

## Chapter 43

# Solution Pipes and Pinnacles in Syngenetic and Soft-rock Karst

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### Abstract

Solution pipes are a distinctive feature of karst developed on soft, porous limestones. Several alternative processes have been suggested for their formation. The early tree-mould hypothesis is rejected in favour of more recent suggestions that interpret the features as solution pipes formed by focussed vertical vadose water flow through the porous calcareous sands (calcarenites, aeolianites). The focussing of the flow may be spontaneous and associated with ongoing patchy cementation of the hard-pan of the soil, or it may be guided by other factors such as concentrated stem-flow beneath trees or the pooling of water in hollows in exposed hard-pans. Solution adjacent to tap roots is also possible. Pinnacles can form locally by coalescence of solution pipes.

### Introduction

Solution pipes (or dissolution pipes), as described here, are the small vertical smoothly cylindrical pipes found in soft (poorly cemented) porous calcarenites, and usually associated with a modern or ancient soil or a calcrete band. They are typically about 0.5 m wide and 2-5 m deep, though there is significant variation. Pinnacles are associated features. A recent detailed review of solution pipes is given by Lundberg and Taggart (1995)—who advocate 'dissolution pipe' as being a more correct term.

Solution pipes are also known as "solution chimneys", "shafts", "pits", "geological organs", and Lundberg & Taggart (1995) list other names. The confusion of terminology is increased by many of those terms also being used for similar features in the epikarst of hard-rock limestones, where the lack of matrix porosity and greater structural control require a somewhat different genesis (see chapter 10, Klimchouk, 2004??).

### *Soft-rock, eogenetic, and syngenetic karst*

This chapter deals with solution pipes formed in soft, porous limestones. These limestones form a special type of karst that has been referred to as soft-rock or eogenetic karst (Myloie & others, 2001; Grimes, 2002). Soft-rock karst occurs in dune limestone (aeolianite) and other calcarenites (e.g. beach or shallow marine sands), in finer-grained material such as chalk and in coarser coquina or reef rubble. It is distinguished from the classic hard-rock karsts in that the host limestone has never been deeply buried and indurated by mesogenetic diagenesis (Choquette & Pray, 1970). Apart from being soft, a critical feature of these limestones is that they still have a significant primary matrix porosity—up to 30%. Within these soft sediments many of the karst features, including the pipes, have formed at the same time as the sand was being cemented into a rock and the term syngenetic karst has been applied to that process (Jennings, 1968; Grimes, 2002). Karst features can continue to form after the sand is cemented, but before it is strongly indurated by deep burial. Thus syngenetic karst is the early stage of what is more broadly called eogenetic or soft-rock karst.

## ***The development of syngenetic karst***

In calcareous dunes, percolating rain water gradually converts the unconsolidated sand to limestone by dissolution and redeposition of calcium carbonate. Initial solution at the surface forms a terra rossa or similar soil depleted in carbonate but enriched in the insoluble grains (e.g. quartz). At the base of the soil, precipitation of carbonate forms a cemented and locally brecciated calcrete layer or hard-pan. Within and below this the downward percolating water becomes focussed to dissolve characteristic vertical solution pipes, and simultaneously cements the surrounding sand. Calcrete hard-pans and solution pipes both appear quite early in the syngenetic sequence, long before the sand is sufficiently cemented to support a cave roof (Bastian, 1964, p.116.). However, the pipes continue to develop and deepen as cementation of the host sand continues. Early cementation tends to be localized about roots to form distinctive rhizomorphs or rhizocretions.

Surface karren forms are rare in syngenetic karst, mainly because there is little hard rock available for their formation. Where soil stripping exposes the calcrete hardpan, rain pits and small grikes may form, and sharply pitted phytokarst occurs in coastal exposures. Subsoil karren are also uncommon, apart from the pipes and pinnacles discussed in this chapter. The top of the hard-pan may show irregular hollows, but it is difficult to be sure whether these are solutional, or merely irregularities in the top of the cemented zone. Rhizomorphs are common.

