10th Australia and New Zealand Geomorphology Group Conference

Nullarbor Field Trip Excursion Guide

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Introduction

The Nullarbor represents one of the largest continuous areas of limestone in the world, and is also distinguished by its flatness, arid climate, lack of vegetation and interesting karst geomorphology. The caves contain the very well preserved remains of extinct animals that roamed the area when the climate was wetter, like the marsupial lion and the Tasmanian tiger. These unique and fascinating features have been sufficient for the Nullarbor to gain nomination for World Heritage listing. Despite its remote location, the Nullarbor has been moderately well studied, particularly its caves; recently cavers have made extensive use of ultralight aircraft to look for new caves. The recent find of a pit-trap cave with abundant fossils of extinct megafauna was made in this way.

Landscape and climate

The Nullarbor has an area of ~200,000 km^2, making it one of the largest outcrops of limestone anywhere (Figs 1, 2). It is astoundingly flat, with the longest stretch of straight railway in the world (478 km), and most of it is nearly treeless. The surface of the plain slopes very gently seawards from 240 m above sea level in the northwest, and terminates abruptly at the Great Australian Bight in a cliff-line 40-90 m high that extends more or less continuously for nearly 900 km (Fig. 3). The cliffs fall sheer into the sea except in two areas in the centre and west, where there are coastal plains (Roe and Israelite Plains respectively; Figs 3, 7).

The climate ranges from semi-arid along the coast (up to 400 mm rainfall) to very arid in the north, where rainfall is less than 150 mm and the mean maximum January temperature is 35°C (Fig. 2). Potential evaporation greatly exceeds rainfall, increasing from 2000 mm near the coast to 3000 mm inland. Most rain occurs as light falls, but occasional heavy storms can cause local flooding.

The coastal belt has a warm semi-arid climate and supports small trees (mallee eucalypts and myalls; Martin 1973; Martin and Peterson 1978). The Eyre Highway runs almost entirely through this coastal woodland, giving travelers a false impression of the Nullarbor vegetation. The vast majority of the Nullarbor Plain is treeless (Fig. 5); its name, from the Latin words meaning 'no trees', was coined in 1867 by an early explorer, Delisser. The dominant plants are bluebush, saltbush and tussock grasses. The soils are thin, stony, well-drained loams and sands. Over much of the plain erosion has stripped the soil, leaving bare stone pavements (Gillieson and Spate 1992).

Geological setting

At the beginning of the Tertiary, about 65 million years ago, Australia lay well to the south of its present position. The southern margin was located at about latitude 60-65° south, compared to 40-45°S today. At this time Australia had begun to split from Antarctica, so an ocean basin had opened up between the two continents, but it wasn't until 35 million years ago that complete separation took place, and present-day patterns of ocean circulation were not established until ~20 million years ago (Bernecker et al. 1997). Cooling of the southern ocean and the development of

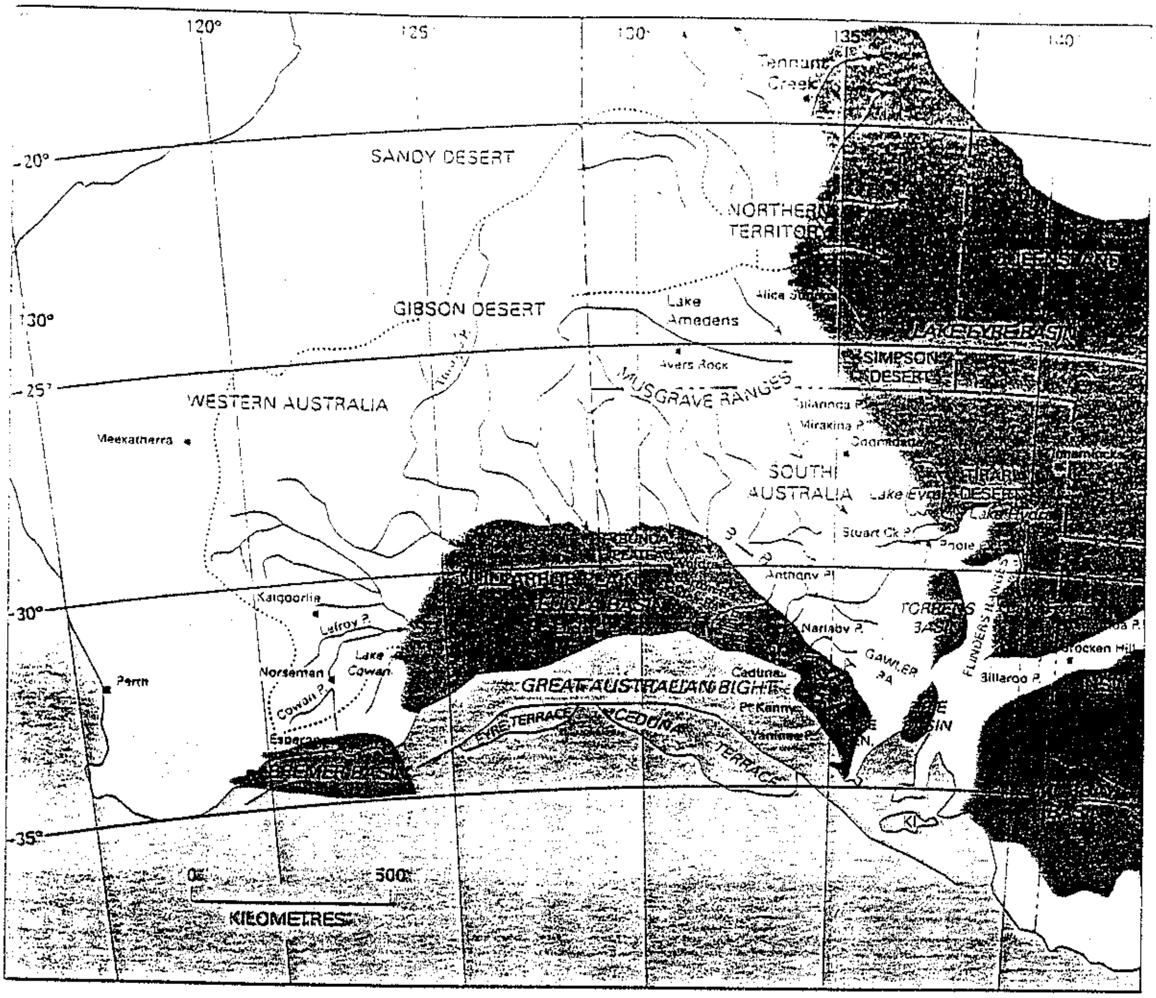


Fig. 1. Regional setting of Nullarbor Plain and Eucla Basin (from Drexel and Preiss 1995)

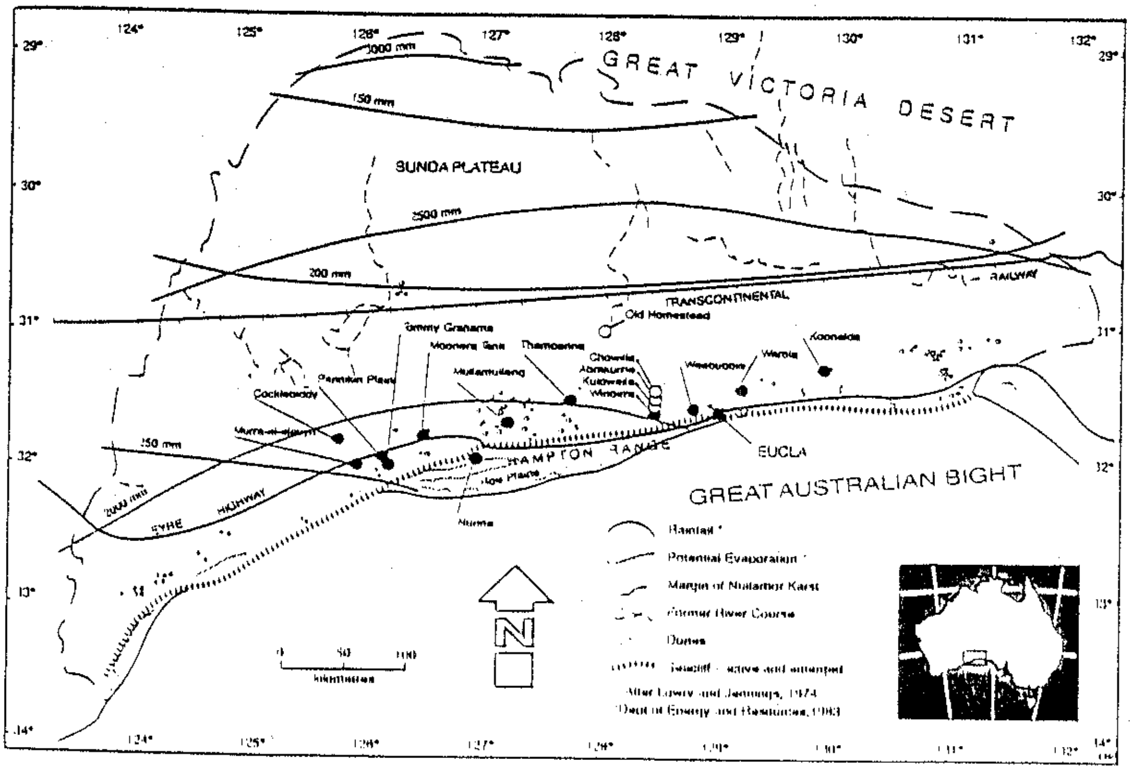


Fig. 2. Rainfall and evaporation on the Nullarbor Plain, with locations of major caves (from James 1992)

