Geomorphology of the South-East Karst Province of South Australia.

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SUMMARY

The South-East Karst Province of South Australia is an extensive area of low relief with dolines, cenotes, uvalas and a variety of cave types developed partly in the soft, porous, flat-lying Tertiary (Miocene) Gambier Limestone, and partly as syngenetic karst in the overlying calcarenite dunes of the Pleistocene Bridgewater Formation. Shallow swampy dolines and subjacent and covered karst depressions occur in superficial Quaternary sediments.

Systematic variations within the province reflect differences in the parent rock types, the extent and nature of the cover and most importantly the hydrology - in particular the depth to the water table and its gradient.

INTRODUCTION

The South-East Karst Province of South Australia (Figure 1) includes the official ASF Lower and Upper South-east cave regions of South Australia (5L & 5U series cave numbers). It also extends a short distance into Victoria (ASF Area codes 3G, 3CR, 3DD, 3KB, 3BR & 3P). The bulk of the caves and karst features are limited to the area south from Naracoorte and east of Millicent.

There have been few comprehensive karst studies of the area - most notable is the regional study by Marker (1975) along with the early summary in Sexton (1965), and the later honours thesis study of the Lower South-east by Lewis (1984). Thurgate (1986, 1992) described some selected caves & cenotes in the Lower South-East. Peter Horne has privately published several reports on studies of caves and cenotes by the cave diving groups (eg. Horne 1988a,b). Geological and geomorphological studies of relevance to the karst include those of Cook & others (1977), Schwebel (1983), Sprigg (1952), Twidale & others (1983) and Wopfner & Douglas (1971). Wells & Pledge (1983) review the fossil deposits of the caves. The hydrology of the region is discussed by Holmes & Waterhouse (1983), and Waterhouse (1977).

The present study is being done by ACKMA for the South Australian National Parks & Wildlife Service and involves an inventory of karst features on Crown land in the south-east of the state. This paper is an abbreviated preliminary version of the geomorphological part of the report that will be presented to the SA NPWS.

GEOLOGY OF THE PROVINCE

The South-East Karst Province lies on the Gambier Embayment in the north-western part of the Cretaceous to Tertiary Otway Basin (Wopfner & Douglas, 1971). The karst is developed on the Tertiary marine Gambier Limestone, on the younger Pleistocene calcareous dune limestones (Bridgewater Formation) and also on calcareous marine and coastal plain sediments of the inter-dune flats

(Figure 1). Its development is locally influenced by the thin younger sediments that partly cover the limestones. The topography is mostly low and flat, with local relief provided by the dune ridges, the volcanic hills and the gorge of the Glenelg River in the extreme south-east.

The *Gambier Limestone* was deposited in a shallow sea that flooded the region in the Oligocene and early Miocene. It is mainly composed of soft, massive to well bedded (sub-horizontal), bryozoan limestones (Waterhouse, 1977; Wopfner & Douglas, 1971). The unit varies in thickness from 300 m at the coast to less than 100 m at Naracoorte, but is reduced to nothing in a few areas near Dismal Swamp where it has been uplifted and eroded above the Tarpeena-Dartmoor Upwarp (Figure 3). The limestone is poorly consolidated in the subsurface but develops case hardening and calcrete cappings on exposure. It is locally well jointed with a dominant north-west trend. The influence of both the jointing and the bedding are exhibited in the cave passage forms.

The *Bridgewater Formation* is a series of calcareous sand ridges that represent the coastal dunes of old shorelines that developed during an overall regression of the sea during the Quaternary (Schwebel, 1983). They form linear north-west trending ranges that rise up to 30 m above the adjoining plains. However there are higher piles of dune sands in the Mount Burr area where dunes have climbed up the sides of older volcanos, and to the south-east of Mount Gambier where several dune ridges have coalesced. Within the study area the innermost, and oldest, ridge is the East Naracoorte Range, where the dunes have piled up on a pre-existing coastal scarp (The Kanawinka Scarp) cut into the Gambier Limestone (Figure 1). This has been dated at about 700 000 years old, and the ridges, and associated karst features, become progressively younger towards the modern coast (Cook & others, 1977; Idnurm & Cook, 1980).