## ***Occurrence of solution pipes***

Solution pipes have been reported from porous limestones in many parts of the world, in particular from the dune limestones, also known as dune calcarenite or aeolianite (Gardner, 1983; McKee & Ward, 1983). Examples include: the western and southern coasts of Australia (Fairbridge, 1950; Boutakoff, 1963; Jennings, 1968; Grimes, 1994, 2004; White, 2000), Southern Africa (Coetzee, 1975), the Mediterranean (Day, 1928) the Caribbean (Lundberg & Taggart, 1995; Mylroie & Carew, 1995) and Bermuda (Herwitz, 1993). Similar pipes also occur in the Chalk of Europe, which is finer grained, but still relatively soft and porous (Burnaby, 1950; Ford, 1984, p262; Rodet, 1992, pp.119-122).

Climate appears to be less important than the nature of the host rock, though the global distribution of dune calcarenites seems to be partly controlled by climate and oceanography (Gardner, 1983; McKee & Ward, 1983). Many aeolianites occur between 20-40 degrees of latitude, either in coastal "Mediterranean" climates that have cool wet winters and hot dry summers, or in hotter or more arid settings. However there are exceptions in cooler and wetter climates.

## **The Nature of Solution Pipes**

### ***Form***

Typically, solution pipes form smooth vertical cylinders which may narrow towards a rounded base ('cigar shaped' is a common description) or terminate abruptly in a hemisphere (Figures 1 & 2). Conical pipes are less common. The pipes are variable in width, averaging about 0.5 m, but can be smaller than 0.2m or over 1 m, although the wider ones tend to be less regular, and some may be due to coalescence of several smaller pipes. Depths are typically 2-5 m, but they can be up to 20 m deep and some may connect with underlying caves (Figure 3). They can occur as isolated individuals, widely spaced sets (e.g. 5-10 m spacing) or in dense fields with spacings that can be closer than one metre (Figure 1). At Cape Bridgewater, Victoria, Webster (1996) measured densities of 0.7 to 2.8 pipes per m<sup>2</sup>

(average 1.8) in ten 3 x 3 m quadrats; and pipe diameters ranging from 0.27 m to 0.54 m (average 0.40 m). At one 5 x 5 m quadrat at the same site this author measured a density of 2.1 pipes per m<sup>2</sup>, a mean inside diameter of 0.27 +/- 0.09 m, and mean distance to nearest neighbour of 0.46 +/- 0.013 m (Grimes, 1993). Herwitz (1993) reported mean diameters between 0.2 and 0.37 m from sites at Bermuda, however his densities were much less at between 0.33 and 0.60 /m<sup>2</sup>, though he mentioned densities in localised areas exceeding 1.2 /m<sup>2</sup>.

Solution pipes are commonly associated with a present or past soil horizon; either descending from it (Figure 4), or cutting through a hard band of pedogenic calcrete that could be a subsoil hardpan. In stacked dune sequences one commonly sees several levels of paleosoils, each with a set of associated soil-filled solution pipes. Where closely spaced sequences occur, solution pipes may terminate on reaching the underlying paleosoil, or may drill through it and continue through the underlying dune unit.

### ***Related features***

In the Bahamas the term '**pit cave**' has been applied both to solution pipes, and to larger pits, up to 7 m in diameter and 10 m depth, that have less-regular forms (Pace & others, 1993; Mylroie & Carew, 1995; González & others, 1997). Some of these have horizontal or inclined extensions at depth. In some cases these larger pits appear to be due to coalescence of smaller solution pipes, but many are too irregular to have that origin.

The Nambung **Pinnacles** in Western Australia appear to be an extreme case resulting from the coalescence of closely spaced solution pipes in a calcrete band. They are discussed later in this chapter.

### ***Rims and fill material***

Solution pipes commonly, but not always, have a calcareous cemented rim around them that is a few centimetres thick. Thin concentric micritic calcrete laminae can also line the pipes. Lundberg & Taggart (1995) describe in detail the rims, fills and host rocks at two sites in Puerto Rico: the rims there were of micrite and microspar, and there was also replacement of bioclasts by those cements. Porosities were much less than in the host rock, typically 0-5%. Cemented rims and fills can be etched out by erosion of the surrounding softer sands (Figure 1).