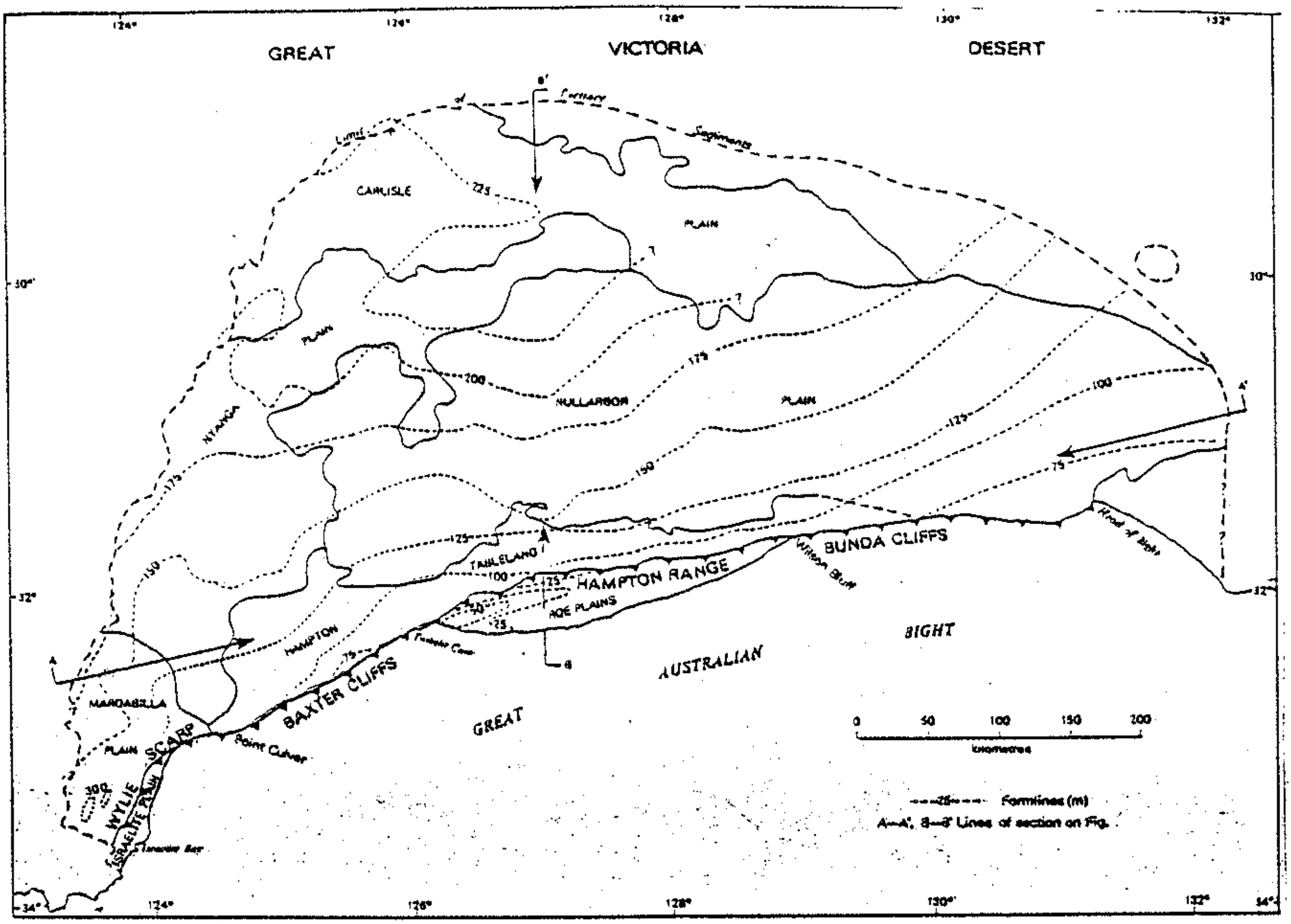


Fig. 3. Topography of Nullarbor Plain (from Lowry and Jennings 1974)

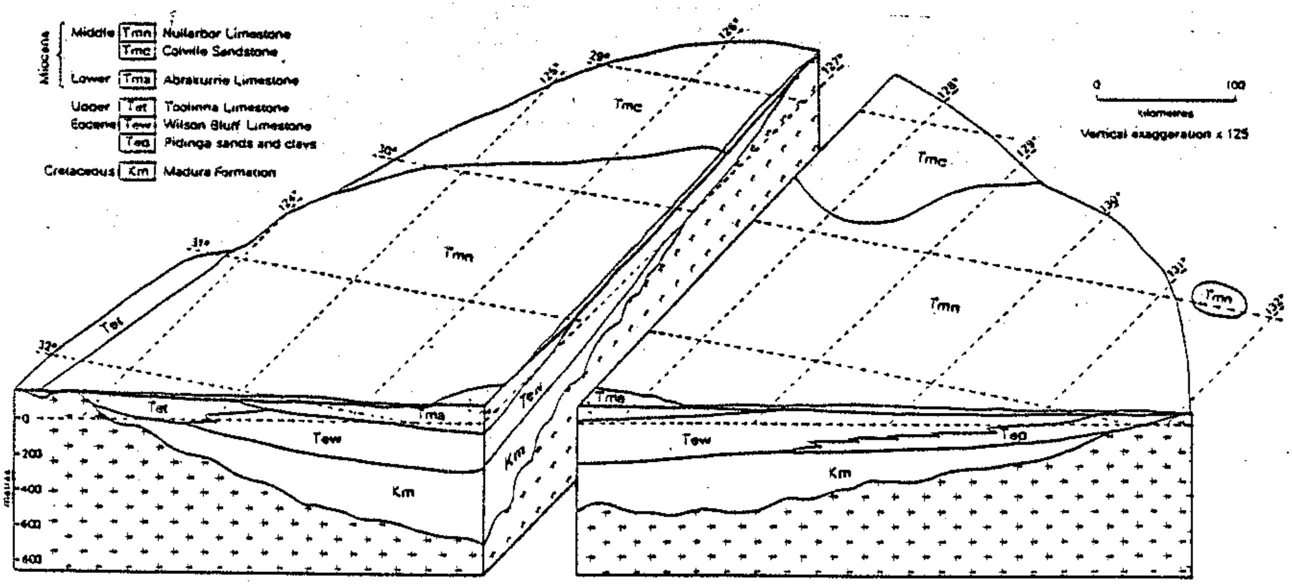


Fig. 4. Geological cross-sections of Nullarbor Plain; for locations, see Fig. 3 (from Lowry and Jennings 1974)

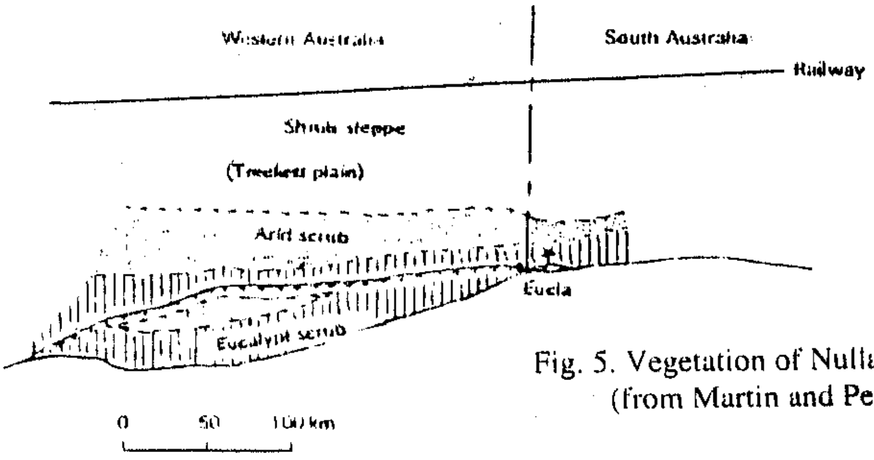


Fig. 5. Vegetation of Nullarbor Plain (from Martin and Peterson 1978)

glaciers on Antarctica began at about this time, but Antarctica was not covered by ice until around 2.5 million years ago. Thus throughout much of the Tertiary the ocean along Australia's southern margin was warm to cool temperate, and was frequently warmer than at present.