These ridges are now partly consolidated calcarenites and contain syngenetic karst features in which caves and solution pipes developed as the sands were being cemented into a limestone (Jennings, 1968). Subjacent karst occurs where the Bridgewater Formation overlies the Gambier Limestone and there are a number of caves that have their entrances in Bridgewater Formation but their main underground extent in Gambier Limestone. The Bridgewater Formation has well developed dune forset bedding in places, and shallow angle medium to thin bedding elsewhere. It shows only minor jointing.

Between the lines of dune ridges there are extensive swampy plains. These are old coastal flats and comprise estuarine to lacustrine marls and clays up to 13 m thick. Some shelly beds occur near the present coast. In the Bool Region the inter-dune flats have been covered in places by thin Pleistocene and Holocene alluvial deposits and aeolian sand sheets of several ages.

Quaternary volcanics in the area are the western end of the Newer Volcanics of Victoria (Sheard, 1983). The main area of volcanics is centred on Mount Burr and ranges from about 2 million years to 20 000 years old. The isolated volcanos at Mount Gambier and Mount Schank are younger (4 000 to 9 000 years old).

HYDROLOGY

Natural surface drainage is absent over much of the province. Exceptions are in the far south-east where the Glenelg River, a major stream rising outside the province, has cut a gorge through the limestones; and in the north where

several creeks in the Naracoorte area have maintained their surface flow across the Naracoorte Plateau.

The Gambier Limestone forms the main aquifer in the area. This has been referred to as one of the best aquifers in Australia. The porous nature of the Gambier Limestone means that much of the groundwater flow is via the primary porosity rather than in channels or fractures, and there is a well defined watertable. The gradient on the water table shows two steep zones and one major divide within an overall slope towards the coast (Figure 2). The groundwater divide in the Dismal Swamp area is caused by thin and relatively less permeable aquifers in that area. The water from further north is diverted further to the west.

Much of the groundwater from the Mount Gambier area is discharged in major springs in the Piccaninnie Ponds and Eight Mile Creek areas on the southern coast, and to lesser springs in the Kongorong area. Clisby (1972) reports a total flow of 5.2 cumecs (5200 l/s) from the coastal springs south of Mount Gambier. Marker (1975) shows a line of springs in the Millicent area, but the resurgence points further west are not well documented.

Marker (1975) considered that the nature of the groundwater regime is the most important control on the character and extent of karst development in the province. She correlated areas of strong cave development with firstly the areas where the watertable was at greater than normal depth, and secondly with areas having steep water table gradients. The areas of deep watertables would have enhanced vertical infiltration and therefore surface percolation which would promote solution. These areas are the Naracoorte Plateau and the Gambier Region both of which have high densities of caves. The steep gradient zones would indicate rapid water flow through the rock which will enhance the solutional enlargement of cavities. In contrast the areas of low and reversed gradients will have relatively sluggish flows and solution will be less effective. The northern steep gradient zone corresponds to the line of the Kanawinka Fault and the edge of the Naracoorte Plateau. This is also a zone of major cave development (Figure 2). The southern steep gradient zone passes north-west through Mount Gambier and is partly the result of the steep rise in the base of the Gambier Limestone which thins over this area (Figure 3) and partly due to permeability changes within it (Waterhouse, 1977; Holmes & Waterhouse, 1983). This zone also has a significant concentration of caves (Figure 2).

During glacial periods the lowering of sea levels would have caused the coast to retreat across the continental shelf. This would have caused a significant drop in the groundwater levels in the Coastal and Schank Regions - as shown by submerged speleothems in some caves (Figure 3). The reduced water table and extension of the steep gradient zone in the northern Schank Region during glacial periods may have been responsible for the concentration of cenotes and underlying large cavities in that area (Lewis, 1984). Reduced sea levels would have had less effect in the Gambier Region and the regions further inland where the distance from the coast would have reduced the sea level effect. In the Gambier Region the local geology, in particular the high levels of the inpermiable bed at the base of the Gambier Limestone, would have been the main factor that determined the glacial water levels (Figure 3).

CLIMATE

The climate of the region is a Mediterranean one (**Csb** in the Koppen system) with wet winters and cool dry summers. The annual rainfall decreases from 800 mm in the south to 550 mm in the Naracoorte area (Penney, 1983). Mean annual temperatures range from 14.4°C at Naracoorte to 13.2°C at Mount Gambier.

During the Quaternary the present conditions would have alternated with colder, drier and windier climates during the peaks of the glacial stages (Colhoun, 1991). Much of the area would have been flooded by the sea during the interglacial periods of the early Quaternary.

