Syngenetic Karst in Australia: A Review

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INTRODUCTION AND TERMINOLOGY

Syngenetic karst is a term coined by Jennings (1968) for karst features, including caves, that form within a soft, porous, soluble sediment at the same time as it is being cemented into a rock. Speleogenesis and lithogenesis are concurrent. Jennings based his discussion partly on prior observations reported in Bastian (1964) for Western Australia and Hill (1984) for South Australia (Hill's paper was written in 1957, but published posthumously).

Jennings was describing the active karst geomorphology of the Quaternary dune calcarenites of Australia. Concurrent studies by sedimentologists of paleokarst horizons at unconformities in the stratigraphic record used the related concept of **eogenetic diagenesis**: processes that affect a newly-formed carbonate or evaporite sediment when it is exposed to subaerial weathering and meteoric waters (Choquette & Pray, 1970). The resulting eogenetic karst (or "soft-rock karst") is distinguished from telogenetic ("hard-rock") karst that has developed on hard indurated limestones that have been re-exposed after a deep burial stage.

Choquette & Pray (1970) defined three major stages in diagenesis of limestones (Figure 1). **Eogenetic diagenesis** refers to processes affecting recently deposited sediments prior to deep burial . The processes include cementation and solution (with brecciation) by meteoric waters and solution of aragonite or its replacement by calcite. **Mesogenetic diagenesis** starts after the sediment is buried; and for limestones involves further cementation, re crystallisation and pressure solution (eg. styolites). **Telogenetic diagenesis** occurs after uplift and erosion returns the limestone to the surface where meteoric waters can dissolve the (now well-cemented) limestone to form "classic"(hard rock) karst.

Early diagenetic effects can be preserved within later diagenetic textures. These include paleokarst cavities, infills and breccias. Dissolutional porosity generated during the eogenetic stage of paleokarsts can direct water flow and further dissolution during the later mesogenetic and telogenetic stages, and also host ore minerals or hydrocarbons. Large solutional cavities (i.e. caves) can form in all three diagenetic stages, but are most common in the eogenetic and telogenetic stages. Those formed in the mesogenetic burial stage are generated from deep hot waters, or from acidic waters derived from oxidation of hydrogen sulphide or pyrite. Repeated cycles of uplift, exposure and reburial can form multiple ages of telogenetic paleokarst features (eg. Osbourne, 2002).

With reference to karst, the terms "syngenetic" and "eogenetic" overlap but involve different viewpoints. The former is best used for geomorphological studies of modern soft-rock karsts; whereas the latter is best retained for diagenetic studies of paleokarst porosities, where the sequence of dissolution and cementation events is much more complex. Some, but not all, paleokarst is eogenetic (Figure 1): the separation of eogenetic, mesogenetic, and telogenetic features requires a detailed study of cement morphology, mineralogy, chemistry, and related dissolutional and brecciation features; at both the microscopic and macroscopic scale (Moore, 1989,2001). Recently some authors have applied the term "eogenetic karst" to modern syngenetic karst features (eg. Mylroie et al 2001) – I recommend retaining "syngenetic" for that setting.

Soft rock Karst is a more general concept that includes both early and late syngenesis (see below), and also more mature sediments that have not been deeply buried and indurated, but in which the early, weak, cementation is essentially complete. In addition to the dune limestones, examples of soft rock karst include the mid Tertiary marine calcarenites of Australia (Lowry & Jennings, 1974, Gillieson & Spate, 1998, Grimes, 1994, Grimes et al 1999), as well as some of the limestones of the Yucatan (Lesser & Weidie, 1988) and Florida (Miller, 1990). The Cretaceous chalk of Europe is a special case of a moderately consolidated limestone that has both a very fine-grained matrix porosity and well-developed fractures - forming linear caves (Rodet, 1991; Gunn et al 1998).

Quaternary dune calcarenites, or aeolianites, show the best development of syngenetic karst. Examples include those of Australia (eg. Bastian, 1964, 1991, 1996; Hill, 1984; Jennings, 1968, White, 1994, 2000; Grimes & others, 1999, Grimes, 2002), South Africa (Marker, 1995), Bermuda (Mylroie et al 1995) the Caribbean (eg. Mylroie et al 1995, Lundberg & Taggart, 1995), and parts of the Mediterranean (eg. Ginés, 2000). However, other porous calcarenites, such as beach and shallow marine sands, can also develop distinctive syngenetic features; in particular solution pipes, calcreted cap-rocks and extensive collapse modification. Examples include the mid Tertiary Gambier and Nullarbor limestones in Australia cited in the previous paragraph. For less porous facies, such as micritic lagoonal limestones of oceanic islands, cementation is stronger and there is greater joint control so the syngenetic karst is more akin to the classical hard-rock karsts (Mylroie et al 2001, Grimes 2001). Other soluble sediments (gypsum, halite) can also develop syngenetic karst when exposed to subaerial conditions shortly after their deposition (eg. Sando, 1987) but these will not be discussed here.