The shallow waters along this margin supported and continue to support abundant marine life, including many organisms with skeletons of calcite such as bryozoans, forams, echinoids (sea urchins) and calcareous red algae (James 1997). Wave energy breaks the skeletons of the dead organisms into sand-sized grains, and together with those skeletons that were already sand-sized (like forams), these accumulated to form extensive Tertiary limestone deposits on the continental shelf along the southern, and to a lesser extent western, margins of the Australian continent (James and Bone 1991). The southern Australian Tertiary limestones are the largest area of temperate water limestone in the world, and continue to accumulate today; on the floor of Bass Strait extensive bryozoan mounds are growing at present, and calcite sands are building up nearby.

The Australian Tertiary temperate limestones accumulated in a number of different basins around the edge of the continent, but only three, known as the Eucla and Otway Basins and the Exmouth Sub-basin, contain karst with significant cave systems, and these are called in turn the Nullarbor, Gambier and Cape Range karsts. Only the Exmouth Sub-basin has suffered significant folding since deposition of the sediments; in the Eucla and Otway Basins the limestones are mostly flat-lying.

These temperate limestones are quite different to tropical and subtropical limestones, which are dominated by corals and calcareous green algae that have hard parts composed of aragonite. Aragonite is easily dissolved in rainwater, so when tropical limestones are exposed to weathering by uplift or a fall in sea level, the aragonite skeletons within them are quickly dissolved, and then reprecipitate within the pore spaces in the limestone as calcite cement. Thus tropical limestones are typically well cemented and resistant to erosion. By contrast, temperate limestones contain little aragonite, because the skeletal grains within them are almost all calcite (James 1997). Calcite is less readily dissolved by rainwater, so when temperate limestones are exposed to weathering, there is less precipitation of cement in the pore spaces between the sand-sized grains. Thus temperate limestones are frequently not well cemented and quite porous. Caves formed in these limestones are generally subject to frequent collapse, because of the relatively low strength of the surrounding rock, and the sediments on the cave floors are usually composed of sand grains derived from breakdown of the limestone.

Geological history

The limestone of the Nullarbor is flat-lying and can be divided into three units deposited at different times (Figs 4, 6). The oldest and thickest is the Wilson Bluff Limestone (up to 300 m thick); it was deposited in the Middle-Late Eocene (from about 43 to 36 million years ago) across the entire Nullarbor in relatively quiet, shallow, cool temperate waters (Drexel and Preiss 1995; James and Bone 1991). It is composed mainly of bryozoan fragments and forams in a calcite mud matrix. Porosity is high (~30%), but because the pore spaces are open chambers within the fossil

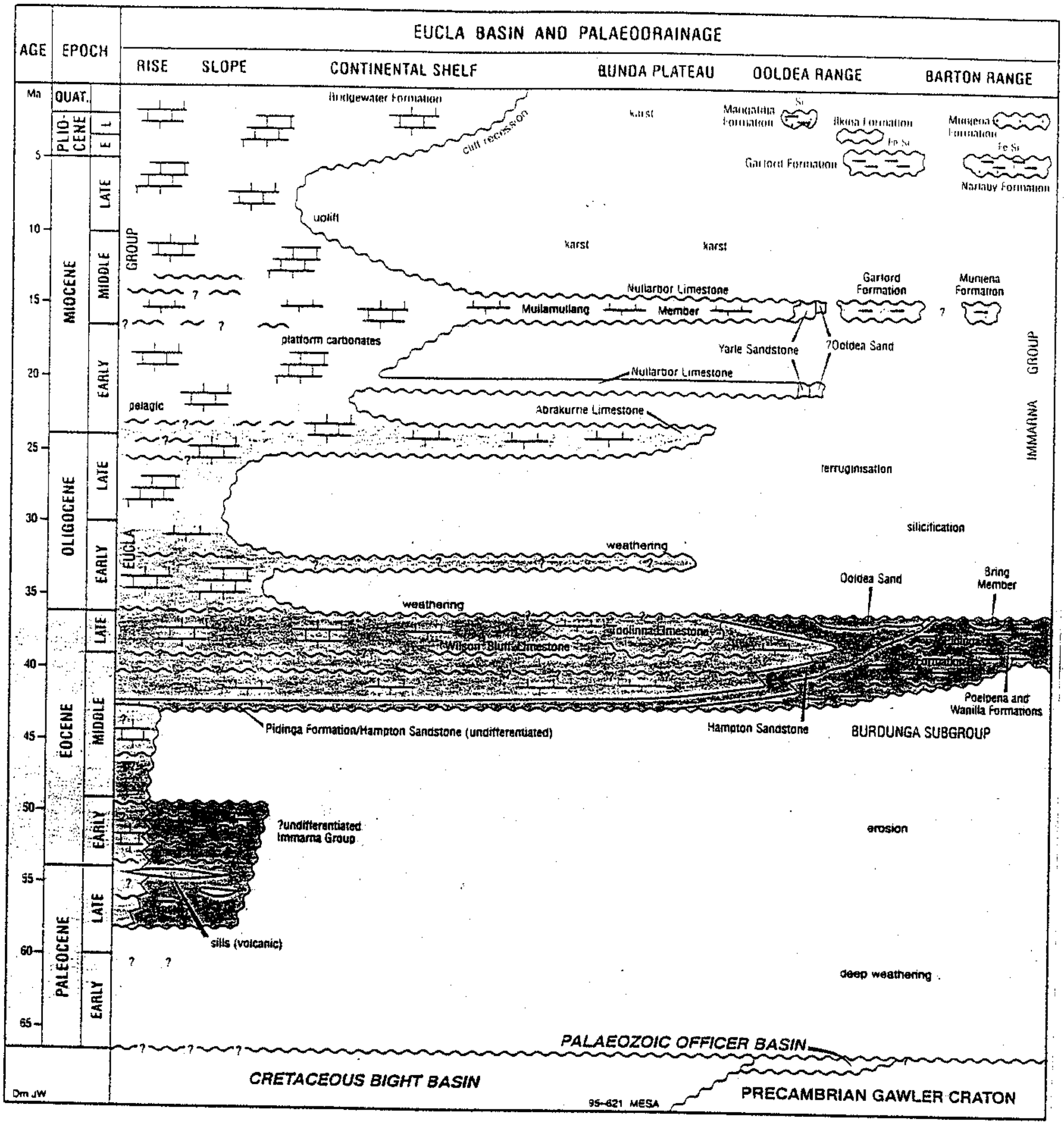
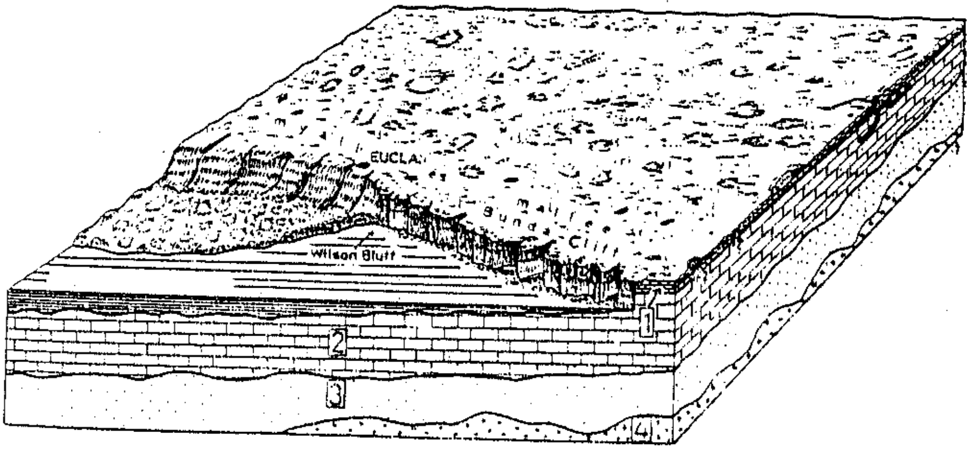