KARST LANDFORMS

Karst landforms comprise the caves, and a suite of surface features that have resulted directly or indirectly from solution of the limestones. Marker (1975) recognised seven regions within the South-East Karst Province. I have adopted most of her subdivisions, but with some changes (Figure 1).

Syngenetic karst

Syngenetic karst (Jennings, 1968) is an important feature of the province. In the calcareous dunes of the Bridgewater Formation some karst features have developed at the same time as the sand was being consolidated into a calcarenite. The main characteristics of syngenetic karst are the development of a calcreted caprock, of vertical solution pipes, and of low, wide, horizontal cave systems at the level of the adjoining swampy plains. The poorly consolidated nature of the rock means that collapse plays a very important role from an early stage. Solutional, subsidence and collapse dolines can occur on the surface, but the former two can be difficult to distinguish from primary dune hollows.

Typical syngenetic **cave** forms are shallow horizontal systems developed beneath the caprock. They have multiple entrances (often via solution pipes or the collapse of the surface crust) and an irregular outline of chambers, pillars and short connecting passages, generally with a roof height less than one metre throughout. Horizontal systems also occur at the levels of the adjoining swamps and are controlled by a water table. These are also low irregular systems, but tend to have thicker roofs and may have multiple levels, tied to older water tables. Most syngenetic caves show extensive instability and collapse domes and rubble filled passages are common.

Solution pipes are vertical cylindrical tubes, typically 0.5 to 1 m in diameter, which can penetrate anything from less than a metre to 20 metres into the soft limestone. They occur as isolated features, or in clusters with spacings as close as a metre or so. They commonly have a cemented rim that is harder than the surrounding rock, and they may be empty, or filled with a reddish soil. In some, the soil fill has been cemented to form a solid plug. Jennings (1968) postulated that the pipes formed around tree roots penetrating the soft calcareous sand, and that they contributed to the consolidation of the dune.

Syngenetic karst development is typical of the Quaternary dune calcarenites; however, the Gambier Limestone is a relatively soft porous limestone, and

consequently it also shows some of the features of syngenetic karst, in particular the development of solution pipes and calcreted caprocks.

Caves

The caves in the South-east Karst Province are dominantly phreatic in origin. The limited relief means that vadose features are extremely rare though some vadose streams occur in the caves of the Glenelg River gorge in Victoria. Both joint and bedding plane control can be seen, but solution at temporary water-table levels can make the latter hard to recognise in this area of flat bedded limestone. Many of the primary phreatic caverns and passages have been modified by breakdown to form collapse domes and rubble filled passages. Cave diving has demonstrated the existence of extensive underwater cave systems, and it appears that in the southern part of the province the bulk of the cave development may be below the present water table, though these passages would have been partly or wholly drained during the low sea levels of the last glacial period.

Speleothems comprise most of the common calcite types, including some black formations in the Naracoorte area. Soft deposits of moonmilk (lublinite) are a common feature in many of the caves.

Bone deposits of Quaternary age have been found in a number of caves (Wells & Pledge, 1983). The most important, and world famous, deposit is in the Victoria Fossil Cave (U-1) at Naracoorte, but other significant finds have been in Henschke Bone Cave (U-91, Pledge, 1990), Tantanoola Tourist Cave (L-12, Pledge, 1980) and underwater in Fossil Cave (L-81, Horne, 1988a; Pledge, 1980).

Dolines

The most spectacular surface karst features are the **collapse dolines**, especially those that extend below the water table to form **cenotes**. These have formed above large phreatic caverns.

The term **cenote** has been used fairly broadly in the south-east to include not only collapse dolines that extend below the water table, but also dry collapse dolines that have water in associated caves, or mainly submerged caves with entrances that are not strictly collapse dolines. Part of the nomenclature problem comes from the emphasis by the cave divers on the presence of deep water in any situation, and partly from Marker's (1975, 1976) use of 'cenote' as a synonym for any collapse doline with sheer walls, regardless of the presence of water. I will follow the usages of Monroe (1970) and Jennings (1985, p 111) who restrict the term cenote to collapse dolines which contain a watertable lake. Goulden Hole (Figure 4) is a typical cenote that has been mapped and described in detail (Horne, 1988b, Thurgate, 1990). An interesting feature of some of the cenotes is the existence of stromatolites: underwater calcareous growths formed by algae (Thurgate, 1990).

