Solution Pipes and Pinnacles in Syngenetic Karst 42

Ken G. Grimes.

Chapter 42, pages 513-523 *in* Angel Ginés, Martin Knez, Tadej Slabe & Wolfgang Dreybrodt.(editors) *Karst Rock Surfaces: Karren Sculpturing.* Založba ZRC, Ljubljana. 2009.

This is my private layout, with a different pagenation. I have used my original figures and photos as the editors removed all scale indications from photos in the book!

Ken Grimes,
RRN 795 Morgiana Rd., Hamilton, Vic 3300, Australia. ken.grimes@bigpond.com

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, but less common. A recent detailed review of solution pipes was given by Lundberg and Taggart (1995) – who advocated "dissolution pipe" as being a more correct term.

Solution pipes are also known as *solution chimneys, shafts, pits, geological organs*, and Lundberg and 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 telogenetic limestones, where the lack of matrix porosity and greater structural control require a different genesis.

Syngenetic and eogenetic 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 syngenetic or eogenetic karst (Jennings, 1968; Mylroie et al., 2001; Grimes, 2002, 2006; White et al., 2007). *Syngenetic 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 (telogenetic) karsts in that the host limestone has never been deeply buried and indurated by mesogenetic diagenesis (Choquette and Pray, 1970). Apart from being only weakly cemented, a critical feature of these limestones is that most of them 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, 2006). White et al. (2007) discuss the usage of the terms syngenetic and eogenetic karst, which overlap in most situations, and suggest that "syngenetic" be used as the general term, and that "*eogenetic karst*" be restricted to the subset of syngenetic karst which postdates the depositional cycle in which the sediments were formed.

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*, also known as a *cap-rock*. Within and below this the downward percolating aggressive water becomes focussed to dissolve characteristic vertical solution pipes, and simultaneously the carbonate dissolved at the surface and within the pipes 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). 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 hard-pan, *rainpits* 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 and Ward, 1983). Examples include: the western and southern coasts of Australia (Fairbridge, 1950; Boutakoff, 1963; Jennings, 1968; Grimes, 1994, 2004, 2006; White, 2000), Southern Africa (Coetzee, 1975), the Mediterranean (Day, 1928; Marsico et al., 2003), the Caribbean (Lundberg and

Taggart, 1995; Mylroie and 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; Rodet, 1992).

Climate appears to be less important than the nature of the host rock, although the global distribution of dune calcarenites seems to be partly controlled by climate and oceanography (Gardner, 1983; McKee and 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 have a range of widths, averaging about 0.5 m, but can be smaller than 0.2 m 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^2 (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). In one 5 x 5 m quadrat at the same site Grimes (2004) measured a density of 2.1 pipes per m^2, a mean inside diameter of 0.27 +/- 0.09 m, and mean distance to nearest neighbour of 0.46 +/- 0.013 m. 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 per m^2, though he mentioned densities in localised areas exceeding 1.2 per m^2.

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 hard-pan. In stacked dune sequences one commonly sees several levels of *palaeosoils*, each with a set of associated soil-filled solution pipes. Where closely spaced sequences occur, solution pipes may terminate on reaching the underlying palaeosoil, 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 et al., 1993; Mylroie and Carew, 1995; González et al., 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.

Pinnacles, such as those at Nambung in Western Australia, may be an extreme case resulting from the coalescence of closely spaced solution pipes in a calcrete band, or they may be due to focussed cementation. 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 and 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

