Flank margin caves on a passive continental margin: Naracoorte and other southern Australian examples.

Sue White[1,2]

[1]Environmental Geoscience Latrobe University Bundoora Victoria Australia
[2]Victorian Speleological Association Inc

Abstract

Flank margin caves (FMC) have been described specifically from the Bahamas and the islands of the north Pacific such as the Marianas. In the former case the relationship of the freshwater lens and the caves is clearly related to the fluctuations of sea level over the past ~20,000 years on a relatively tectonically stable basement. In the Marianas the relative sea level has dropped and there are a series of caves now well above the active cave forming level. FMC are typically described from relatively young, highly porous and permeable limestones, usually aeolianites.

Australia has a significant amount of aeolianites and other highly porous and permeable marine calcarenites. There is a lot of evidence that caves have formed in previous coastal locations in such host rocks. However the passive passive continental margin tectonic conditions of southern Australia are significantly different from either the Bahamas or the islands of the north Pacific.

This paper will discuss the speleogenesis and characteristics of caves forming in this context. The areas discussed will include the Nullarbor, Naracoorte, Glenelg River and Rottnest Island.

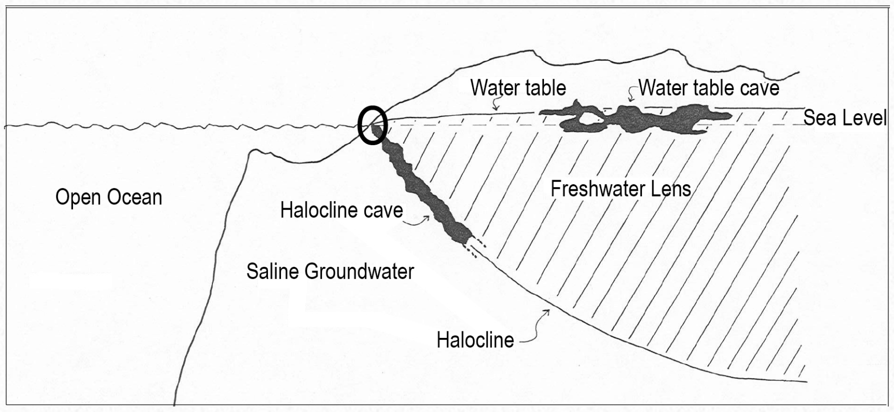

FIGURE 1. *Superposition of the vadose/phreatic and fresh/marine mixing zones at the lens margin means cave development is favored at the lens margin, under the flank of the land; hence the name "Flank Margin Cave". (After Mylroie and Carew)*

The Characteristics of Flank Margin Caves

Flank Margin Caves form along the margins of the freshwater lenses just beneath the flanks of the enclosing land mass (Mylroie and Carew 1995, Mylroie *et al.* 2004) (Figure 1). This is where aggressive solution occurs as the result of mixing corrosion (Bogli 1980) and either the saline halocline or the meteoric water/water table. They have predominantly been described in island environments, partly because island fresh water lenses are more intensively studied that the equivalent on continental margins. The cave development is primarily related to the geometry of the freshwater lens.

These caves have a distinctive passage shape and configuration due to their development as isolated entrance-less chambers (or groups of chambers) often described as "beads on a string" (Mylroie *et al.* 2001). These chambers are breached as surface erosion occurs. The complex cave perimeters show dissolutional wall morphologies such as bell holes and very large scallops. As the chambers were sealed and with ~100% humidity, dense crystalline calcite spelothems are common. Solution has cut across carbonate facies disregarding differences in porosity and grain size and primary structures such as bedding planes.

Southern Australian coastal karst

Across southern Australia highly porous and permeable carbonates occur in a coastal setting. These carbonates are either Oligocene to Pliocene cool water marine limestones or Pleistocene aeolian calcarenites derived from them (Figure 2).

The tectonic setting is a passive continental margin, which has been developing since the Late Mesozoic when the break up of the Gondwanan super continent occurred. The active spreading centre, the Southeast Indian Ridge, separates the Antarctic Plate from the Australian Plate and is some 2500 - 3000 km to the south. The structure of southern Australian continent is largely inherited from the pre-existing Cretaceous extensional faulting.