Fig. 6. Stratigraphy of Eucla Basin (from Drexel and Preiss 1995)



1 = Lower Miocene Nullarbor and Abrakurrie limestone; 2 = Upper and Middle Eocene Wilson Bluff limestone and Hampton sandstone; 3 = Cretaceous Madura Formation (mainly sandstone); 4 = Precambrian granite. The covering rock in the Roe Plain is Pleistocene calcarenite and recent dune sand

Fig. 7. Block diagram of Nullarbor Plain and underlying stratigraphy (from Denes 1974)

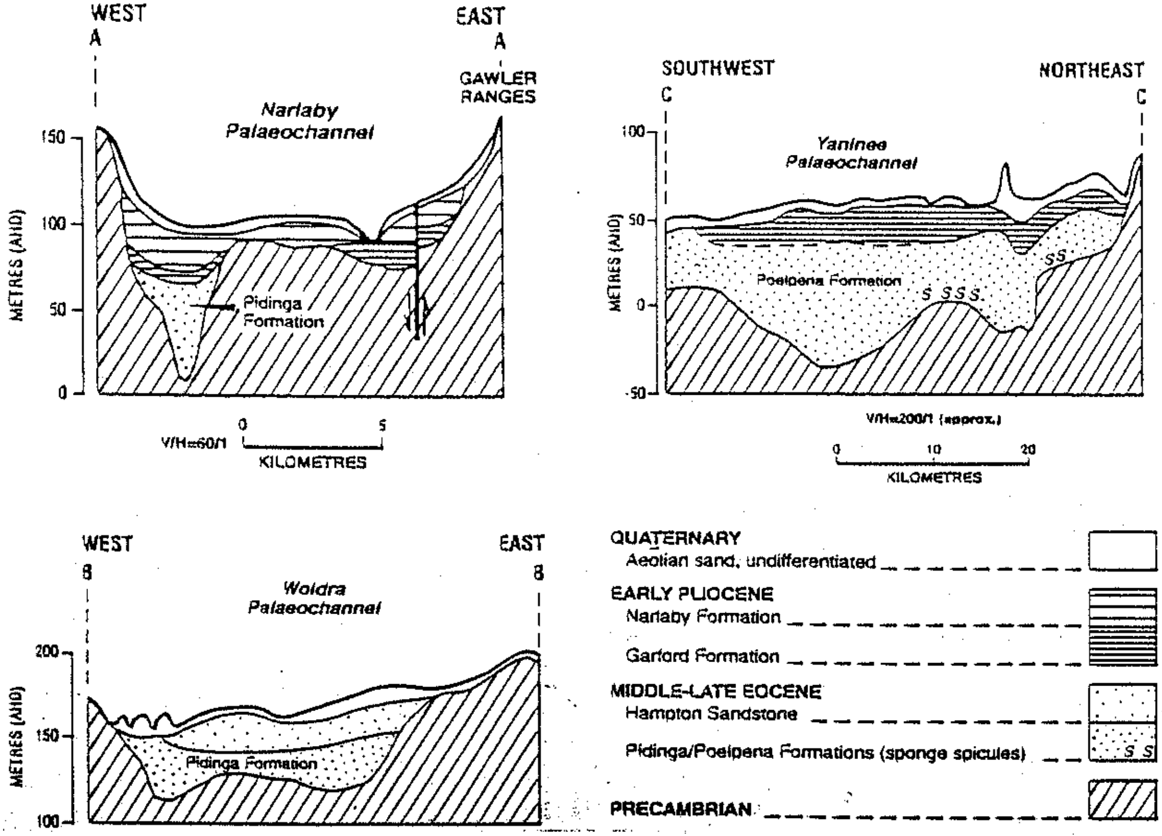


Fig. 8. Palaeochannels of the eastern Nullarbor Plain; for locations, see Fig. 1 (from Alley et al. 1999)

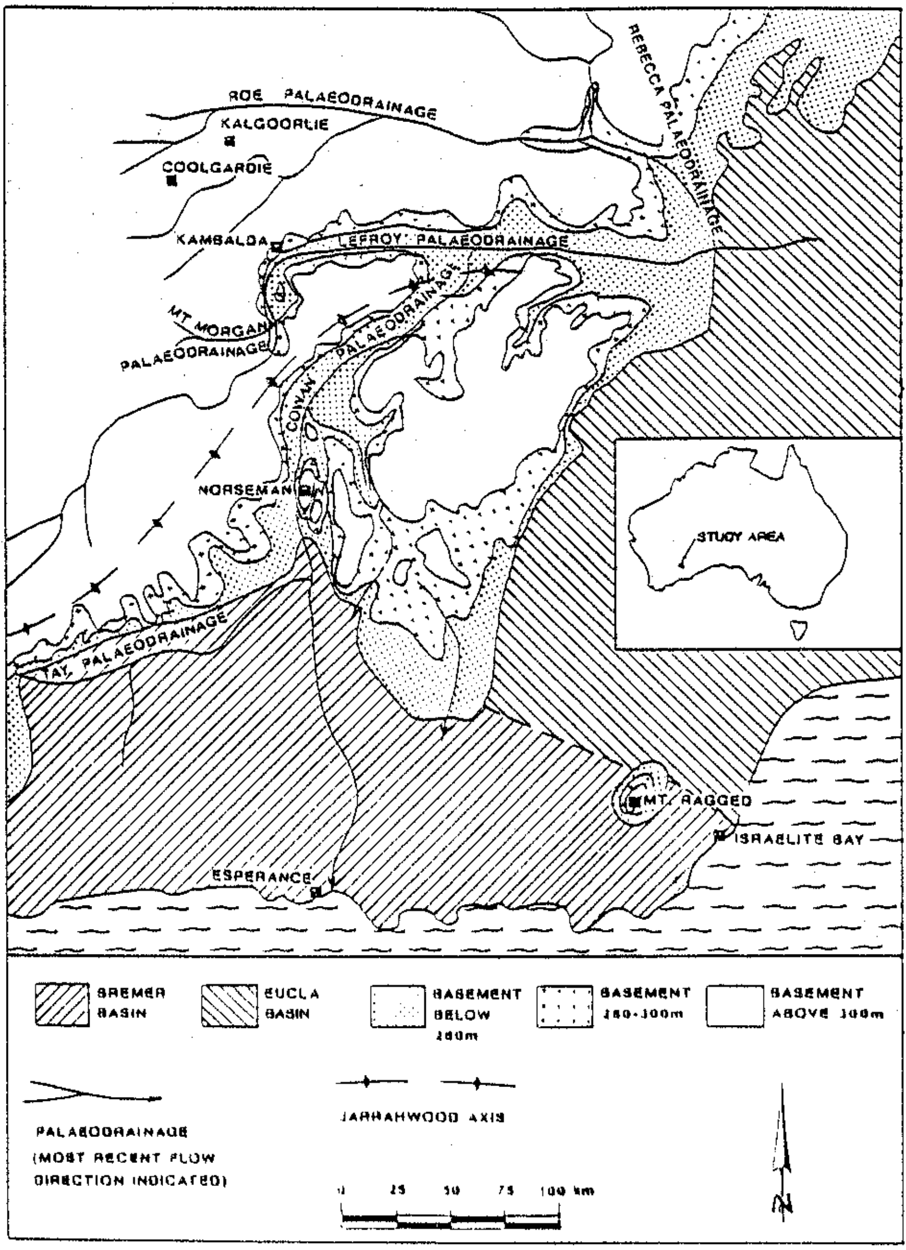


Fig. 9. Palaeochannels of the western Nullarbor Plain (from Clarke 1994)

fragments, they are separated by the muddy calcite matrix and do not interconnect, so the permeability of the limestone is low, i.e. water does not pass through it easily.

At this time the climate was warm with a strongly seasonal rainfall (Alley et al. 1999). On land rainforest grew along watercourses, and monsoon woodland (similar to that in northern Australia today) covered the hills and probably also the Nullarbor. Brown coal was deposited on the flood plains along river channels.

In the Early Oligocene the sea withdrew from the Nullarbor, and the surface of the Wilson Bluff Limestone was exposed to weathering and erosion for probably 10 million years, forming a prominent surface soil and calcrete layer (Drexel and Preiss 1995). This layer is clearly visible in the sides of the dolines at Koonalda and Old Homestead Cave.