In the following discussion Australian dune calcarenites in a "Mediterranean" climate are used as an example (Figure 2).

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 (eg. quartz). At the base of the soil precipitation of carbonate forms a cemented and locally brecciated calcrete layer or hard-pan, also known as cap-rock. Below this the downward percolating water becomes focussed to dissolve characteristic vertical "solution pipes, and simultaneously cements the surrounding sand. Early cementation tends to be localized about roots to form distinctive rhizomorphs or rhizocretions. Cementation can progressively occlude the primary inter-granular porosity, but simultaneously, dissolution can generate localized secondary porosity of a moldic, vuggy or cavernous character.

Mixing corrosion occurs where percolation water meets the water table, which is commonly controlled by the level of a nearby swampy plain that also provides acidic water. In coastal areas, water levels fluctuate with changing sea levels and further complexity results from a fresh-water lens floating above sea water which results in two mixing zones, above and below the thin lens (Mylroie & Carew, 2000, Mylroie et al 2001; Figure 3). Solution is strongest at the coast where the lens thins so that firstly the two zones overlap (within the fluctuating zone of the sea level) and secondly the thinning of the lens causes stronger flow rates which also promotes solution. Tidal pumping may also assist. The result is a "flank margin cave" (Mylroie et al 2001) that has an irregular form of interconnected "mixing chambers" (Figure 4). The name refers to the tendency for these caves to cluster at the island margin. Similar clustering can occur along the edge of dune ridges adjacent to swamps that provide aggressive water.

In the early stages of dissolution (**Early Syngenesis**, Figure 5a) the loose sand subsides at once into any incipient cavities, possibly forming soft-sediment deformation structures. Subsidence dolines may form without caves (as described in South Africa by Marker, 1995). An exception is that beneath the cap-rock, which appears to form quite early, some shallow caves may form. Once the bulk of the rock is sufficiently hardened to support a roof (**Late Syngenesis**, Figure 5b), caves can develop. The presence of buried cap-rocks (and associated paleosoils) may also assist in cave development. The uniform matrix porosity, slow moving groundwater, and lack of joint control means that directed linear conduits seldom form. Instead, horizontal cave systems of low, wide, irregular, interconnected chambers and passages (Figure 4) form either in the zone of maximum solution at the water table, or by subsidence of loose material from beneath stable cap-rock layers. Flat cave ceilings are common: either marking the limit of solution at the top of the water table, or where collapse has reached the base of an indurated (cap-rock) zone. Bastian (1999) coined the term "watertable slot" for broad horizontal slots, too thin for humans to enter, that form at the top of the watertable at Yanchep, Western Australia. Where a shallow impermeable basement occurs, as in southwest Western Australia, its topography may concentrate water flow along buried valleys to form linear stream caves (Figure 6). Strong flows, in areas of steep gradients, can also concentrate flow into linear paths and form stream caves, as at Yanchep (Bastian, 1996).

Collapse is ubiquitous in these soft rocks and large collapse domes commonly obscure much of the original solutional caves. Breccia structures are common in paleokarst exposures, and are also sometimes seen in the walls of modern syngenetic caves or in the calcrete cap-rocks.
Sizable syngenetic caves can form in less than 100 thousand years (Mylroie & Carew, 2000).

Surface dissolutional sculpturing is rare, as there is little solid rock for it to act upon. However, some sculpturing can occur on exposed calcrete layers.

Variations on the above-described styles can occur in different climates, hydrological settings and host sediments. For example, calcrete is supposedly best developed in semi-arid climates, whereas dissolution and brecciation are thought to be more abundant in wet climates (Esteban & Klappa, 1983).

SOME FEATURES OF SYNGENETIC KARST

Syngenetic karst has several distinctive features as well as many that are shared with classical (hardrock) karst.

Solution pipes (or, more strictly, dissolution pipes) are distinctive features of syngenetic karst on porous host rocks (Lundberg & Taggart, 1995, Grimes, 2003). They are vertical cylindrical tubes with or without cemented walls, typically 0.3 to 1.0 m in diameter, which can penetrate down from the surface as far as 20 m into the soft limestone. The top is the present surface, or a buried paleosoil. The bottom, where seen, is generally abrupt and hemispherical. The pipes may contain soil and calcified roots (and root growth may have occurred hand-in-hand with dissolution of the pipe). They occur as isolated features, or in clusters with spacings that can be closer than a metre. In the Bahamas they have been referred to as Pit Caves, but that term also includes larger and more complex features (Mylroie & Carew, 2000). The pipes form by focussed vertical vadose flow through the porous sediment. The focussing may be spontaneous and associated with partial cementation of the hard-pan of the soil, or it may be guided by other factors such as concentrated stem flow beneath trees, or along tap roots (Grimes, 2003).