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

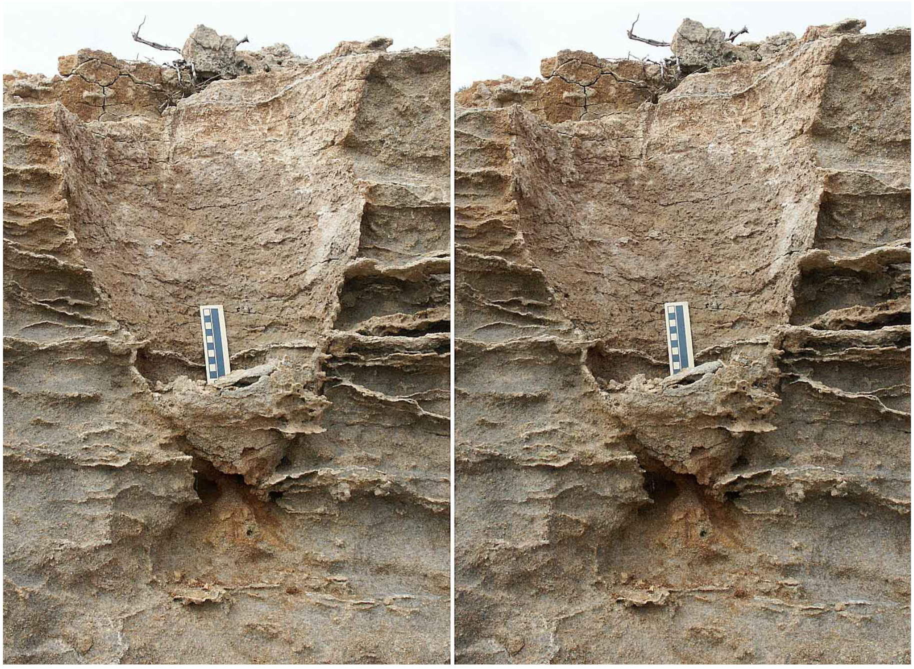

Figure 2: Stereopair of the cigar-shaped base, with thin cemented rim, of a pipe near "The Petrified Forest", Victoria. Scale-bar is 10 cm.

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).

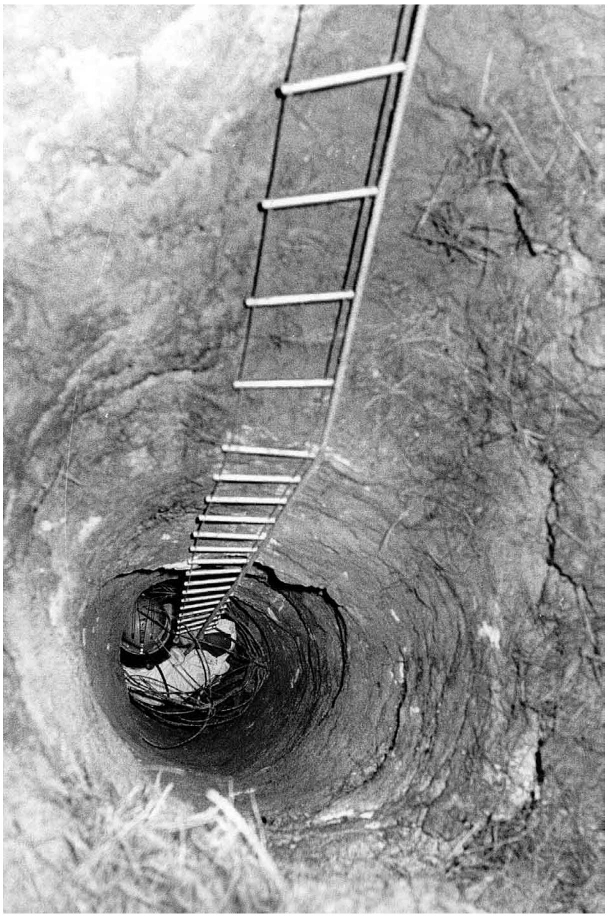

Figure 3: A deep, open, solution pipe that forms a cave entrance. Ladder rungs are spaced 30 cm. (Photo by R.K. Frank).

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 Pace et al., 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 *palaeokarst* exposures, where complex multi-generation fills can occur (e.g. see figure 3 of Mylroie and 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 (or *rhizocretions*) 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.

Figure 4: A red paleosoil 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.