Some pipes appear to be filled with a modified version of the original host sediment, and relict structures of the original bedding may be preserved (the "ghost tubes" of Page & others, 1993). Most, however, are filled with a downward extension of the overlying red or pale brown soil (typically a terra rossa that has been enriched in insoluble components of the host sediment). Some of the associated soils are partly allogenic rather than entirely residual (e.g. Herwitz, 1993). Pipes can be emptied by loss of their fill downward into an underlying (younger) cave, where they may form soil cones, or by erosional undermining, or by excavation by sea water or a stream. These empty pipes may later be refilled by younger allogenic material, for example by a younger dune, or during a subsequent marine transgression. Secondary fills are common in paleokarst exposures, where complex multi-generation fills can occur (e.g. see figure 3 of Mylroie & Carew, 1995).

Fills can be massive, or crudely bedded, or have concentric cemented layers or calcrete laminae (Figure 5). Brecciated material and calcareous veins occur in some pipes. Many pipe fills have traces of thin calcareous root structures (rhizomorphs) embedded in them; as

does the surrounding host sand.

### ***Rhizomorphs***

Rhizomorphs are hard calcified root structures that are commonly associated with the pipes. Rhizomorphs are common in calcareous dunes and have an obvious branching root structure. They form from carbonate that has been precipitated around the root, and are thus thicker than the original root - which may be identifiable as a thin hollow core if that has not been infilled by younger cement.

### ***Paleokarst***

Solution pipes can be preserved in paleokarsts and are an important clue to the existence of subaerial disconformities and hardgrounds in the geological record (e.g. Ford, 1984; Wright, 1987; Sandler, 1996). The fill material in paleokarst pipes may be an important record of deposition events that have been destroyed elsewhere during the subsequent transgression (e.g. Walkden & Davies, 1983).

## **Mode of formation**

An early suggestion, by Boutakoff (1963) among others, was that the pipes were "petrified forests"; that is, moulds of buried tree trunks. This had some initial support from workers in Bermuda, where the pipes were regarded as moulds of palmetto stumps; however, recent work has discredited this (Herwitz, 1993, Grimes, 2004).

Lundberg and Taggart (1995) note that dissolution by focussed vertical vadose 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 formed around rootlets 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 overlying material can progressively fill them as they deepen.

But why is the downward water flow focussed into narrow routes 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 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 Grimes (2004) added a fourth: areas of higher porosity in the developing soil hard pan (Figure 6).

In passing, it is worth noting that similar vertical pipes occur in the giant podsoles that develop on the porous quartz sand dunes of the Queensland coast (e.g. Thompson and Bowman, 1984, p.282). These have a deep, leached, white A2 horizon over a dark humic-rich, less permeable, B horizon. Pipes of the leached A2 material from a few centimetres to nearly half a metre wide penetrate several metres down into the enriched B horizon. Spontaneous focussing of downward water flow through the porous sand seems to be involved in that setting also.

### ***Stem-flow***

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 (Figure 6-a). Herwitz (1993) measured stem flow under a variety of trees in Bermuda and showed that it could generate significant concentrations of water and noted that multiple generations of trees could produce the dense spacing of pipes which is observed in places.

### ***Roots***

The influence of tree roots was suggested by Jennings (1968) and Brink & Partridge (1980). Roots generate organic acids and raised CO<sub>2</sub> levels that enhance solution in their vicinity (Figure 6-b). A vertical tap root 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***

Surface hollows were suggested by Coetzee (1975) and Spenser (1980) as a way of concentrating inflow (Figure 6-c). If hollows exist (on a partly indurated surface, or on the top of the soil hard-pan) 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.

### ***Variations in hard-pan porosity***

Uneven cementation of the developing hard-pan is a possible fourth process (Grimes, 2004). Rain dissolves carbonate grains as it penetrates the soil, and some of this is re-precipitated lower down to form a hard pan or calcrete band near the base of the soil. In the initial stages this cemented band would not develop evenly (Figure 6-d). The better-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.

### ***Ongoing evolution of the pipe***

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 and also contribute to the general cementation of the sand body (Figure 7). Lundberg & Taggart (1995) noted that the linings have many features of pedogeneic calcretes. Where pipes become emptied, case-hardening of the exposed pipe walls would also contribute to rim cementation. Some fills show 'ghost structures' which indicate that the host sand has had its porosity enhance, without being actually removed. Most fills are associated soils that have subsided into the pipe as it formed, or later allogenic material that has entered an empty pipe. These fills can also be cemented and may show structures of pedogenic calcretes.