Many **small shallow hollows** occur throughout the province, but are particularly common in the Bool, Nangwarry and parts of the Naracoorte Regions. There are several types of these small hollows, and a range of gradations occurs between them.

The first type of hollow has a saucer to basin shape, and may even be funnel shaped in some extreme cases. These are typically much less than 100 m

across, and from 1 to 3 m deep, though they can reach depths of 8 m and some extreme cases have widths up to 300 m. They appear to be mainly subsidence dolines in either soft soil or superficial sediments over buried karst cavities in limestone, though where the cover is thin some might be simple solutional dolines. They may be dry or contain small intermittent waterholes. In some a small 'runaway hole' is seen at the base where the surface runoff has been soaking into the porous soil. These were referred to as 'funnel dolines' by Marker (1975).

A second type consists of shallow flat-floored hollows which Marker called 'swamp dolines'. These are typically less than a metre or two deep and can be from 50 to over 500 m across. They are generally swampy and may have seasonal lakes. The shallow swampy form is probably due to a restriction on vertical development as a consequence of a shallow water table or the thin limestone beds in which they have formed. Where they occur in association with deeper basinal dolines this could indicate a local perched water table. Not all of these swamps are necessarily karst features, some may be primary hollows in alluvial or coastal deposits, or shallow deflation hollows.

A third type are the shallow lakes with lunettes seen in the Bool Region. These are a larger variant of the flat floored swampy hollows. They may not be karst features, but rather primary coastal lagoons that have been modified by waves and the wind since the sea withdrew from the flats.

Uvalas

Uvalas are composite hollows. They are most common in the Naracoorte Plateau, the Nangwarry Region and the Gambier Region. They have formed in part by the coalescence of simple solution or subsidence dolines, in part as chains of hollows along old dry valleys and in part by the karst modification of primary dune hollows.

Dry Valleys

In the Naracoorte Plateau, and in the south-eastern end of the Gambier region there are old surface drainage lines that have been abandoned as a result of underground capture of their flow. Most are just chains of dolines and uvalas, and are not immediately obvious; however there are two better examples. The first, in the Naracoorte Plateau, is a meandering valley that cuts through the East Naracoorte range near Jerboa, east of Struan. The second is Dry Creek near the Glenelg River, in the Gambier Region, which is a well preserved incised meandering valley which now has no surface drainage and a number of shallow closures along its floor.

Quasi-karst forms

Primary **dune hollows** occur in the high dunes - these are not true karst, but may have had some modification by karst processes. All sizes and depths occur up to a maximum length of several kilometres, and depths of 15 m or more. They are typically smoothly rounded basins or closed valleys, but where the base of the dunefield has been limited by a water table they may have flat swampy floors.

Areas of '**hummocky**' terrain occur in several places in the Mount Gambier Region. These areas consist of an irregular to elongated pattern of rounded hills separated by basin shaped hollows. The larger hummocks, in the

immediate vicinity of Mount Gambier, have a vertical relief ranging from 10 to 25 m and a 'wavelength' of between 300 and 700 m. The hollows are nearly always dry - indicating a well developed underground drainage. This terrain seems to be a primary dune topography that has been modified by karst processes, as the bases of the hollows commonly extend well below the contact between the old calcareous dunes and the underlying limestones of the Gambier Formation. The hummocks are gradational to a true high dune topography, as in the Gambier Forest, and also into true karst dolines and uvalas, as in the Wandilo area north-west of Mount Gambier.

CONTROLS ON KARST DEVELOPMENT

Marker(1975) referred to the South East Karst Province as a doline and uvala karst region with dominantly covered karst. Marker (1975) discussed the possible controls on the overall distribution and nature of the karst features within the province. She considered the effects of variations in climate, vegetation, lithology, topography, overburden (thickness and character), and hydrology. She concluded that the main control on variations in karst character within the province was the hydrology: in particular the depth to the water table and the water table gradient. Other factors that have had local control are the topography, the nature and thickness of the cover, and the nature and structure of the parent rocks, in particular the degree of joint control. There is also a possible effect from carbon dioxide derived from the volcanic activity (Lewis, 1984).