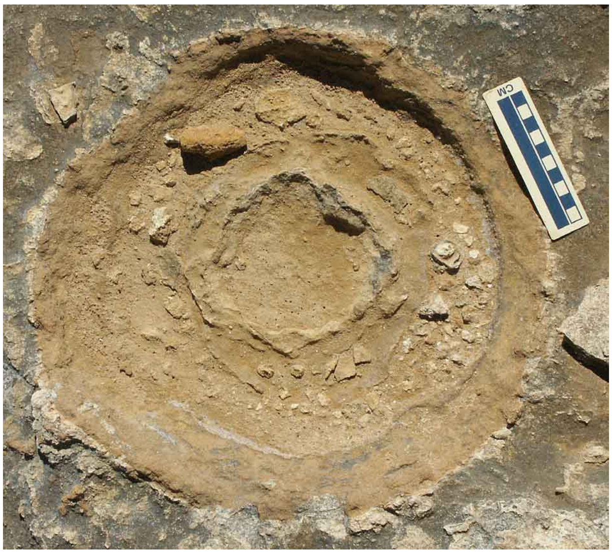

Figure 5: Concentric laminae in the partly cemented fill of a solution pipe near "The Petrified Forest", Victoria. Scale-bar is 10 cm.

Palaeokarst

Solution pipes can be preserved in *palaeokarsts* and are an important clue to the existence of subaerial disconformities and hardgrounds in the geological record (e.g. Ford, 1984; Wright, 1988; Sandler, 1996). The fill material in palaeokarst pipes may be an important record of deposition events that have been destroyed elsewhere during the subsequent transgression (e.g. Walkden and 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, non-porous, 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 within the developing soil hard-pan (Figure 6).

In passing, it is worth noting that similar vertical pipes occur in the giant podsols that develop on the porous quartz sand dunes of the Queensland coast (e.g. Thompson and Bowman, 1984). 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. Solution pipes also occur in laterite karsts, as discussed in the section on pinnacles.

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 localized solution and pipe development (Figure 6a). 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 and Partridge (1980). Roots generate organic acids and raised CO_2 levels that enhance solution in their vicinity (Figure 6b). 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.