The influence of an impermeable basement: In the southwest of Western Australia, the dune limestone lies on a basement of impermeable gneiss. This has an irregular topography of old valleys and rises which channels the groundwater flow at the base of the limestone - forming linear stream caves (Williamson, 1980). Figure 6 shows an example taken from Williamson & others (1976).

Water from below: At Yanchep, Western Australia, dune limestone overlies a quartz sand aquifer and aggressive water enters from below to dissolve caves at the base of the limestone (Bastian, 1991,1996, 2003). A belt of caves forms along the eastern threshold where the water first rises into the limestone. Bastian used the term "paraphreatic" for this type of cave. The increased transmissivity of the caves captures diffuse flow from the adjoining calcarenite as well as from the quartz sand below and forms local cave streams which follow the base of the limestone. This high conduit transmissivity maintains the water table at the dipping contact.

Dune swales: Where the watertable is at or above the surface in the swales between dune ridges, swamps or lakes will form. The aggressive swamp waters can undercut the edges of the dunes to form small cliffs, and "sharpen up" the topography to form a steep sided, flat floored depression not unlike a polje (eg. at Codrington, Victoria; Berryman & White, 1995). The analogy to a polje is further emphasised in some places, eg. Yanchep, where springs feed into the hollow from the inland side, while the swamp water sinks into ponors on the coastal side of the same depression.

Collapse modifications: The subsidence of partly-consolidated material can form a variety of breccias and sag structures; these can be further cemented as diagenesis continues. Mantling breccias can occur as part of the surface soil. Within the caves breakdown of the soft rock is extensive. In many cases the original solutional cave system at the water table is largely replaced by rubble-filled collapse domes (Figure 7). Where the base of the rubble lies within aggressive groundwater the broken material can be dissolved and removed as it falls so that a large open dome will result. If not removed, the growing rubble pile rises faster than does the roof above and eventually meets it. Collapse will stop at this point but narrow spaces may be left over and around the sides of the domes. These have been called "inclined fissures" in Western Australia (Bastian 1964), and similar narrow collapse domes and fissures have been described in South Australia (Hill, 1984) and elsewhere (eg. Ginés, 2000). Subsidence may reach to the surface to form dolines; a special type referred to as a "banana hole" in the Bahamas results from the collapse of the near surface calcrete band above a shallow cave to form a shallow overhanging doline. In paleokarst exposures these collapse areas appear as both discordant and concordant (intrastratal) breccias. In extreme cases mass subsidence of broad areas can generate a chaotic surface of tumbled blocks and fissures (Bastian, 1995).

Multi-level systems: Fluctuating water tables, possibly controlled by sea level or climatic changes, can result in stacked sets of horizontal cave systems. Rising watertables can flood and partly redissolve speleothems then re-expose them when the watertable drops (examples occur at Codrington, Victoria.

SYNGENETIC KARST IN AUSTRALIA

In Australia, syngenetic karst and softrock karst is restricted to a coastal belt running from Barrow Island down the western coast of Western Australia, and then along the southern coasts of Australia into Bass Strait (Figure 2). There is an isolated occurrence on Lord Howe Island, off the New South Wales coast.

Some of the Western Australian areas will be described in detail by others in this symposium – I will provide only a broad summary here. Starting in the north, the Barrow Island caves are in a marine Tertiary softrock limestone, though a small area of dune limestone is present. Cape Range is also in Tertiary limestone, but south from there we find a long belt of dune limestones that continues all the way to Perth. Within this the most interesting karst areas are probably the Nambung Pinnacles (McNamara, 1995) and the Yanchep area (Bastian, 1996 etc) which has the special hydrological setting mentioned in the main text above. South from Perth there are a few caves and springs on the Swan and other rivers. In the Leeuwin-Naturaliste region a belt of dune limestone up to 6 km wide contains numerous caves (Bastian, 1964, Williamson, 1980, Williamson & Bell, 1980). The caves are best developed in the older dunes and are of three types: linear caves formed by cave streams (eg. Figure 6), the inclined fissure type, which includes other breakdown forms (eg. Figure 7), and the horizontal maze caves of the Augusta area - which are relatively rare in Western Australia. The allogenic streams to the east of the dune barrier have mostly been dammed by the dunes and sink into the limestone to feed the stream caves, however some of the larger streams have managed to keep their channels open and flow through gorges of construction (Jennings, 1968). Some springs are known on the coast, but much of the underground water flow seems to be lost offshore. Water tracing experiments are being done (eg. Eberhard, 2001).