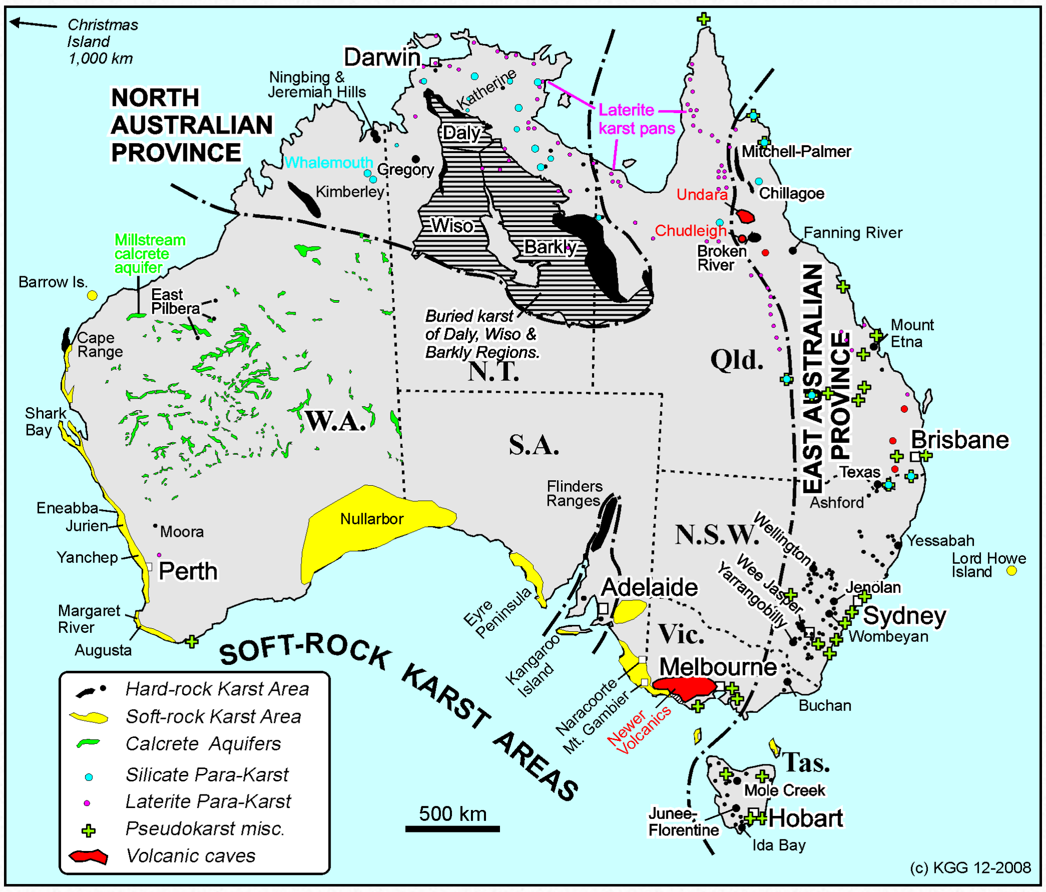

FIGURE 2. *Australian Karst areas (after K.G. Grimes). Soft Rock karst areas are the Cainozoic marine cool water carbonates and the aeolianite strand line dunes.*

(Dickinson *et al* 2002, Dickinson *et al* 2001, Paine *et al* 2004). During the Pleistocene, as the sea regressed, bioclastic carbonate beach, barrier and sub-parallel calcareous and karstic dune complexes (Bridgewater Formation eolianites) were deposited over extensive areas of the western Otway Basin in a high-energy coastal environment with barrier dunes and associated lagoons (Figure 3). Dune building occurred from at least 1.3 Ma through to present times, and continues today on the coast where suitable conditions of sediment supply are available. The gradual uplift of the coastal plain (~0.07 mm/year) west and south of the Kanawinka Fault resulted in a well dated, punctuated, time-transgressive aeolianite sequence associated with sea-level high stands spanning most of the Pleistocene (Belperio *et al* 1995). Uplift is a factor in the preservation of these dunes and their karst.

