Speleogenesis in Cenozoic Limestones, Southeastern Australia.

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Abstract:
Southeastern Australia has extensive areas of Cenozoic limestones. These include both Oligo-Miocene marine calcarenites and calcilutites and Pleistocene dune calcarenites. This paper will illustrate the factors involved in speleogenesis in these limestones and outline the relationships between speleogenesis, hydrogeology and lithology in relatively young limestones.

These limestones, whilst more extensive in area than the Palaeozoic impounded karsts of eastern Australia, are less well known especially for cave exploration. However they have both extensive and intensive cave systems including the flooded cenotes of the Mount Gambier area, the large caves of the semi arid Nullarbor Plain and maze-like systems in the Pleistocene dune ridges.

Speleogenesis in these lithologies is an interplay between the groundwater conditions and the lithification and diagenesis of the calcareous sediments. As such sediments are highly variable in their calcareous content, the solution/precipitation balance also varies from site to site. This variability is combined with both high primary porosity and permeability resulting in diverse surface and underground karst features.

The caves are dependent on the ability of the calcarenites to develop sufficient structural strength in the form of an indurated layer. This "caprock" is necessary for the development of many karst forms, especially caves, as it gives the relatively unconsolidated calcarenite structural strength. The caprock develops in both limestone sequences where conditions are favourable but somewhat better in the Pleistocene dunes.

The development of cave systems is also directly related to the groundwater conditions. Evidence of fluctuating groundwater conditions over time can be seen in the caves, especially the drowned cenotes of the Lower Southeast of South Australia. The inter-relationship of groundwater conditions and relatively horizontal lithologies, combined with the development of an indurated layer are the keys to understanding speleogenesis in these limestones.

Introduction:
Karstification is a complex process controlled by the nature of the lithology, tectonic structure and climatic conditions. In particular, lithological variation of porosity, chemical composition and strength can be extremely high. Whereas massive, well jointed and relatively chemically pure limestones are traditionally perceived as having the best karst development, the extensive but relatively poorly consolidated Cainozoic shallow marine carbonates and Pleistocene dunes in southern Australia have developed extensive karst systems and can offer interesting insights into speleogenesis.

Cenozoic Geology of Western Otway Basin:
Although southeastern Australia has a complex Cenozoic geology involving Eocene and Plio-Pleistocene volcanism, deposition of cool water and coastal carbonates characterises a substantial area of coastal and continental shelf areas. The Otway Basin in southwestern Victoria and southeastern South Australia is a typical sedimentary basin and includes Miocene and Oligocene marine limestones and Pleistocene calcareous dune and beach facies. Both these limestones are generally poorly lithified but their responses to karst forming processes, despite some strong similarities are not identical. The limestones vary in texture and lithology, and are not equally soluble. Although the limestones extend northward, progressively thicker non-calcareous sediments and volcanics limit karst potential.

Lithologies:
The Tertiary marine limestones are generally horizontally bedded; well-sorted fine to medium grained bioclastic cool water carbonate sandstones of variable purity and cementation. They were deposited in shallow marine environments during the Oligocene and early Miocene and are extensive across the basin. More than one geological formation is calcareous (KENLEY, 1971) but the limestones that extend to the north and east show very little karst development. The limestone is a relatively soft and poorly cemented rock that develops localised thin case hardening and limited calcrete capping. It is locally well jointed with generally northwest joint trends in the western part of the basin and a northeastern trend in the east. The sequences of Tertiary limestones show variable purity; predominantly calcite with a variable presence of aragonite, and have intermittent beds of more siliceous material. The Tertiary limestones are similar to those

of the Nullarbor, but although there are some similarities of cave styles there are none of the huge passage systems that occur there (GRIMES & WHITE,1996).

Overlying the Tertiary limestone in many areas of the Otway Basin are Pleistocene aeolian calcarenite (aeolianite) stranded dune ridges and beach facies. These Pleistocene deposits are well sorted fine to medium grained bioclastic carbonate sands of variable purity showing crossbedding, variable cementation, strong laminations and a well developed kankar or caprock. Dating of a sequence of dunes overlying some of the coastal area, by thermoluminescence techniques, indicates they were deposited and stranded over the past 800 thousand years (HUNTLEY et al., 1993). Particular dunes at Codrington and Bats Ridge, which have a high degree of karstification, have been dated at 238 $\pm$ 45 ka to 244 $\pm$ 74 ka, and 295$\pm$ 35 ka respectively (WHITE, 2000b).