The depth to the watertable controls the amount of free vertical drainage. The areas of best cave and surface karst development are all areas of relatively deep watertables: the Naracoorte, Gambier and Glencoe Regions at present, and the Schank and Coast Regions during the glacial stages. The two belts of steep watertable gradient may also be significant as they would have accentuated water movement and thus promoted solution; these belts also correlate with areas of high cave density (Figure 2). The southern steep gradient zone would have been more extensive during the reduced sea levels of the glacial periods, and may have been partly responsible for the high density of cenotes and associated caves in the Schank region.

The topography in the province is mostly low and flat, with local relief provided by the dune ridges and the volcanic hills. Only in the gorge of the Glenelg River in the extreme south-east is there sufficient relief to allow the development of vadose streams.

Most of the karst is covered, but some areas of bare karst occur in the Schank Region. The cover is of Quaternary age and consists of partly calcareous coastal swamp and lagoonal deposits, quartzose and calcareous sand dunes and aeolian sand sheets and minor alluvial flats. Thicknesses can be up to 30 m. Thick cover can have an inhibiting effect on surface karst and thick soil cover can clog any potential cave entrances.

The karst features of the province are typified by development on relatively soft and porous parent rocks. Most of the caves and large collapse dolines are developed in the Gambier Limestone but some are partly or wholly developed in the Bridgewater Formation and these are of syngenetic type. Joints in the Gambier Formation provide strong control on the orientation and character of many caves in the southern part of the province, but joint control is less obvious in the Gambier Limestone in the north and almost absent in caves in the dune calcarenites of the Bridgewater Formation. The Tartwarp fault has

a line of elongated dolines and uvalas developed along it. Dolines in the flat parts of the Bool Region and in the Nangwarry Region may be developed on thin limestones equivalent to the Whalers Bluff Formation.

Lewis (1984) refers to the reserves of carbon dioxide gas found at depths between 2500 and 2800 m during oil exploration (Wopfner & Thornton, 1971) and suggests that there could be movement of this gas along fractures into the karst aquifer. Wopfner & Thornton (1971) attribute the carbon dioxide to the volcanic activity in the area and Lewis notes the proximity of the cluster of dolines and cenotes in the Barnoolut area to the Mount Schank volcano and points out that the existence of lineaments in the area might indicate geological fractures. He therefore suggests that the movement of the gas into the groundwater may have been responsible for the increased solution in the area. This is an interesting hypothesis but the argument is rather tenuous, and there are other explanations for this area of enhanced karst development such as the reduced and steeper watertables during the glacial periods.

There are some similarities with the Nullarbor Karst Region (also developed on extensive, soft, flat-lying, Tertiary limestone) but the climate is wetter (at present) and the watertable variations, the younger dune ridges and the surficial sediments provide additional complications not seen on the Nullarbor.