The Australian continent is generally considered a 'stable' intra-plate region despite having high levels of seismicity (Blewett *et al* 2012). Its passive margin, where the transition from oceanic to continental crust occurs, exists along the south coast. However the plate is moving generally northwards at a rate of ~7cm pa; the fastest moving plate on Earth.

Australia also has significant neotectonic activity especially across the southern coastal area. There are kink folds in ~125 ka old cemented aeolianite at Cape Liptrap (Sandiford, 2003). The Eucla Basin has been tilted, expressed as a west-side up, east-side down tilting of ~100–200 m during the Neogene; a broader north-down southwest-up dynamic topographic tilting of the Australian continent associated with relatively fast (6–7 cm/yr) northward plate motion since fast spreading commenced in the Southern Ocean at ~43 Ma (Hou *et al* 2008). Similarly there is significant uplift across southeast Australia where a significant Late Miocene uplift caused a regional angular unconformity, at around the Miocene-Pliocene boundary onshore (Dickinson *et al* 2002, Dickinson *et al* 2001). This event occurred across and coincided with a change in the dynamics of the Australian plate to the current compressional regime. A second, but less significant, uplift occurred in the Late Pliocene to Early Pleistocene

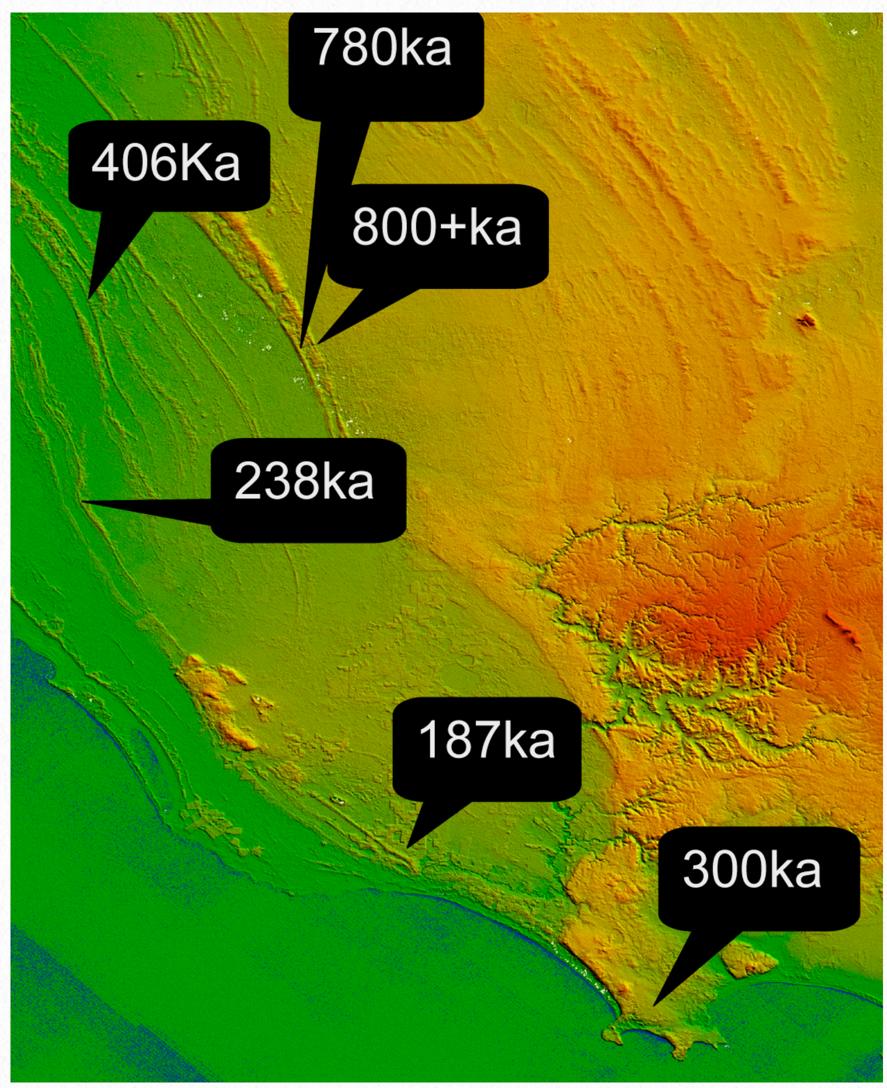

FIGURE 3. *Dated dunes. Dunes dates do not include confidence levels. Dates are thermoluminencense dates from a number of published sources (Belperio, 1995 & White, 2000)*