In South Australia the karst of the discontinuous dune limestones of the Eyre Peninsula is not well documented. Kangaroo Island was the base for Hill's (1984) work, which parallelled that of the West Australians. Most of the caves there are large collapse domes, but Hill also documented the influence of allogenic water derived from the swampy flats on the inland side of the dunes. The Gambier Karst Region is best developed in South Australia, but extends eastward into Victoria (Grimes, 1994, Grimes & others, 1999). Here we find both calcareous dune limestone, and the older Tertiary softrock limestone. Caves occur in both types and some caves have their entrances in the dune limestone but their main horizontal development is in the underlying Tertiary limestone. In South Australia the dune limestones form a broad series of discrete ridges separated by extensive swampy plains that extends up to 100 km inland. However, to the east in Victoria the dune ridges become confined to a narrow belt close to the coast with only thin swampy swales between them. In some of the older ridges minor joint control becomes apparent. Many syngenetic caves in the Gambier region are dominated by collapse but where the original solutional parts are preserved the typical form is a horizontal maze. This differs from SW Western Australia where linear stream caves are considered typical and mazes are the exception.

In the Victorian part of the Gambier Karst, Bats Ridge and Codrington are two particularly densely cavernous areas (White, 1995, 2000). Caves also occur in the Tertiary limestones. Some of the islands in Bass Strait have dune limestone, but there are only a few small caves (Kiernan, 1992).

On Lord Howe Island, off the New South Wales coast an isolated area of dune limestone hosts a few small caves (Standard, 1963 and H.Shannon, pers. comm.)

CONCLUSIONS

Syngenetic karst shows a number of distinctive forms as a consequence of its formation from soft sediments that are being consolidated and cemented at the same time as karst cavities are forming within them. These include: solution pipes, shallow cap-rock caves, brecciated zones, irregular horizontal mazes, "flank-margin caves" in coastal situations, caves that are dominated by collapse domes and "inclined fissures" - with little or none of the original solutional passage remaining.

Syngenetic karst is quite different to classical "hard-rock", telogenetic karst. The related term "Eogenetic karst" is best kept for diagenetic studies of paleokarsts. Recently some authors have applied the term "eogenetic karst" to modern syngenetic karst features (eg. Mylroie et al 2001) - I recommend retaining "syngenetic" for that setting.

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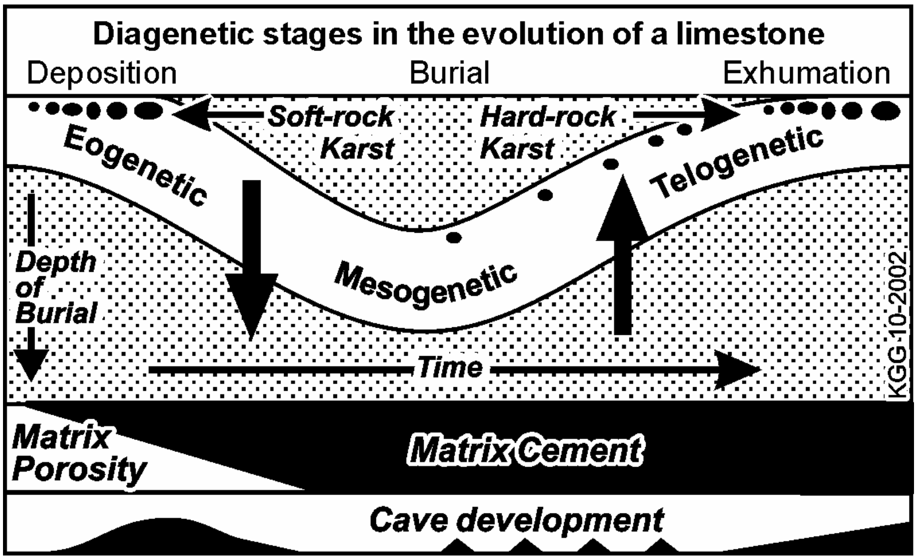

Figure 1 - Diagenetic stages in the evolution of a limestone, and of its karst Black dots indicate possible cave formation