### ***Special cases***

Some special cases include the larger of the pit caves of the Bahamas and the pinnacles of the Nambung area in Western Australia. The **larger pit caves** are distinguished by their less regular form. Instead of smooth cylinders they have irregular outlines and may be inclined or

bell out at depth. Pace & others (1993) attributed the Bahaman pit caves to the "concentration of meteoric water by surface and subcutaneous channelization"; the same process described above. However, the more complex forms of these larger pits do not agree with the concept of simple focussed flow through a uniformly porous sand. Possibly the larger pit caves are late syngenetic or even post syngenetic (but still eogenetic) features where the more strongly cemented limestone exerts structural controls on the shape of the pit. For example, the inclined pits may be following indurated dune cross-bedding, and the irregular vertical profiles may reflect various degrees of cementation in the host rock. Some pit caves seem to show joint control.

## **Pinnacles**

The Pinnacles at Nambung and other parts of the coastal dune limestone in Western Australia appear to be an extreme case resulting from the coalescence of closely spaced solution pipes in a calcrete band (Lowry, 1973; McNamara, 1995). These are generally discrete pinnacles with a conical form (Figure 8), or are cylindrical with a round top (Figure 9). A few are hollow. They are up to 3 m high and 0.5 to 3 m wide. The broader pinnacles are composite structures with multiple peaks (Figure 8). They are the dissected remnants of a cemented band. The upper part of this band is a hard pedogenic calcrete in which the primary depositional structures have been destroyed, but it grades down into a cemented dune sand where the dune bedding is still visible. At the base cemented rhizomorphs extend downward into the soft parent sand. Those pinnacles developed in the calcrete have smooth surfaces (Figure 8), but those developed below have rough surfaces resulting from the fretting of the dune bedding and rhizomorphs (Figure 8). Where both types occur together the calcrete may form a phallic bulb at the top of the pinnacle. Sections of an earlier generation of small solution pipes (0.1 to 0.4 m wide) with a hard concentric fill are exposed in both the calcrete and the bedded material (Figures 5 and 8). The tops of the pinnacles show a summit conformity which would be the sharp upper surface of the original calcrete band. Where exposed, their bases may end abruptly or, more usually, grade downward into less-cemented material characterised by abundant rhizomorphs (Figure 10).

### ***Genesis***

The pinnacles at Nambung appear to be residual features resulting from coalescence of densely spaced solution pipes that dissected a cemented calcrete band (Lowry, 1973; McNamara, 1995). The genesis is complicated by the presence of an earlier generation of solution pipes, with cemented concentric-banded fill, that is exposed in the sides of the later pinnacles (Figures 5 & 8). Lowry (1973) suggested the following stages in development of the Nambung Pinnacles:

1. Formation of the dunes as loose calcareous sand.
2. Development of a hard cap-rock comprising cemented calcarenite, recrystallised micritic limestone and banded secondary limestone [calcrete]. Solution pipes develop and become filled with concentric layers of calcrete.
3. Continued leaching sculpts the cemented limestone into pinnacles up to 4-5 m high, which cut across the earlier structures of dune bedding, rhizomorphs, cemented solution pipes, and calcrete. The pinnacles are covered by 4-5 m of loose yellow quartz sand.
4. Erosion of the loose sand has exposed the Pinnacles.

McNamara (1995) extended Lowry's model to suggest that some of the more cylindrical pinnacles might have formed by cementation around tap roots in zones up to 1 m wide. He also noted that some of the small pinnacles could be the cemented fill of prior solution pipes.

### ***Other pinnacles***

In France, Rodet (1992, p.121) described subsoil pinnacles in the Chalk, exposed at the coast and known as "bonshommes de craie". These formed by coalescence of conical solution pipes, his "racines du manteau d'altération".