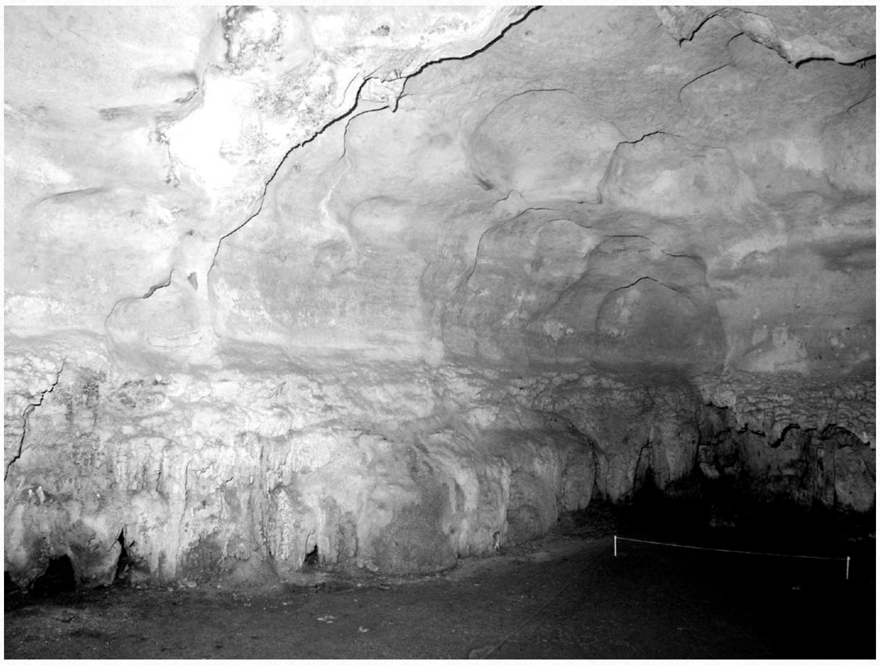

FIGURE 4. *Large scallops (S) on the wall of Wet Cave, Naracoorte. These are high up on the walls and are not obscured by collapse. Some are over a metre in length indicating very slow, almost stagnant water.*

Charactersitics of the karst

Distinctive characteristics of the karst on calcareous dunes include a range of features that are distinctively associated with Flank Margin Caves. These include shallow caprock caves, irregular horizontal mazes, caves that are either dominated by collapse domes or "inclined fissures", with little or none of the original solutional passage remaining. Many of these features are also found in the caves in the poorly consolidated marine cool water carbonates, although these have a stronger linear orientation in the larger caves. The caves in both lithologies have been modified by extensive collapse, solution pipes, bell hole development and speleothem deposition, especially moonmilk, can be extensive.

Wall morphologies indicate phreatic dissolution without turbulent (conduit) flow as is typical for FMC conditions. Four main solutional features found are horizontal grooves (notches), speleogens, spongework and large non-directional scallops (Figure 4). In addition, ceilings with avens and bell holes are found in many caves.

Bell holes or ceiling pockets are cylindrical cavities with vertical long axes, varying between 0.3 to 1 m in diameter and 0.5 to 1.0 m deep, tapering upwards and are present in the ceilings of many caves. These have not been extensively reported in the literature in temperate climates but are common in the poorly consolidated limestones in southern Australia indicating that they are not necessarily restricted to tropical and sub-