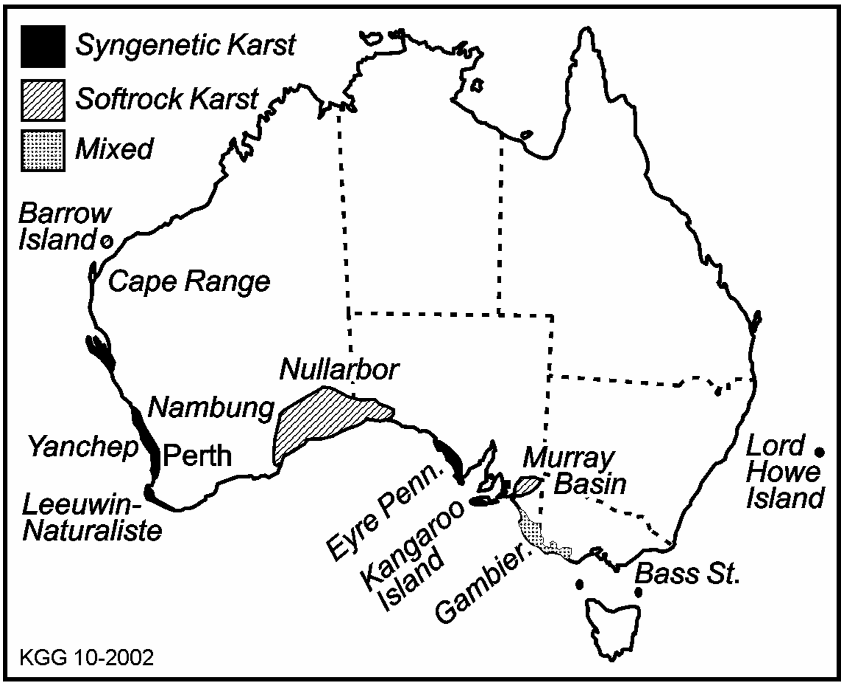

Figure 2 - Areas of Syngenetic and Softrock Karst in Australia

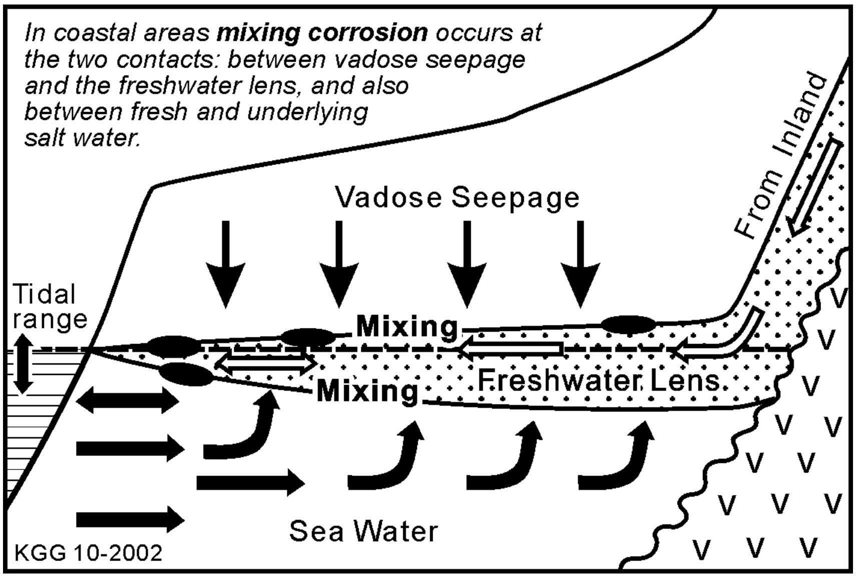

Figure 3 - The coastal freshwater lens, and its mixing zones
Note that the vertical scale is strongly exaggerated in all diagrams of this type.
The lens is thin and the slopes are not as steep as they appear.

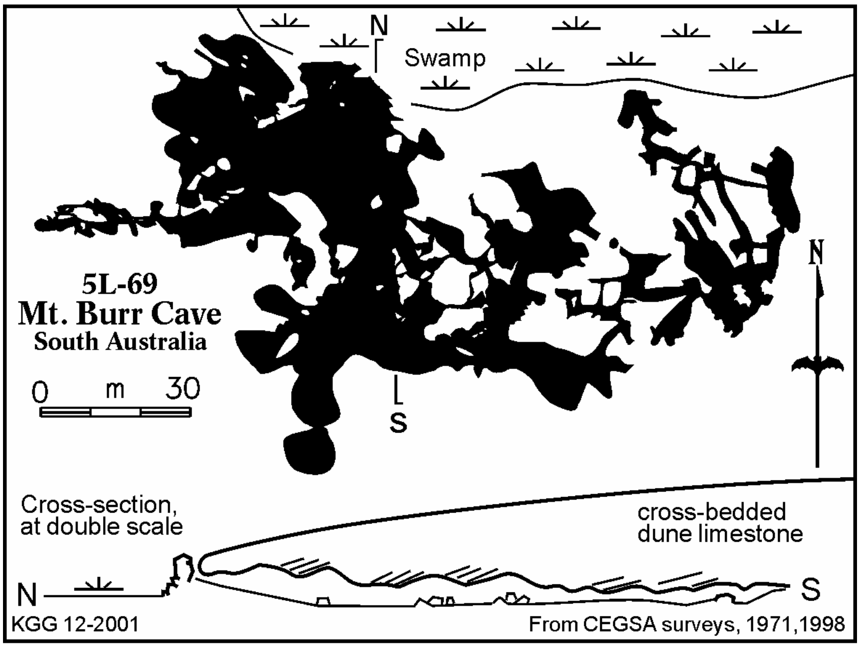

Figure 4 - A typical horizontal syngenetic maze cave in dune limestone adjacent to a swamp