Pinnacles are also reported as epikarst features buried beneath phosphate deposits on several oceanic islands (e.g. Jacobson, & others, 1997 and Chapter 29? of this book, [Williams 2004? Editor please to substitute appropriate cross-reference](#)), but unfortunately there is generally insufficient information on the character of the host limestone (in particular, its matrix porosity and cement) to allow comparison with the Nambung Pinnacles. On Christmas Island, in the Indian Ocean (Grimes, 2001), the pinnacles beneath the phosphate are formed on a hard, micritic limestone that has minimal matrix porosity. Those pinnacles are best classed with hard-rock epikarst features (see chapter 10??, Klimchouk, 2004??[Editor please to substitute appropriate cross-reference](#)); they are not the same as the soft-rock pinnacles at Nambung.

## **Conclusion**

Solution pipes are distinctive features of soft porous limestones, in particular dune calcarenites. They are syngenetic karst features, developing in the early stages of cementation of the loose sand, but continuing to deepen and evolve after the sand has been converted to a soft limestone. They can contain a variety of fill materials, which may give clues to the history of the karst surface and are particularly useful in the interpretation of paleokarst exposures.

Solution by focussed vertical vadose seepage through the porous sand can account for both isolated pipes, and the dense fields of pipes. Note that the four alternative modes of focussing water flow discussed above are not presented as mutually exclusive hypotheses—all could act, either together or separately, according to the local situation in any area.

The associated pinnacles appear to be an extreme case in which solution pipes cutting through a cemented band have coalesced to leave residual areas of hard limestone.

## **Acknowledgements**

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## **References**

- Bastian, L., 1964: Morphology and development of caves in the southwest of Western Australia. *Helictite*, **2(4)**: 105-119.
- Boutakoff, N., 1963: The geology and geomorphology of the Portland area. *Geological*

*Survey of Victoria, memoir, 22.*

- Brink, A.B.A., & Partridge, T.C., 1980: The nature and genesis of solution cavities (Makondos) in Transvaal cave breccias. *Palaeontology Africa*, **23**: 47-49.
- Burnaby, T.P., 1950: The tubular chalk stacks of Sheringham. *Proceedings of the Geological Association*, **61**: 226-241.
- Choquette, P.W., & Pray, L.C. 1970: Geologic Nomenclature and Classification of Porosity in Sedimentary Carbonates. *American Association of Petroleum Geologists Bulletin*, **54**: 207-250
- Coetzee, F., 1975: Solution pipes in coastal aeolianites of Zululand and Moçambique. *Transactions of the Geological Society of South Africa*, **78**: 323-333.
- Day, A.E., 1928: Pipes in the Coast Sandstone of Syria. *Geological Magazine*, **65**: 412-415.
- Fairbridge, R.W., 1950: The geology and geomorphology of Point Peron, Western Australia. *Journal of the Royal Society of Western Australia*, **34**: 35-72.
- Ford, T.D., 1984: Palaeokarsts in Britain. *Cave Science*, **11(4)**: 246-264.
- Gardner, R.A.M., 1983: Aeolianite. in Goudie, AS., & Pye, K., [eds] *Chemical sediments and geomorphology*. Academic Press, London. pp. 265-300.
- Grimes, K.G., 1994: The South-East Karst Province of South Australia. *Environmental Geology*, **23**: 134-148.
- Grimes, K.G., 2001: Karst features of Christmas Island (Indian Ocean). *Helictite*, **37(2)**: 41-58.
- Grimes, K.G., 2002: Syngenetic and Eogenetic Karst: an Australian viewpoint. in GABROVŠEK, F. [ed] *Evolution of Karst: from Prekarst to Cessation*. Inštitut za raziskovanje krasa, ZRC SAZU, Postojna. pp. 407-414.
- Grimes, K.G., 2004: Solution Pipes or Petrified Forests? Drifting sands and drifting opinions! *The Victorian Naturalist*, **121(1)**: 14-22.
- González, L.A., Ruiz, H.M., Taggart, B.E., Budd, A.F., & Monell, V., 1997: Geology of Isla de Mona, Puerto Rico. in Vacher, HL., & Quinn, T., [eds] *Geology and Hydrogeology of Carbonate Islands. Developments in Sedimentology, 54*. Elsevier Science, BV. 327-358.
- Herwitz, S.R., 1993: Stemflow influences on the formation of solution pipes in Bermuda eolianite. *Geomorphology*, **6**: 253-271.
- Jacobson, G.J., Hill, P.J., & Ghassemi, F., 1997: Geology and Hydrogeology of Nauru Island. in Vacher, HL., & Quinn, T., [eds] *Geology and Hydrogeology of Carbonate Islands. Developments in Sedimentology, 54*. Elsevier Science, BV. 707-742.
- Jennings, J.N., 1968: Syngenetic Karst in Australia. in P.W. Williams and J.N. Jennings, *Contributions to the study of karst*. Australian National University, Department of Geography Publication G/5(1968). pp 41-110.
- Кlimchouk, A.B., 2004??: [Chapter 10 of this book (Wells and Small Shafts). Editor please | to fill in details.]