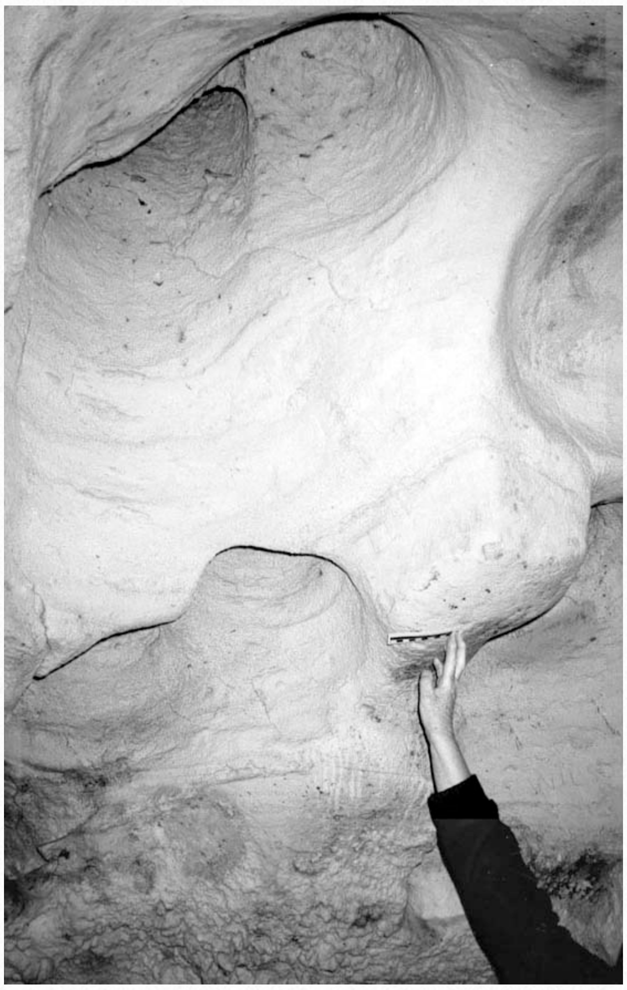

FIGURE 5. *Bell holes and speleogens Wet Cave (U10) Naracoorte Photo N. White*

tropical climates. The most spectacular are in the roof of Wet Cave (U 10), where over 50 densely spaced, narrow vertical cones of up to I m depth and 0.5 to 0.8m diameter are found (Figure 5). As a feature of ceilings rather than walls, and not associated with jointing in the cave ceilings, bell holes show that these large chambers were primarily formed by solution, and these chambers generally lack collapse debris.

Speleogenesis

Karst phreatic caves formed in coastal environments on an upwarping continental margin, where specific localised conditions created enhanced solutional conditions over relatively short time periods. Subsequent modification of the karst was controlled by the combination of continuing neotectonic uplift combined with falling sea levels throughout the rest of the Pleistocene. The position of the dated dunes in the western Otway Basin e.g. Naracoorte, mean that we have a well documented sequence of host rocks over the past ~1M years.

When deposition of the East Naracoorte Range occurred in the Early Pleistocene, the coastline lay approximately along the Kanawinka Fault, about 70m above present sea level (Figure 6). Thus cave development was probably influenced by