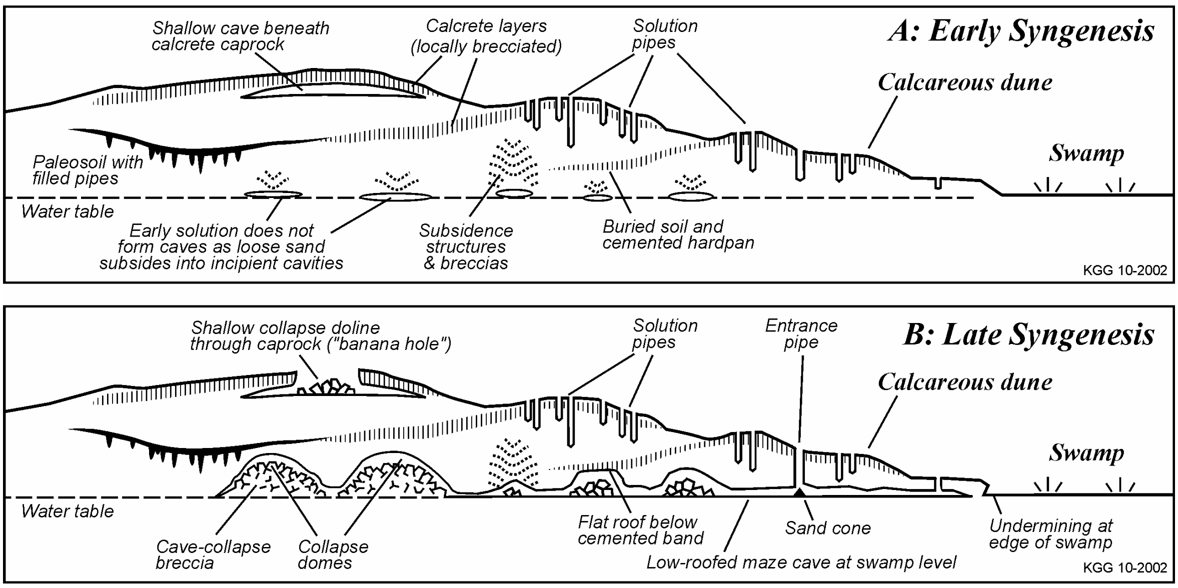

Figure 5 - Features of syngenetic karst developed on a calcareous dunefield adjacent to a swamp

Part A is Early Syngenesis – before the sand is sufficiently cemented to support a cave roof.
Part B is Late Syngenesis – the limestone is now strong enough to support a cave roof.