From the Late Oligocene to Early Miocene (about 25 to 23 million years ago), the sea returned and deposited the 100 meter thick Abrakurrie Limestone, but only in the central Nullarbor area (Drexel and Preiss 1995). This limestone is rich in bryozoans but lacks a muddy calcite matrix, because it accumulated under high enough energy conditions to wash away the fine-grained material. As a result this limestone has both high porosity (~40%) and permeability.

The sea then retreated but returned in the Middle Miocene to deposit the Nullarbor Limestone (Fig. 10), a relatively thin blanket (maximum 45 m) of limestone, similar in properties to the Abrakurrie Limestone, covering the entire Nullarbor region. This limestone contains a greater variety of fossils than the older limestones, including abundant red algae and occasional patches of corals (although no reefs formed).

By this time the climate had become hotter and drier, still with a strong seasonality, and the vegetation on the hills consisted of woodland with pockets of rainforest (Alley et al. 1999).

The sea withdrew for the last time about 14 million years ago (Fig. 11), and soon afterwards the Nullarbor region was gently uplifted. Later sea level rises eroded the coastal cliffs and formed the Roe and Israelite Plains. During the 14 million years that the surface of the Nullarbor Limestone has been exposed, a thickness of only 30-70 m of limestone has been eroded away, the greatest erosion occurring closest to the coast where rainfall is highest (Lowry and Jennings 1974; Denes 1974).

The climate became increasingly dry around 5 million years ago, at the beginning of the Pliocene, and the vegetation was similar to that today, except the dry woodland extended further inland (Fig. 11). This increasing aridity was interrupted by a warm, wet episode from about 5 to 3 million years ago, when there was substantial deposition of muds and sands in the river channels (Clarke 1994; Alley et al. 1999). The climate reached its present level of dryness, with extensive development of sand dunes in central Australia, only about 1 million years ago (Bowler 1982; Colhoun 1991; Chen and Barton 1991).

Surrounding the Nullarbor Plain, particularly to the north and west, are low hills of Precambrian basement rocks. Cut into these are old river courses (palaeochannels; Figs 8, 9), that probably first formed in the Cretaceous (perhaps 100 million years

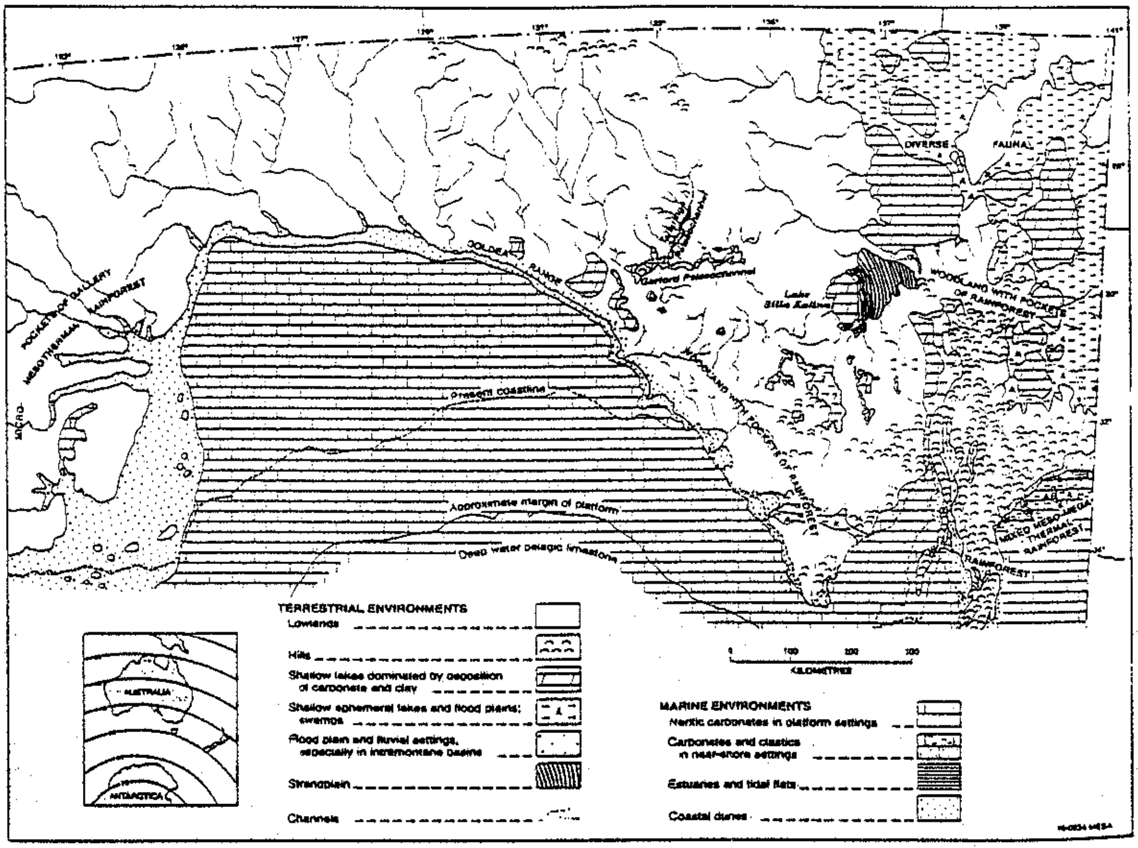


Fig. 10. Palaeogeography of the Nullarbor Plain region in the Early-Middle Miocene (from Alley et al. 1999)

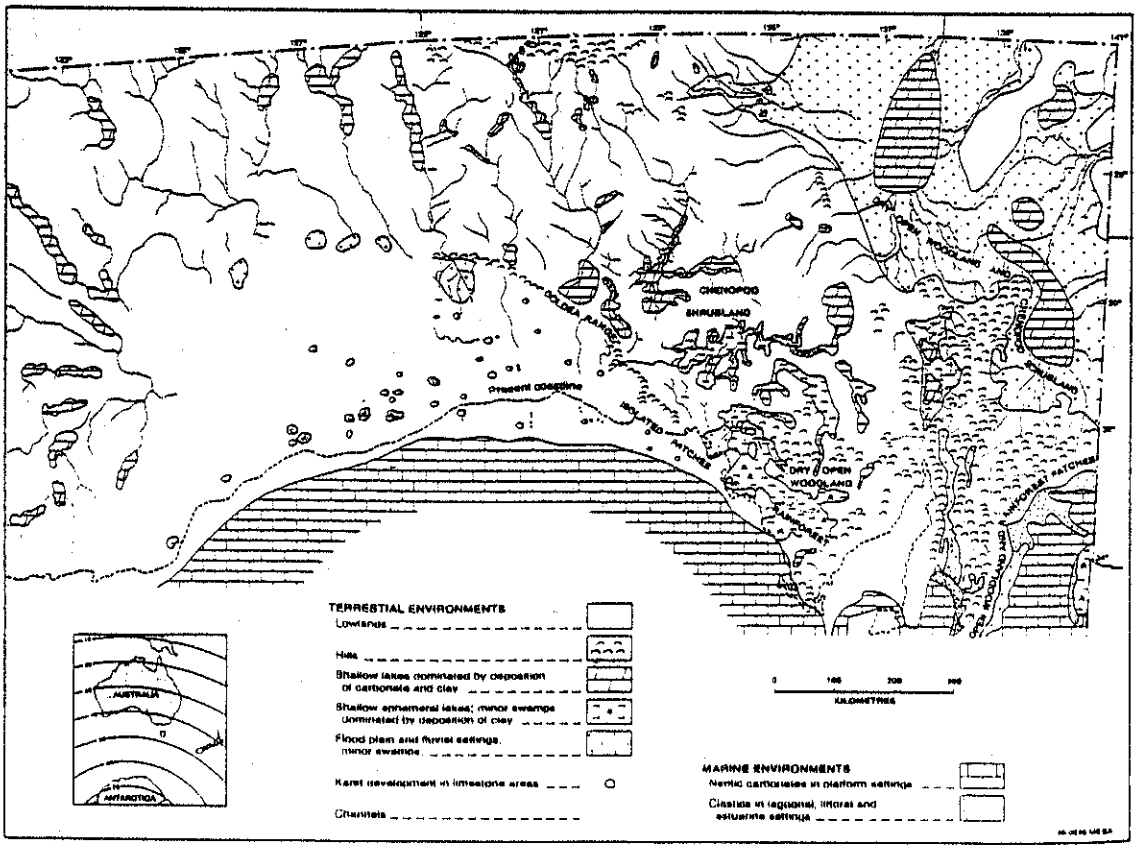


Fig. 11. Palaeogeography of the Nullarbor Plain region in the Late Miocene-Early Pliocene (from Alley et al. 1999)

ago). Sediments deposited in these channels record the changes in vegetation, climate and sea level of the region. At times the rivers from these channels may have extended southwards across the Nullarbor for 100 km or more (Fig. 2), before the water seeped into the porous limestone to become part of the groundwater.