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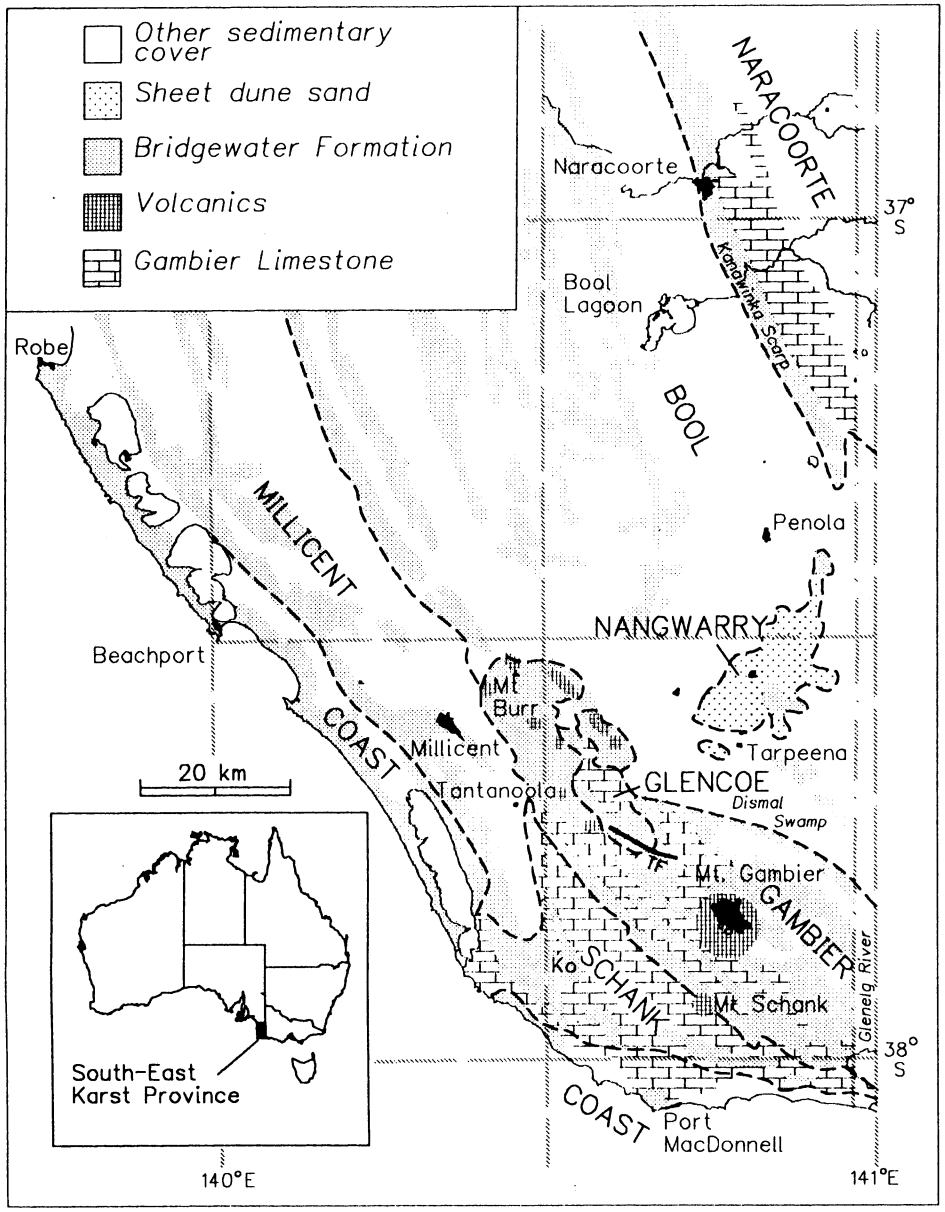

Figure 1: South-east Karst Province, Regions and Geology
TF = *Tartwarp Fault*. Ko = *Kongerong*.