The Cenozoic limestones of the Otway Basin show some similarities in their variable cementation, variable purity of calcium carbonate and poor consolidation, but also show strong differences in their bedding, jointing and ability to develop a strong caprock or kankar. The passage orientation of the karst features in the two types of limestone is distinctive. Cave passages in the dune limestones show a spread of passage directions whereas cave passages in the Tertiary limestones are more obviously directional; commonly either NE-SW or NW-SE reflecting the jointing patterns of the limestones. It is differences such as these, which are important in the differential development of the karst.

Speleogenesis in Oligo-Miocene Limestones:

The Otway Basin can be divided into two quite distinct karst provinces: the southeastern South Australian and the western Victorian provinces. The more westerly extends further east than described by MARKER(1975). The boundary zone of the two provinces is the narrow tectonically active zone associated with the Portland area. Significant differences in the karst occur between the two provinces.

Karst in the Tertiary limestones is characterised by single linear joint controlled systems showing extensive horizontal development and collapse features. The karst development is directly related to lithological variation, especially between the eastern and western sections of the basin. In the east, the Tertiary (Port Campbell) Limestone is extensive in but is of variable carbonate purity and has only limited cave development despite the extensive area of carbonates. Spectacular limestone rock stacks are found along the coast. These rockstacks show prominent basal notches and are up to 50m high.

More extensive karst occurs in the Naracoorte and Glenelg River areas. Important Pleistocene vertebrate deposits occur in a number of caves eg. Victoria Fossil Cave (Naracoorte), McEachern Cave (Glenelg River). Many caves show impressive sand cones. Phreatic preparation can be seen in the walls and roof pendants are a feature of some caves, but the easily eroded nature of the soft limestone precludes many of these being preserved.

Major cavern development in thought to have occurred in the very late Pliocene and early Pleistocene. (MORIARTY et al 1998, MORIARTY et al 2000). Speleothem dating and environmental reconstructions show cyclical alternation of "Wet Phases" and more arid phases over the past 500ka (AYLIFFE et al., 1998; MORIARTY et al., 2000). The dates indicate that the major caverns were formed over 500ka ago, probably during the period of high water tables in the Pliocene (MORIARTY et al., 1998). It is clear that <u>major</u> solutional development in caves in the Naracoorte area ceased prior to 500,000 years ago. and the caves have since undergone modification by collapse, minor solutional activity and filling with both clastic and chemical sediments. The initial conduit development is in a direction oblique to the dune direction and away from the present direction of the sea and further development as the result of beam failure in the relatively "weak" Miocene limestone roofs resulted in collapse especially where passages intersected. Evidence of the solutional origin of the passages is present on the walls but only limited areas of the roof due to the large amount of collapse. Solutional cave development has possibly been reactivated during wetter periods over the past 500ka is most probably minor and has mainly been in the removal of the collapse material, but is difficult to document

Cenotes, drowned collapsed dolines, are a common feature of the Mt Gambier part of the basin where water tables are relatively high.

Speleogenesis in Pleistocene Dune Calcarenites:

Karst in the Pleistocene limestones is characterised by shallow sinuous systems with multiple entrances, low flat, wide chambers and horizontal development, solution pipes and roof avens and extensive cap rock (kankar) development. The dune landscape has characteristic interdune lakes & swamps that have increased the aggressivity of the surface and ground waters.

Although there are a number of dune areas where karst development has occurred, two particular sites (Codrington and Bats Ridge) show the karst development in these dunes very clearly. Codrington is an area of cave development in a mid Pleistocene dune ridge predominantly composed of calcareous sand. The characteristic karst features are found in this dune which is considerably lower in altitude than the more seaward two dunes, indicating some landscape lowering.

(BERRYMAN & WHITE, 1995). Karst features also occur in more complex mid Pleistocene dune sequence at Bats Ridge. This ridge, about 100 m above present sea level, has a general alignment north east/south west, with low spurs on the northern side. There are peat swamps in the swales on both northern and southern sides of the dune, some of which hold water in wet seasons (WHITE, 1994).