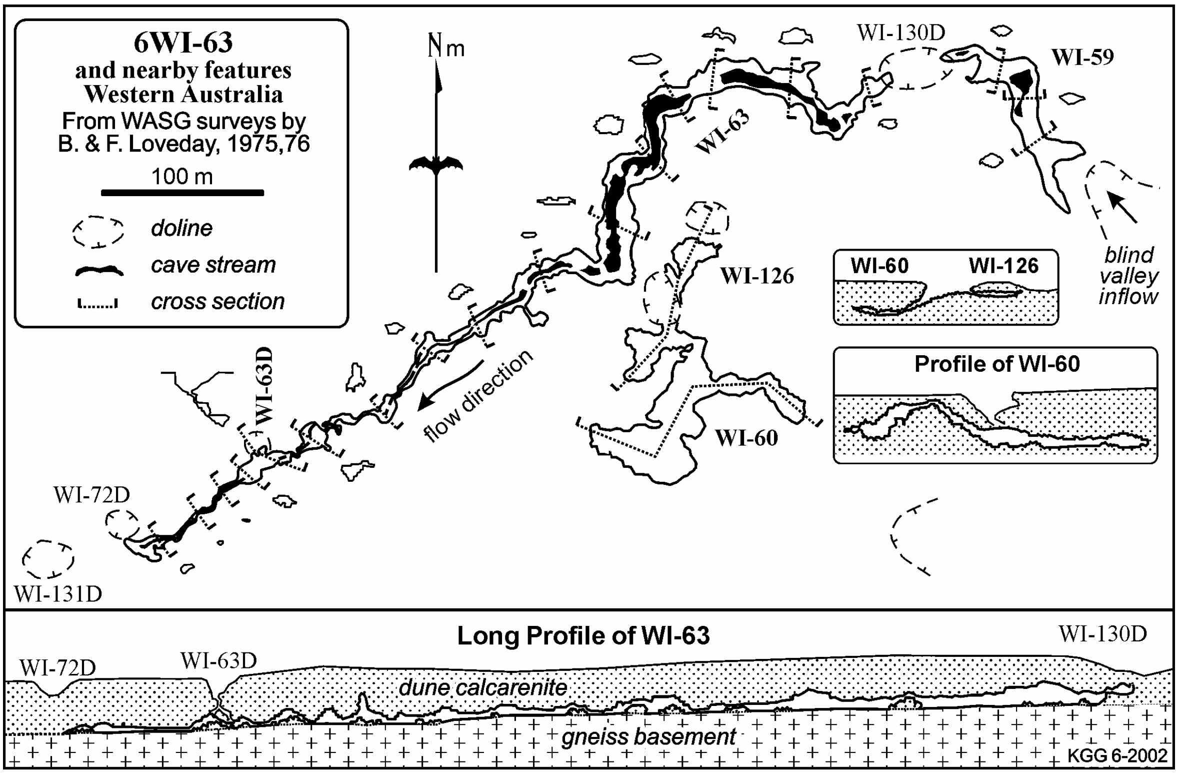

Figure 6 - 6Wi-63 is a linear stream cave that follows the basal contact between the dune limestone and impermeable gneiss

Note the downstream decrease in passage size, away from the source of aggressive water.

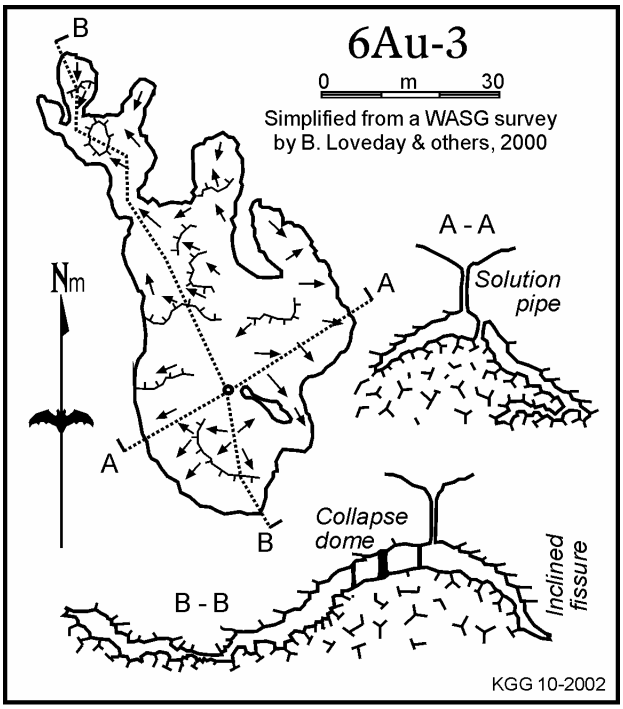

Figure 7 - An example of a small breakdown cave with a collapse dome inclined fissures at the edges, and a solution pipe entrance

