of the individual members were measured rather than the unit as a whole.

The mean inside diameter of the pipes was 270 mm, with a standard deviation of 92mm., but the total size range was from 60mm to 460mm. The rim thickness varied within individual pipes as well as between pipes and was difficult to estimate accurately, but averaged 48mm.

A nearest neighbour analysis was based on the method described in Swan & Sandilands (1995). Mean distance to nearest neighbours was 458 mm, with a standard deviation of 12.8 mm. This gives a nearest-neighbour statistic (R) of 1.35 (slightly uniform), however the Z statistic of 0.52 indicated that the result was not significantly different from random. A plot of the direction to nearest neighbour shows a slight peak in the NNW-SSE direction (Fig. 8), the mean bearing was 153 ° magnetic.

Other morphometric studies

Webster (1996) also measured pipes at the 'Petrified Forest'. He reported results from ten 3 x 3m sites as follows: The mean density of pipes at all sites was 1.80 pipes/m^2, ranging from 1.22 to 2.78 pipes/m^2. The average diameter (presumably the inside diameter) ranged from 275 to 540mm at the different sites, with an overall mean of 401mm.

Herwitz (1993) measured pipes at four sites in Bermuda and reported that the mean diameter ranged from 200 to 370mm. He reported densities of between 0.33 and 0.60 pipes/m^2 in his table (much less than at the 'Petrified Forest') , but mentioned in his text that densities in other, smaller, plots exceeded 1.2 pipes/m^2. For comparison he measured a Palmetto stand which had mean trunk widths of 320mm, but a density of only 0.06 trunks/m^2 — much less than that of the pipes. Coetzee (1975) reported from southern Africa an average pipe density of 1pipes/m^2 with exceptional cases up to 3 pipes/m^2. His diameters were between 300 and 400 mm.

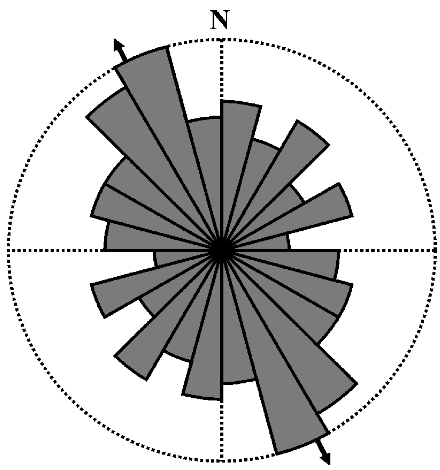


Figure 8: Rose diagram of directional frequency of nearest neighbouring pipe, using magnetic bearings. N=53, plotted by area of sector.