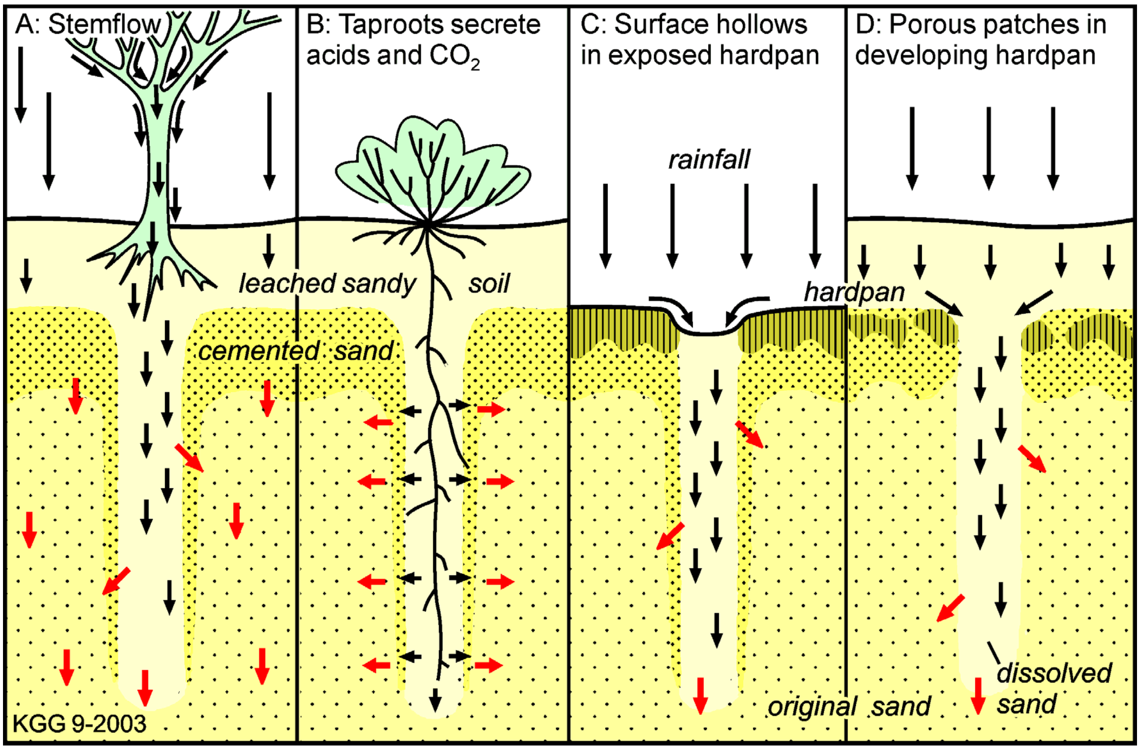

Figure 6: Alternative ways in which the downward flow of water can become focussed to generate solution pipes (see text). Black arrows are aggressive water flow and red arrows are saturated water. Note, the alternatives are not mutually exclusive, they could all contribute in different settings.

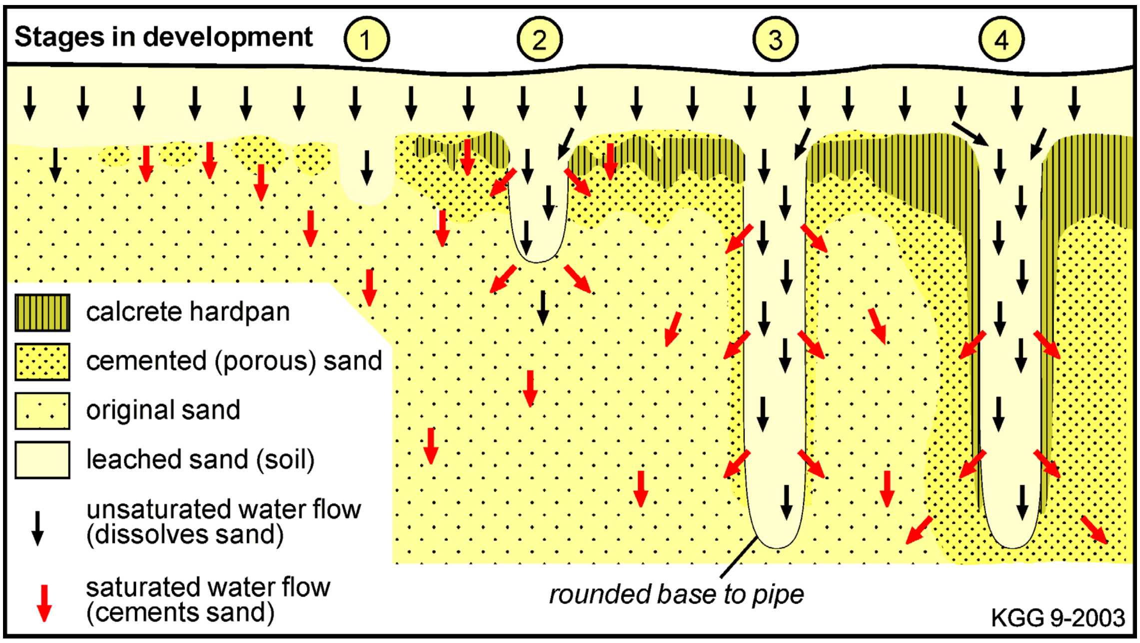

Figure 7: Stages in which a solution pipe deepens and develops a cemented rim. A possible further stage in which the fill is cemented is not shown.

Surface hollows

Surface hollows were suggested by Coetzee (1975) as a way of concentrating inflow (Figure 6c). 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 6d). 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 and Taggart (1995) noted that the linings have many features of pedogenic 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 enhanced, 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 et al. (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 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 may be an extreme case resulting from the coalescence of closely spaced solution pipes in a calcrete band (Lowry, 1973; McNamara, 1995), or they may be due to focussed cementation.