Groundwater

The Nullarbor Plain lacks surface water, but contains substantial quantities of groundwater. The water table slopes very gently towards the coast (Commander 1990; Smith 1989; Fig. 13); in the north it is only 30-45 m below the surface, but close to the coastal cliffs it is as much as 120 m down. As the groundwater flows slowly southwards (Fig. 14), its salinity increases (Fig. 13), from 1,000-4,000 ppm TDS (total dissolved solids; normal drinking water should have less than 500 ppm) to 5,000-20,000 ppm near the coast (sheep can drink water as salty as 14,000 ppm).

The groundwater composition strongly resembles that of seawater (Fig. 12). This is not due to the presence of Tertiary seawater in the limestones; this was flushed out long ago. Instead it represents the input of both rainfall and salt spray. The increase of groundwater salinity towards the coast is related to infiltration of rain falling on the porous limestone; as the water seeps slowly downwards, it is concentrated by evaporation in the very arid climate. The rain has incorporated salt spray from the coast, so evaporation causes the soil water to have a composition like that of seawater, but even more saline (see the dripwater composition on Fig. 12). The south-flowing groundwater receives progressive additions of this very saline water seeping from above, causing the coastwards increase in salinity. In addition, there is probably a direct input from salt spray blown inland from the waves crashing against the coastal cliffs. Groundwater closest to the coast, beneath the Roe Plain, has a salinity of 30,000 ppm, approaching that of seawater (35,000 ppm).

Surface features

The surface of the Nullarbor Plain is not completely flat. It rises and falls several meters between clay-floored depressions, up to 1 km wide, separated by stony ridges of the same width (Fig. 15). The ridges are frequently aligned parallel to jointing in the underlying limestone (Lowry and Jennings 1974; Benbow and Hayball 1992).

The Nullarbor surface is covered with a layer of calcrete, or kankar, generally ~1 m thick. This is a hard, white, cemented crust, formed by fungi and microbes in the soil precipitating very fine grained calcite in the pore spaces of the limestone. Calcrete forms in semi-arid and arid climates.

A few old river courses run southwards across the northern and western parts of the plain as meandering, often clay-floored channels (Fig. 16). These represent southerly extensions of palaeochannels incised into the basement rocks around the plain (described above; Fig. 1).

Small-scale solutional sculpture of the limestone outcrops is restricted (Lowry and Jennings 1974). Irregular shallow solution pans are common on calcreted limestone pavements, and often contain water after rain. Vertical pits up to 10 cm deep are

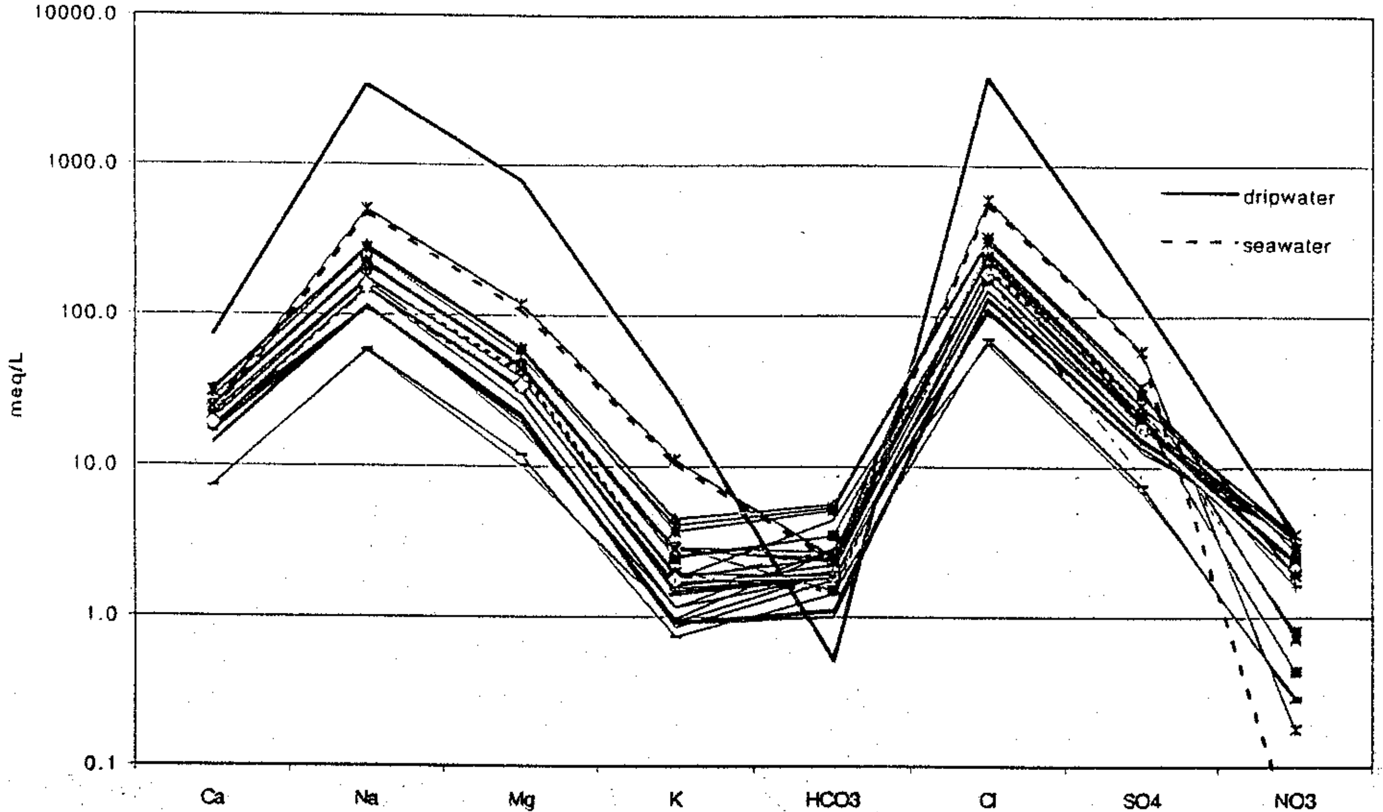


Fig. 12. Geochemistry of Nullarbor groundwater (data from James 1991, Totterdell 1997, James pers comm in Totterdell 1997, and Turin and Webb 2002)

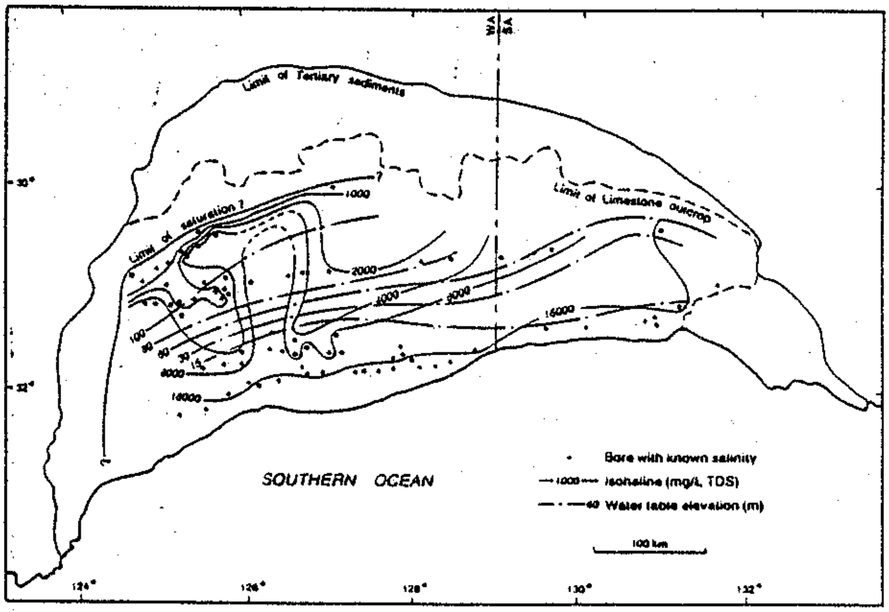


Fig. 13. Water table elevation and groundwater salinity on the Nullarbor Plain (from Commander 1990)