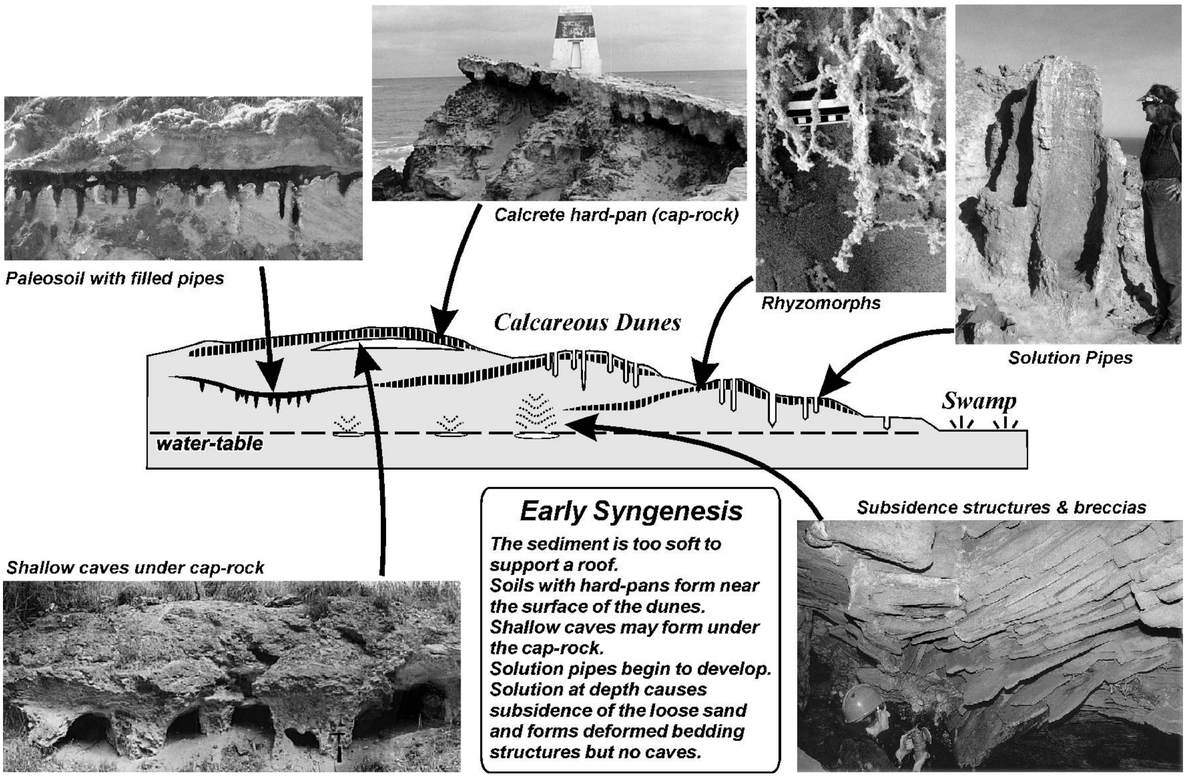

Figure 8 - Early Syngenesis

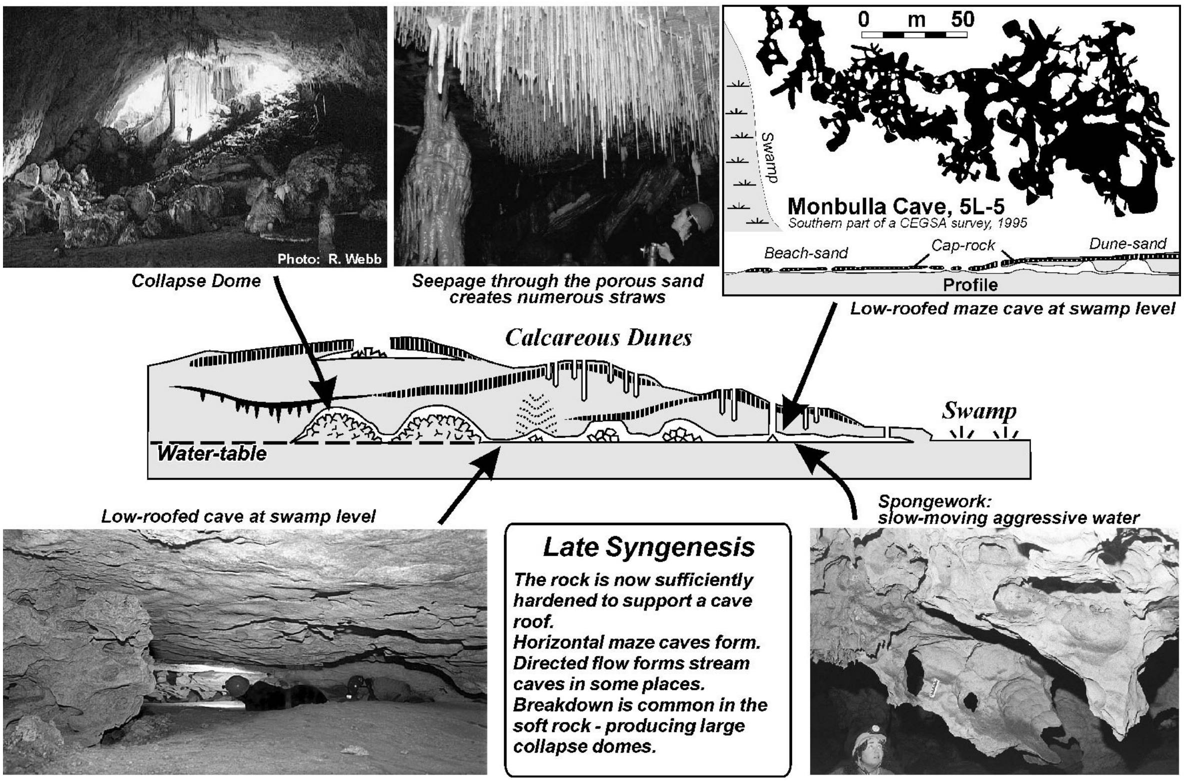

Figure 9 - Late Syngenesis