- Lowry, D.C., 1973: Origin of the Pinnacles. *Australian Speleological Federation Newsletter*. **62**: 7-8.
- Lundberg, J., and Taggart, B.E. 1995: Dissolution pipes in northern Puerto Rico: an exhumed paleokarst. *Carbonates and Evaporites*, **10(2)**: 171-183.
- McKee, E.D., & Ward, W.C. 1983: Eolian Environment. in Scholle, P.A., Bebout, D.E., & Moore, C.H., [eds] *Carbonate depositional environments*. AAPG memoir, **33**. 131-170.
- McNamara, K.J., 1995: *Pinnacles [revised edition]*, Western Australian Museum, Perth. 24 pp.
- Myloie, J.E. & Carew, J.L. 1995: Karst development on Carbonate Islands. in Budd, D.A., Saller, A.H., & Harris, P.M., [eds] *Unconformities and Porosity in Carbonate Strata*. AAPG Memoir **63**. 55-76.
- Myloie, J.E., Jenson, J.W., Taborosi, D., Jocson, J.M.U., Vann, D.T., & Wexel, C. 2001: Karst Features of Guam in Terms of a General Model of Carbonate Island Karst. *Journal of Cave and Karst Studies*, 63(1): 9-22
- Pace, M.C., Myloie, J.E. & Carew, J.L., 1993: Investigation and review of dissolution features on San Salvador Island, Bahamas. in White, B., [ed] *Proceedings of the Sixth Symposium on the Geology of the Bahamas*. pp. 109-123.
- Rodet, J., 1991: *La Craie et ses Karsts*. Centre de Géomorphologie du CNRS, Caen. 560 pp.
- Sandler, A., 1996: A Turonian subaerial event in Israel: karst, sandstone and pedogenesis. *Geological Survey of Israel, Bulletin*, **85**. 56 pp.
- Thompson, C.H., and Bowman, G.M., 1984: Subaerial denudation and weathering of vegetated coastal dunes in eastern Queensland. in Thom, B.G., [ed], *Coastal Geomorphology in Australia*. Academic Press, Sydney. pp. 263-290.
- Walkden, G., & Davies, J., 1983: Polyphase erosion of subaerial omission surfaces in the late Dinantian of Anglesey, North Wales. *Sedimentology*, **30**: 861-878.
- Webster, C.L., 1996: The Intrigue of the Question about the Bridgewater "Fossil Forest", Victoria, Australia. *Origins*, **23(1)**: 50-60.
- Williams, P.W., 2004??: [Chapter 29? of this book (Nauru Pinnacles). Editor please to fill in details.]
- White, S. 2000: Syngenetic Karst in Coastal Dune Limestone: A Review. in A.B. Klimchouk, D.C. Ford, A.N. Palmer and W. Dreybrodt [eds] *Speleogenesis: Evolution of Karst Aquifers*, Huntsville, Alabama: National Speleological Society. pp. 234-237.
- Wright, V.P., 1988: Paleokarsts and paleosoils as indicators of paleoclimate and porosity evolution: a case study from the Carboniferous of South Wales. in James, N.P., & Choquette, P.W., [eds] *Paleokarst*. Springer-Verlag, NY. pp. 329-341.

**Figures for Chapter 43, on Solution Pipes, by K.G. Grimes**



Figure 1: Stereopair of a cluster of pipes at 'The Petrified Forest', Cape Bridgewater, western Victoria. Note the cemented rims.