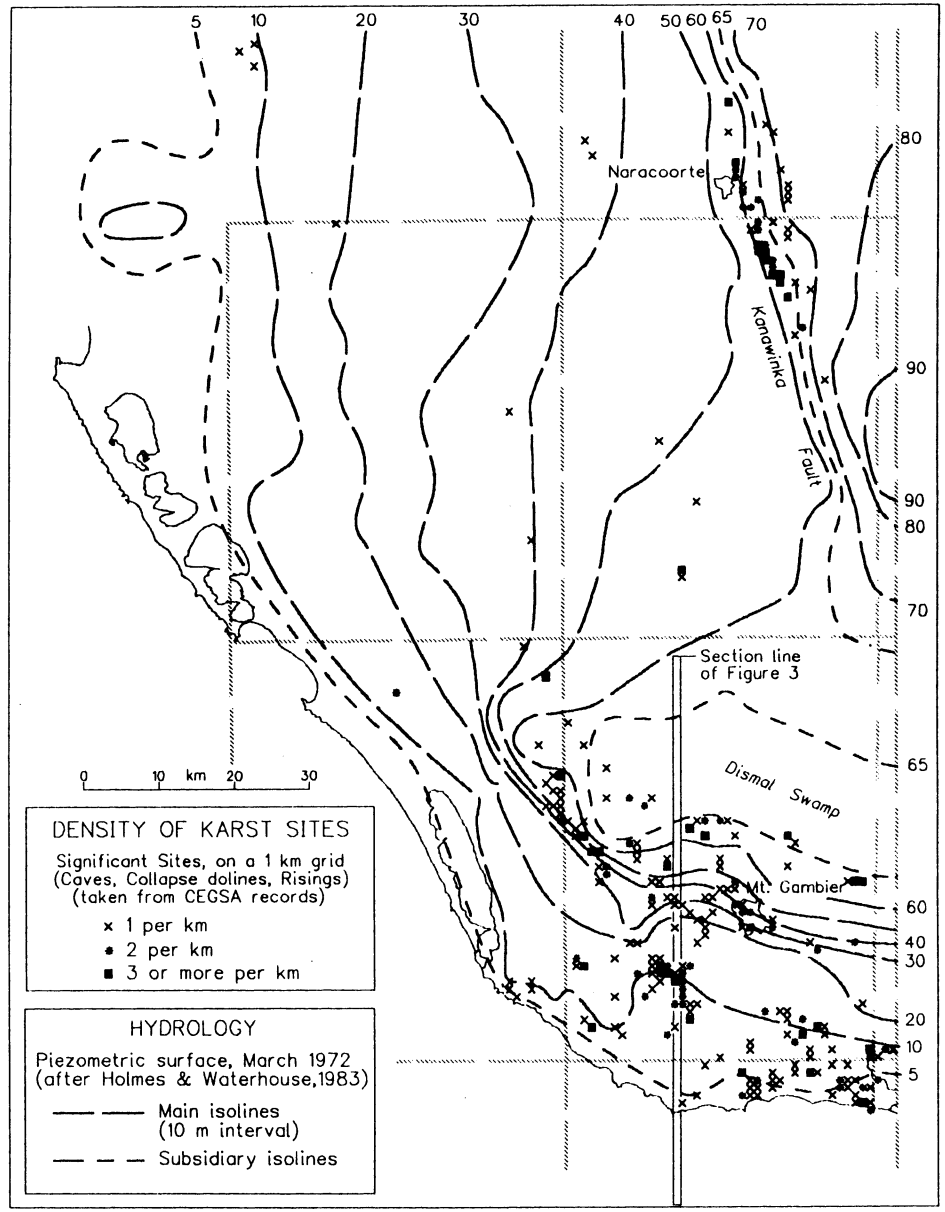

Figure 2: Hydrology and Distribution of significant karst sites

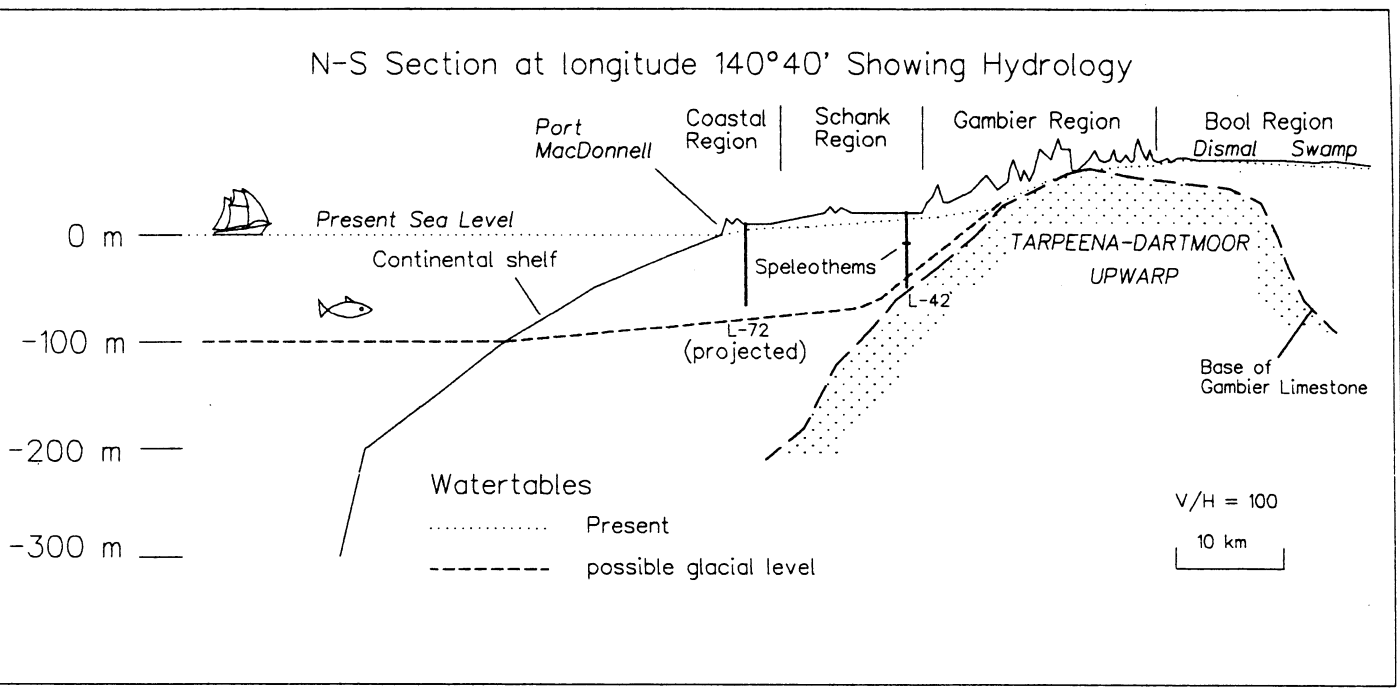

Figure 3: Cross section showing present