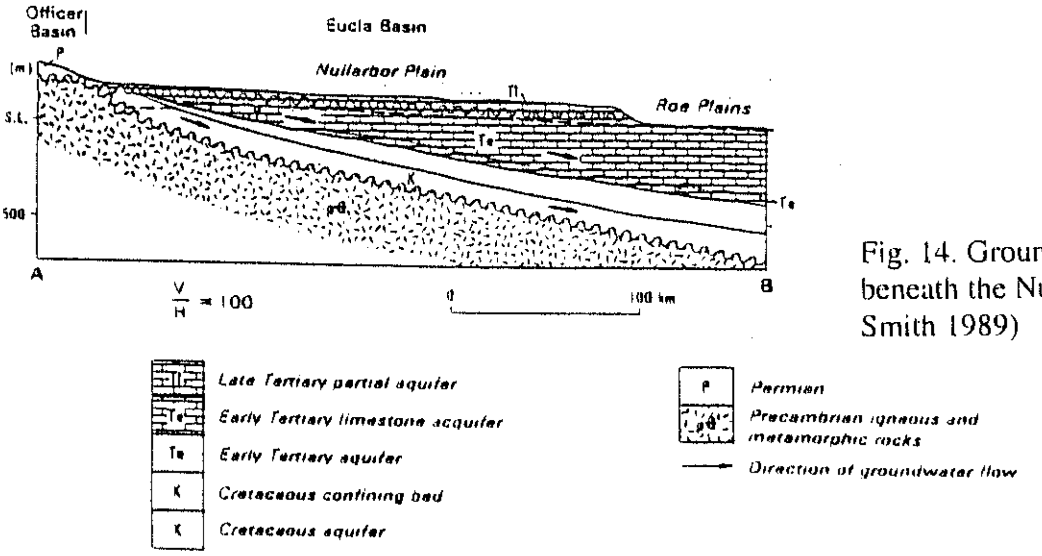


Fig. 14. Groundwater flow paths beneath the Nullarbor Plain (from Smith 1989)

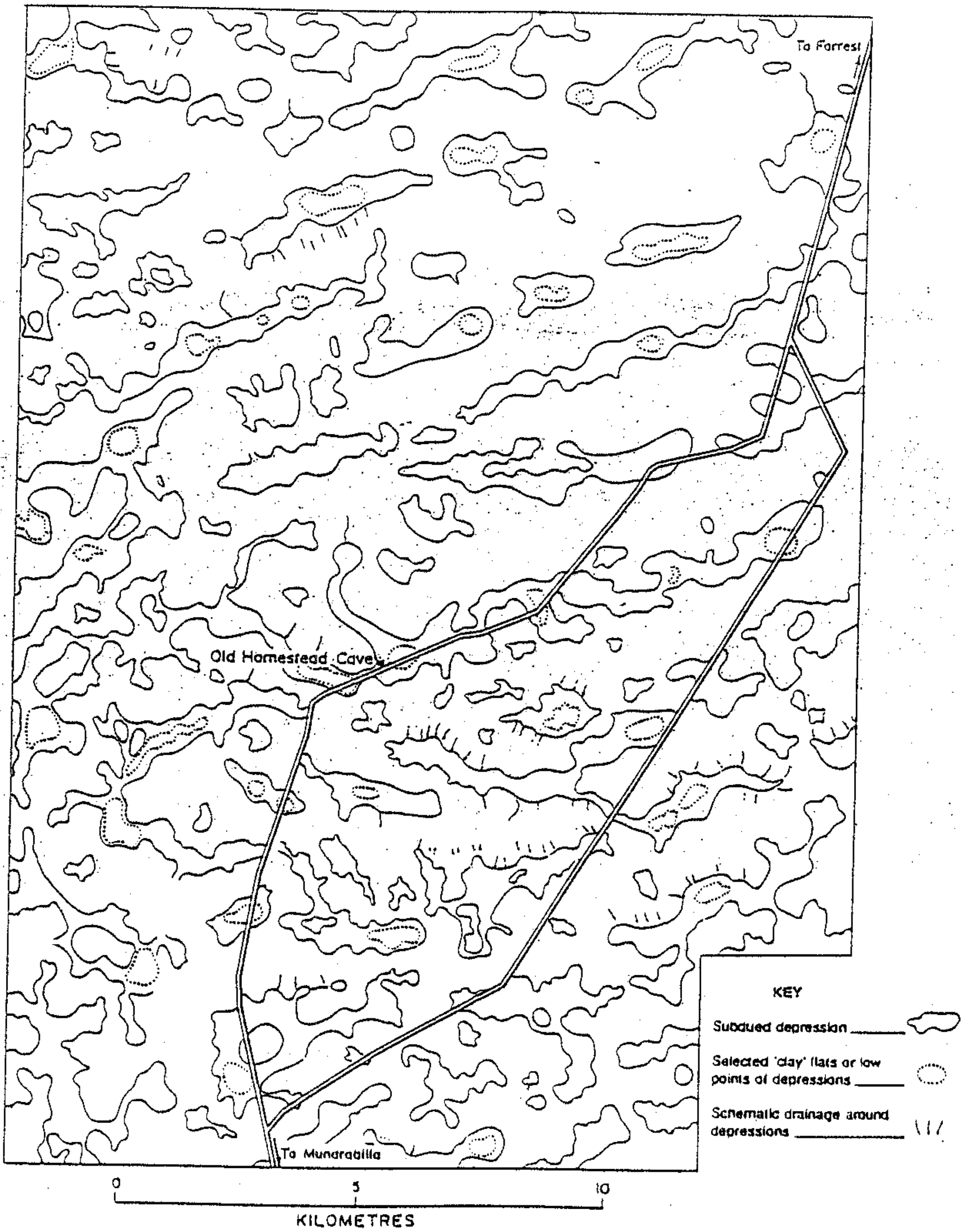


Fig. 15. Detail of surface topography of central Nullarbor Plain; for location, see Fig. 2 (from Benbow and Hayball 1992)

found in the limestone along cliff lines, but solution fluting (rillenkarren) is never well developed.

Dolines and caves

Apart from its great extent, remarkable flatness and lack of trees, the most spectacular features of the Nullarbor are its dolines and caves (Lowry and Jennings 1974; Fig. 16), although given the vast size of the Nullarbor, the numbers of these are really rather small. More than 150 collapse dolines are present, mostly within 60 km of the coast, as steep-sided, closed depressions 2-35 m deep and 10-240 m across (Fig. 17). A large proportion are partially or wholly walled by cliffs, which may be overhanging. Many are degraded; erosion since the original collapse has weathered the sides and partially filled them with sediment. However, some are still actively collapsing, as shown by a recent rockfall in Weebubbie doline. Some dolines lead to caves, but many do not.

Caves in the Nullarbor, like the dolines, are mostly restricted to the coastal belt (Fig. 16); there are about 100 that have significant passage lengths. They vary in depth and form. Extensive collapse is a feature of most of them (Figs 18, 19), and in many has completely obscured the original phreatic form of the cave. The breakdown passages so formed are irregular in outline, with flat, bedding plane roofs and rubble (rockfall) floors, and can be very large; the biggest is the main hall of Abrakurrie Cave, which is 300 m long, 30 m wide and 15m high. Collapse is prevalent for probably two reasons. Firstly, the limestone is poorly cemented and structurally weak, so it collapses readily. Secondly, the arid climate on the Nullarbor promotes salt weathering, which weakens the limestone still further. Salt weathering occurs when evaporation of groundwater within the pore spaces of the limestone causes salt crystals to precipitate; these wedge apart the fossil grains and break the cement binding them together. Within caves this process detaches particles from the cave walls, sometimes enlarging the caves upwards as domes, and depositing sand on the cave floor. In Mullamallang Cave this sand has been blown into dunes, and in places forms 'coffee-and-cream', banks of sand streaked with cream and dark brown.