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 obliterated, 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

Figure 8: A composite conical pinnacle at Nambung, Western Australia, that shows the dune cross-bedding and sections of several small filled 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.

sand. Those pinnacles developed in the calcrete have smooth surfaces (Figure 9), 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 (Figure 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

Lowry (1973) and McNamara (1995) suggested that the pinnacles at Nambung may be residual features resulting from coalescence of densely spaced solution pipes that dissected a cemented calcrete band. 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 (Figure 8). Lowry (1973) suggested the following stages in development of the Nambung Pinnacles:

- formation of the dunes as loose calcareous sand;
- development of a hard cap-rock (hard-pan) comprising cemented calcarenite, recrystallised micritic limestone and banded secondary limestone (calcrete). Solution pipes develop and become filled with concentric layers of calcrete;
- continued leaching sculptures 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;
- 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.

Figure 11: Cemented lobes descending from a hard-pan layer at Naracoorte, South Australia, suggest focussed cementation by downward moving water. Note hammer for scale.

An alternative origin for the pinnacles could be as a result of focussed cementation – the focussing would be in a similar way to that described for solution pipes, but in this case instead of the down-flowing water being aggressive, it was saturated and so cemented the sand in vertical cylindrical patterns. The source of the saturated water would be the topsoil of the dune, or possibly younger dune sands which buried the initial dune. The latter situation could explain the earlier generation of solution pipes exposed within the pinnacles at Nambung. Alternatively, the change from unsaturated water that produced the earlier generation of pipes, to saturated water flow might reflect a climate change.

Supporting evidence of this process is given by some calcrete hard-pans which have bulbous cemented pendants descending from them into the softer sand below (Figure 11). These inverted pinnacles could result from focussed cementation.

The focussed cementation process differs from that of the solution pipes in that the pipes are self-perpetuating and can drill down to great depths, whereas the vertical cemented zones would reduce the permeability and deflect the flow so that the cemented area spreads horizontally and eventually cements the whole dune. Perhaps pinnacles are less common than pipes because we only see them where the cementation is incomplete.

Both of the suggested processes, coalescing solution pipes and focussed cementation, could be valid. The cylindrical pinnacles (Figures 9 and 10) might have formed by focussed cementation, as would the hollow pinnacles which would be due to cementation around a solution pipe. However, the composite pinnacles (Figure 8) might be the result of coalescing pipes.

Other pinnacles

In France, Rodet (1992) described subsoil pinnacles in the *Chalk*, exposed at the coast and known as *bonshommes de craie*. He attributed these to coalescence of conical solution pipes, his *racines du manteau d'altération*. Waltham (2001) described 2-4 m high pinnacles in chalk in the Egyptian desert and attributed them to the same solutional processes that produce stone teeth in hard limestones. The Egyptian chalk pinnacles have been modified by sand-blasting and thermal shattering and are larger than those at Nambung, so it is difficult to compare the two areas.

Pinnacles are also reported as *epikarst* features buried beneath phosphate deposits on several oceanic islands (e.g. Jacobson et al., 1997), 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 epikarst features on hard, telogenetic, limestones; they are not the same as the syngenetic pinnacles on the calcarenites at Nambung.

There are analogies with *laterite karsts*. In northern Australia deep weathering profiles and associated ferruginous and siliceous cemented duricrusts show both pinnacles and solution pipes (Grimes and Spate, 2008). These are also "syngenetic" in that they formed at the same time as the weathering profile, and they also appear to have formed by focussed cementation (the pinnacles) and solution (the pipes). A significant number of laterite pinnacles are hollow, which suggests cementation adjacent to a pipe.

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 palaeokarst 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 may be an extreme case in which solution pipes cutting through a cemented band have coalesced to leave residual areas of hard limestone; or they may be the result of focussed cementation by down-flowing saturated vadose water.

Acknowledgements

My colleague, Susan White, has contributed to many discussions on the nature of these and other features of the calcareous dunes. Andy Spate commented on an early draft of this paper. I also thank my wife, Janeen Samuel, for assistance in the field.

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