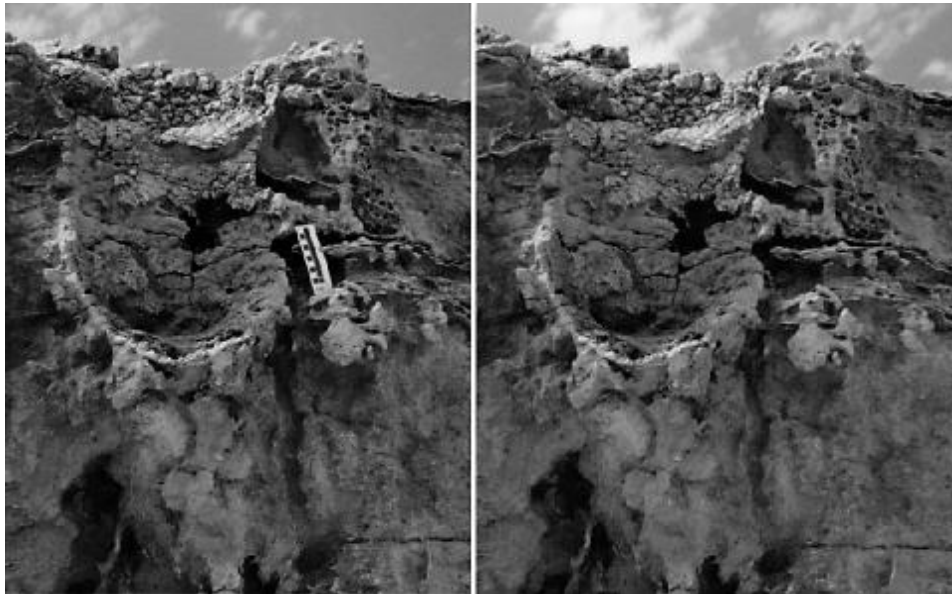


Figure 2: Stereopair of the hemispherical base, with thin cemented rim, of a pipe at 'The Petrified Forest', Victoria, about 30 m west of the main group shown in Figure 1. Scale-bar is 10 cm.



Figure 3: A deep, open, solution pipe that forms a cave entrance. Ladder rungs are spaced 30 cm. (Photo by R.K. Frank).



Figure 5: Concentric laminae in the cemented fill of a small pipe exposed in the side of a pinnacle at Nambung, Western Australia. 10 cm scale.

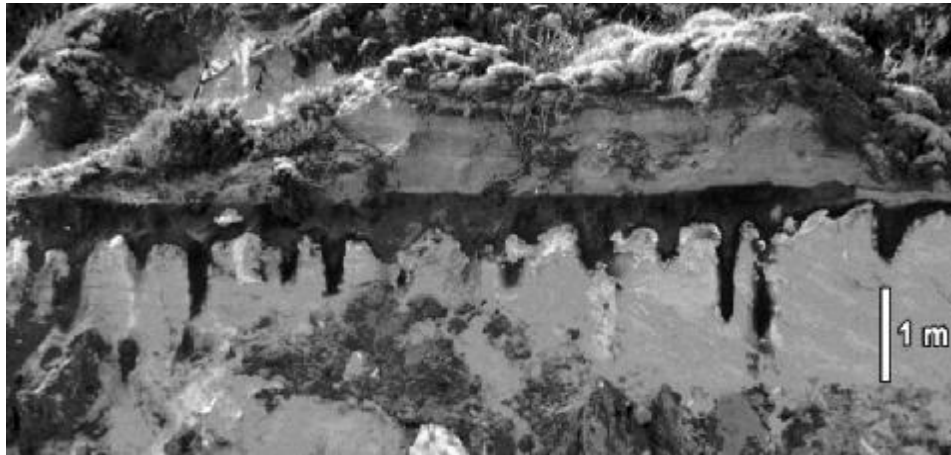


Figure 4: A red paleosol and soil-filled pipes beneath a younger sand dune exposed in a cliff at Canunda National Park, South Australia. These pipes lack a cemented rim.