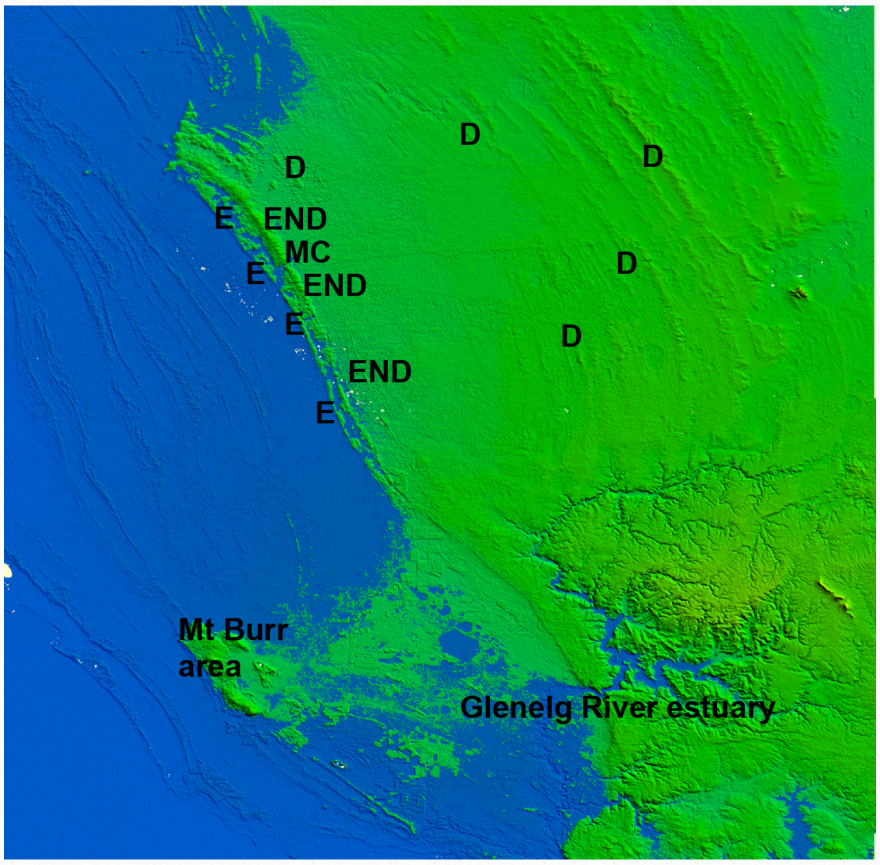

FIGURE 6. *Relative Sealevel at 70 higher ASL than present showing the coastal and estuarine conditions of the Naracoorte area.*
E = estuarine areas,
D = Dunes (mostly older than the East Naracoorte Dune),
MC = Mosquito Creek,
END = East Naracoorte Dune.

the halocline mixing zone at the base of the fresh water lens, enhancing aggressiveness. The groundwater mixing zone geometry is controlled by sea level and the water table in high permeability limestones such as the Miocene cool water Gambier Limestone. Additionally the watertable would have been generally very flat at Naracoorte. The caves show many characteristic features of FMC. The main area of cave development lay probably between 400 m to 500 m inland from the high water mark when sea level was at 70 m above present conditions. If the water table were between 1 and 2 m above sea level in this area (assuming a similar very low gradient of 1:250 to that inland from the present coastline), the fresh/seawater zone would have been at least 40 m below sealevel. This appears to be below the depth at which most caves at Naracoorte have developed (~61 m ASL and 25 to 30 m below present surface). However, if the area was an estuarine or back swamp environment similar to the present coastal areas, e.g. Glenelg River estuary, the water table would have been lower, e.g. at 0.75 m above sea level or less. The halocline would then be at ~30 m depth and halocline enhanced formation is possible.

Similar development and features can be seen on the Nullarbor (Burnett *et al* in review), and on both Rottnest and Kangaroo islands (Mylroie and Mylroie 2009). However in all cases the length of time of the landscape development means that significant landscape lowering has occurred and the caves may now be closer to the present land surface than when they formed.

In the case of Kangaroo Island, Mylroie and Mylroie (2009) have argued for the presence of FMC but have over emphasised the role of the Pleistocene eustatic sea level fluctuations and under estimated the role of neotectonics which has overprinted the global sea level fluctuations on the southern Australian continental margin.

Conclusions

Limestone dissolution is enhanced at the vadose/phreatic and fresh-water/saltwater interfaces due to mixing effects and oxidation of organic matter at these density interfaces. The position of the fresh-water lens has fluctuated through a vertical range of over 100 m, due to Quaternary glacio-eustasy, but local tectonics can overprint glacio-eustatic events, adding to the complexity of the record. The karst is eogenetic, having been formed in eogenetic rocks, which are rocks that never underwent burial beyond the range of meteoric diagenesis.

The karst landscape development on the Cenozoic cool water marine limestones and eolianites along the southern Australian margin are related to the coastal conditions when the main karstification has occurred. This much more extensive than previously thought and helps explain the complex speleogenesis. The uplift of the land coupled with the fluctuating Pleistocene sea levels has resulted in a much more complex scenario than previously thought and explains the relatively sparse karst areas interspersed with very intense karstification.

Acknowledgements

Thanks to John Webb and Nicholas White for their assistance.

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