The characteristic landforms associated with these Pleistocene calcarenite strandline ridges are the result of karst processes of solution and collapse. The caves are shallow with horizontal development and have formed under a hardened cap rock (kankar layer) in the calcarenite dune. This formed as the result of solution and redeposition of calcium carbonate, under sub-aerial conditions. The cementation is primarily as meniscus cement that confirms that diagenesis has occurred under sub-aerial conditions. The position of the caves within the dune can reflect a previous higher water table. These near coastal dune systems show karst development that is contemporaneous with lithification (syngenetic karst). (WHITE, 2000a).

There is very limited calcite speleothem development; often expressed as moon milk or calcite straws in both the limestone types.

Hydrogeology:

Groundwater is essential for the development of karst features. The development of karst features in landscapes dominated by high primary porosity and minimal, if any, secondary porosity associated with joints, differs significantly from that in karst landforms where secondary porosity development occurs. This is largely due to the relationship between groundwater movement in these zones. In addition, coastal karst groundwater systems are often influenced by the boundary between seawater and freshwater and this junction as well may contribute to the development of karst.

Very little work has been conducted on the groundwater systems of the Otway Basin in relation to the development of karst in the region. Examination of existing groundwater bore records indicated that despite the existence of a large number of bores, most of these are for stock and domestic purposes and little groundwater monitoring has occurred. Nevertheless, assumptions about groundwater flow processes can be made drawing on theory of flow systems (FREEZE & CHERRY, 1979). A significant component of future studies could be to examine whether these flow processes do indeed exist. It can generally be assumed that groundwater flow is towards the coast, based on the relatively uniform lithology towards the coast and assumptions about flow between land and water bodies.

The Tertiary Limestone forms a major aquifer in the region and the Gambier Limestone has been referred to as one of the best aquifer systems in Australia (STADTER, 1999). In the western area of the basin there is a well-developed water table sloping gently towards the coast. with two zones of steeper gradients, along the line of the Kanawinka Escarpment and to the north of Mount Gambier. MARKER (1975) reported a correlation between high cave densities and zones of steep gradients and with areas of greater than normal depth to the water table. Certainly there is ample evidence of karstification at times of different water tables than the present, as many of the cenotes of the Mount Gambier area have submerged speleothems and mudcracks and stomatolites are found up to 2m above present water levels. (GRIMES & WHITE, 1996).

Although more than one aquifer system has been shown to occur within the Oligo-Miocene limestones, examination of the bore logs suggests that where the aeolian calcarenites overly Tertiary limestone, generally only one aquifer system occurs within the calcarenites. In spite of this, while the general flow direction is towards the coast, minor variations occur as a result of localised flow within the dune systems, similar to localised flow systems which have been shown to exist within glacial till on the Great Plains of northern USA. The similarities are important, suggesting that localised flow processes may only occur seasonally and may sometimes override a general coast flow of groundwater.

Collection of groundwater levels in February 1994, indicates a close relationship between the watertable level and cave floor levels, and suggests that the watertable effected an important control over cave development (BERRYMAN, & WHITE, 1995). However, it must be noted that any correlation of present cave levels with present watertable levels must be considered in the light of recent anthropogenic changes to the water table. In this instance, although there are not data to support it, development of drains within the swales between the dunes, in many of the areas over many years, has resulted in a lowering of the watertable, in the vicinity of the drains, if not overall.

Nevertheless, there is sufficient observational evidence to suggest that groundwater levels do contribute to the development of karst in the region. In order to link this to landform development it is perhaps more important to consider the role of groundwater in relation to sea level and changing sea levels. The karstification in these dunes can be correlated with the overall high water tables that in turn relate to higher sea levels. Dune formation in particular, relates to higher than present sea levels and the fluctuating sea levels of the Pleistocene had corresponding higher ground water tables.

Conclusion:

Karstification in lithologies that have not been traditionally regarded as having high potential for caves can bring insight into the interplay of factors controlling speleogenesis. The variation in host lithology, hydrogeology and an ability to develop a structurally competent roof must be taken into account in the context of the time available for solution and speleogenesis.

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