water table, and possible glacial water table in the Mount Gambier area.

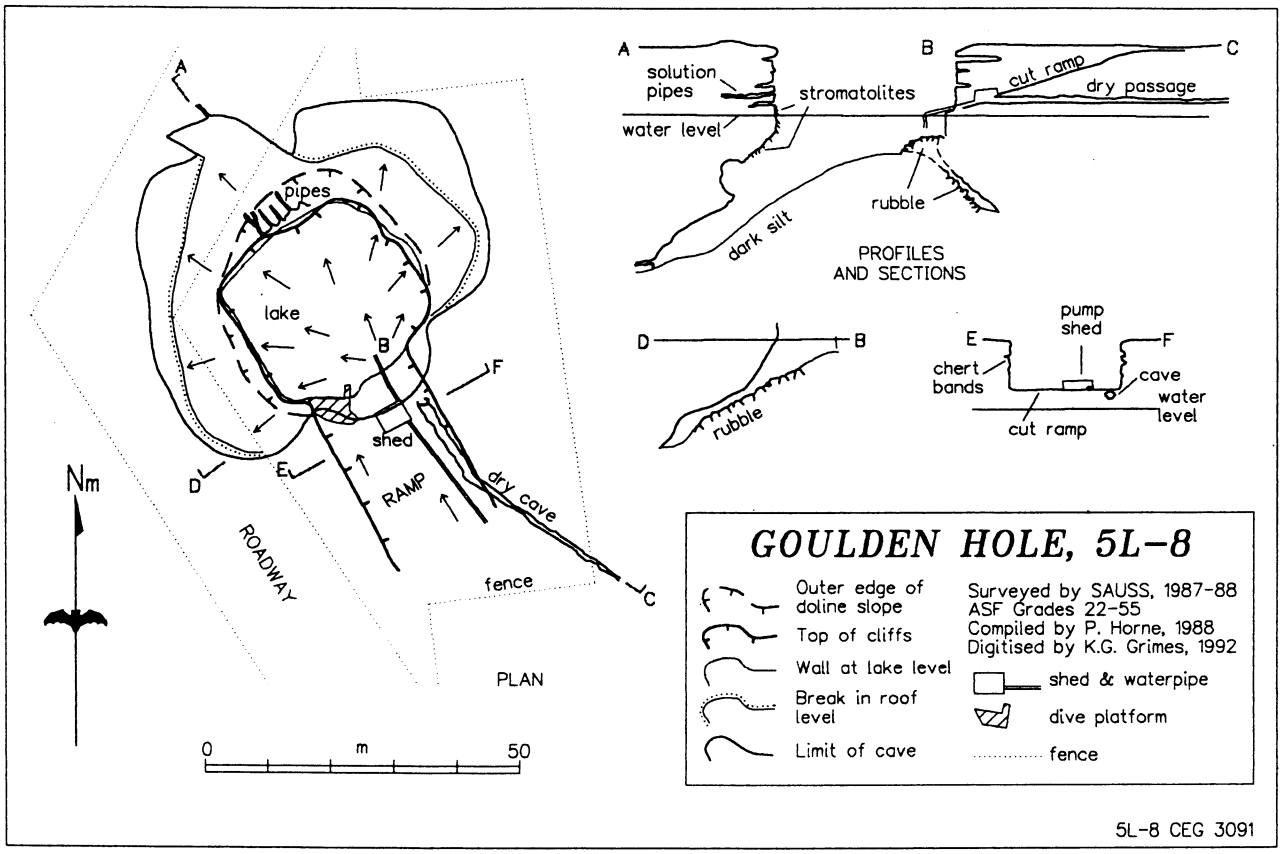

Figure 4: Goulden Hole (L-8), a typical cenote in the Schank Region.