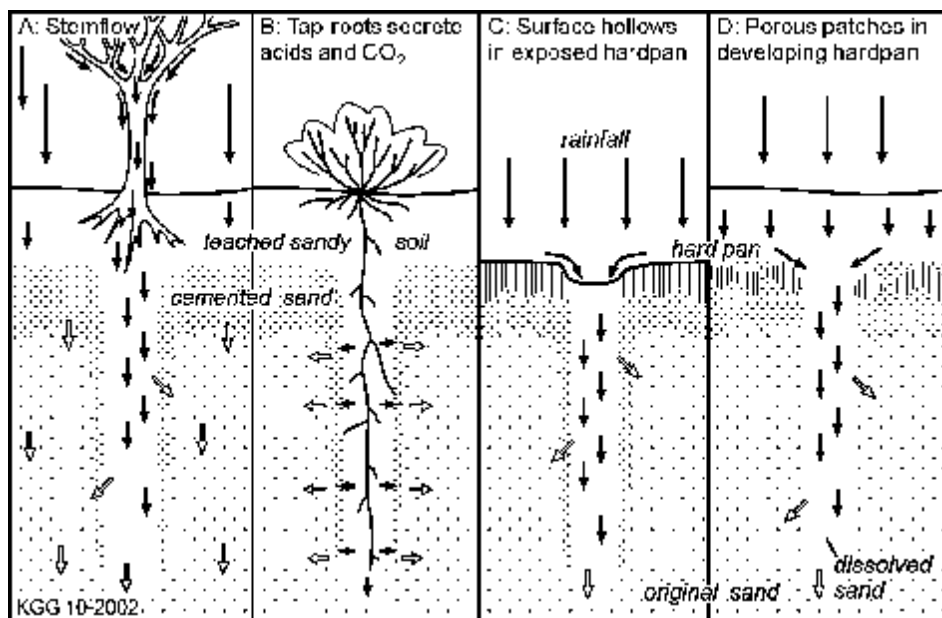


Figure 6: Alternative ways in which the downward flow of water can become focussed to generate solution pipes (see text). Note, the alternatives are not mutually exclusive, they could all contribute in different settings.

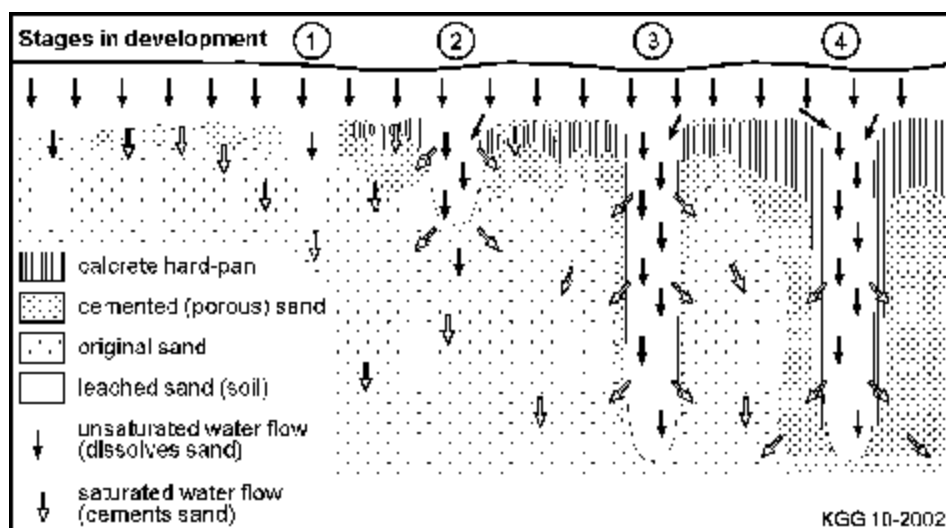


Figure 7: Stages in which a solution pipe deepens and develops a cemented rim. A possible further stage in which the fill is cemented is not shown.



Figure 8: A composite conical pinnacle at Nambung, Western Australia, that shows the dune cross-bedding and several small solution pipes that have been intersected by the pinnacle. Height is about 2 m.



Figure 9: Smooth cylindrical pinnacles at Nambung developed in the hard calcrete band.



Figure 10: A fallen pinnacle shows a smooth, strongly cemented, upper part and a rougher area below that is less cemented, and mainly composed of rhizomorphs.