However, a number of caves still contain original phreatic passages, and the best developed of these are Thampanna and Old Homestead Caves (Figs 20, 21). The latter is notable for being 100 km from the coast, at the northern edge of the cavemiferous part of the Nullarbor. Old Homestead Cave is also the longest Nullarbor cave, with about 30 km of surveyed passage; the furthest points of the cave are around 4 km apart in a straight line. Overall the cave trends north-south, but individual passages follow joints that run generally either northwest-southeast or northeast-southwest. The cave is entered through a double collapse doline; the rockpile leads rapidly downwards to a very extensive horizontal phreatic system developed on two levels, lying about 63 m and 70 m below the plain. The phreatic passages often show large-scale wall scalloping and spongework with projecting rock blades and pendants, and may have flat roofs (not bedding planes). The cave lies more or less directly south of an old river channel on the surface of the plain (Figs 2, 16); this channel represents the southerly extension of a palaeochannel cut into the basement to the north (Fig. 1). Thus it seems most likely that Old Homestead Cave formed where water sank into the porous limestone at the termination of the old river course, and a phreatic system developed at or just beneath the water table (the flat roof marks the water table at the

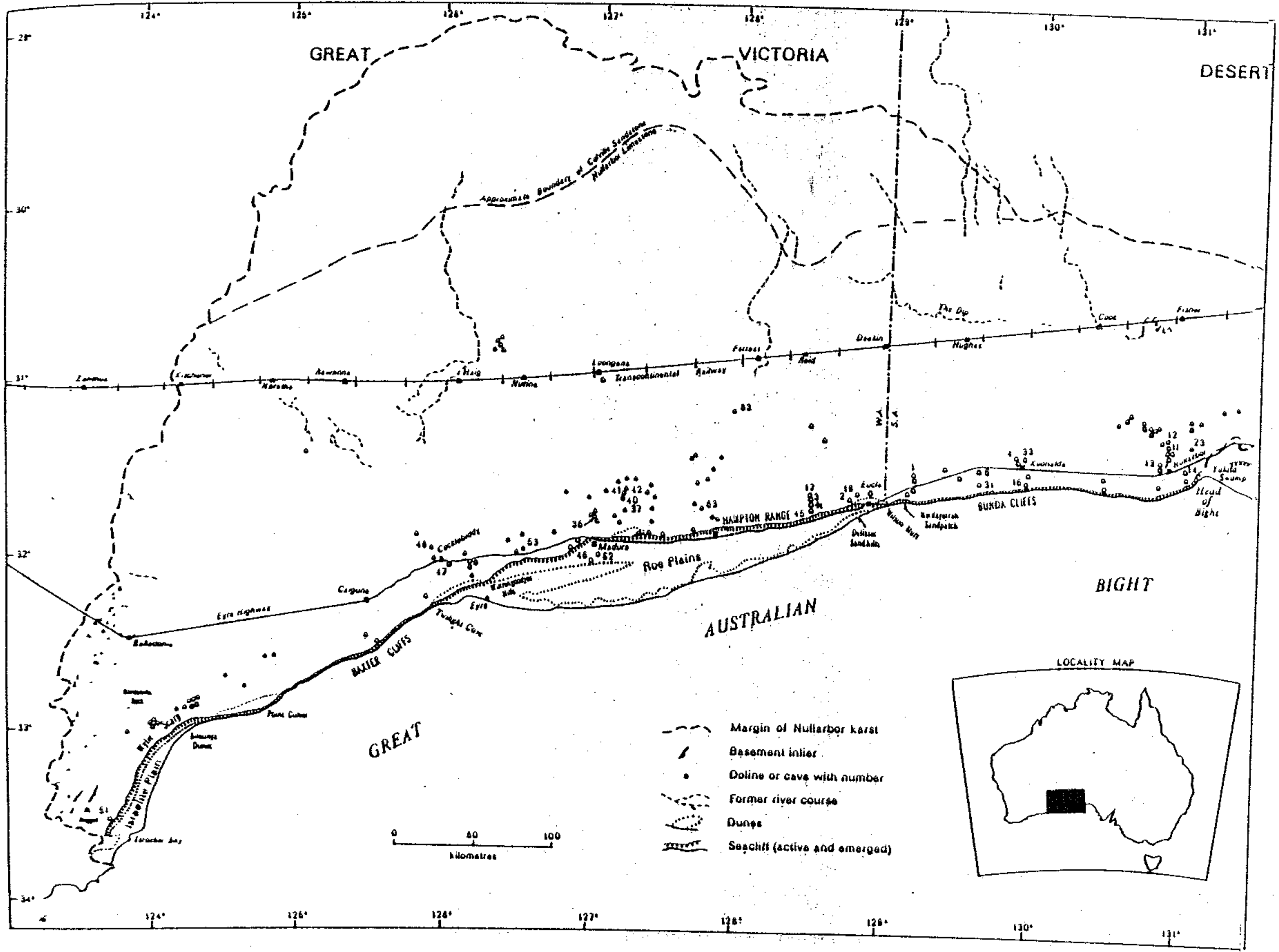


Fig. 16. Distribution of caves and dolines on Nullarbor Plain (from Lowry and Jennings 1974)

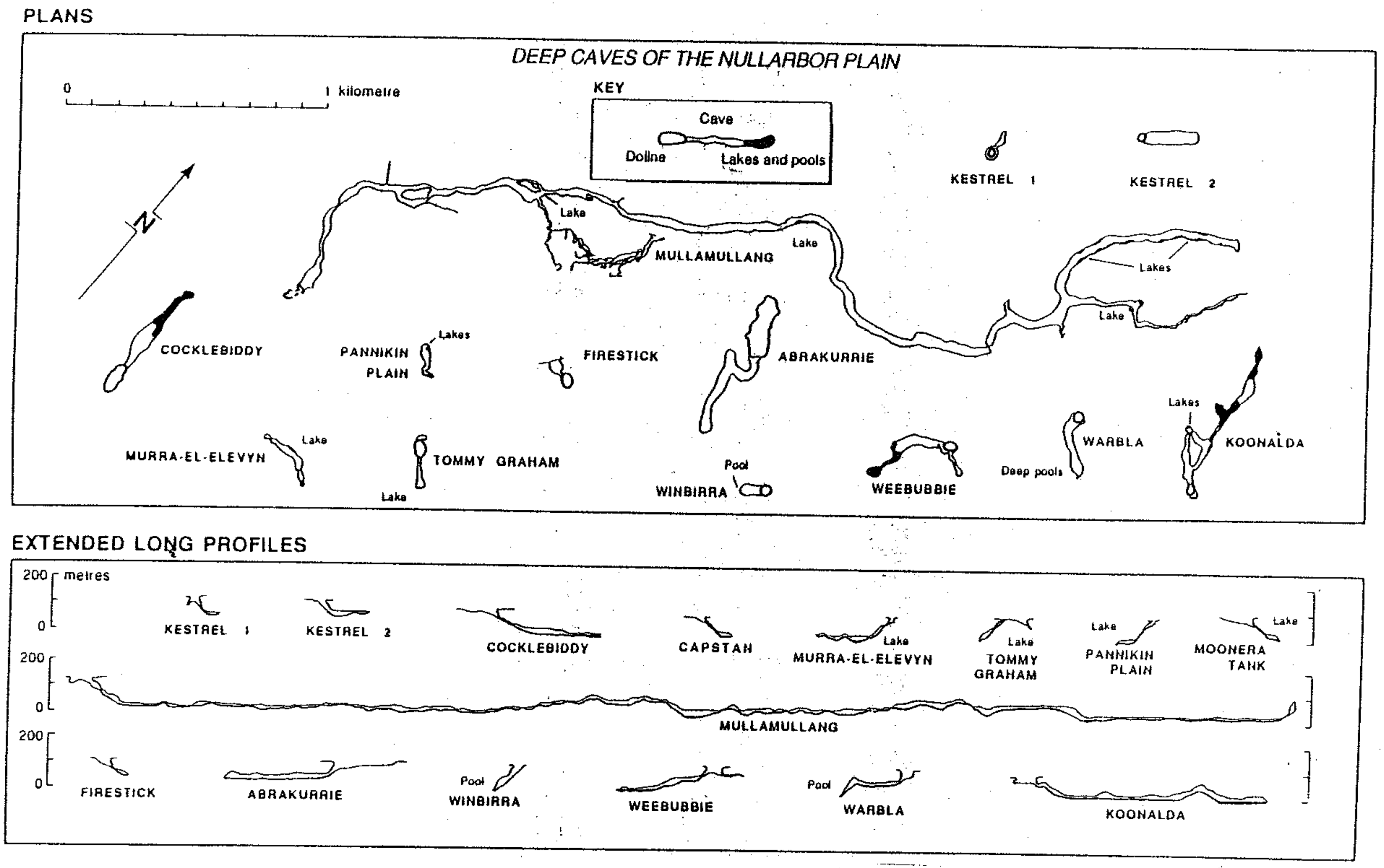


Fig. 17. Maps and cross-sections of representative caves; for locations, see Fig. 2 (from Gillieson and Spate 1992)

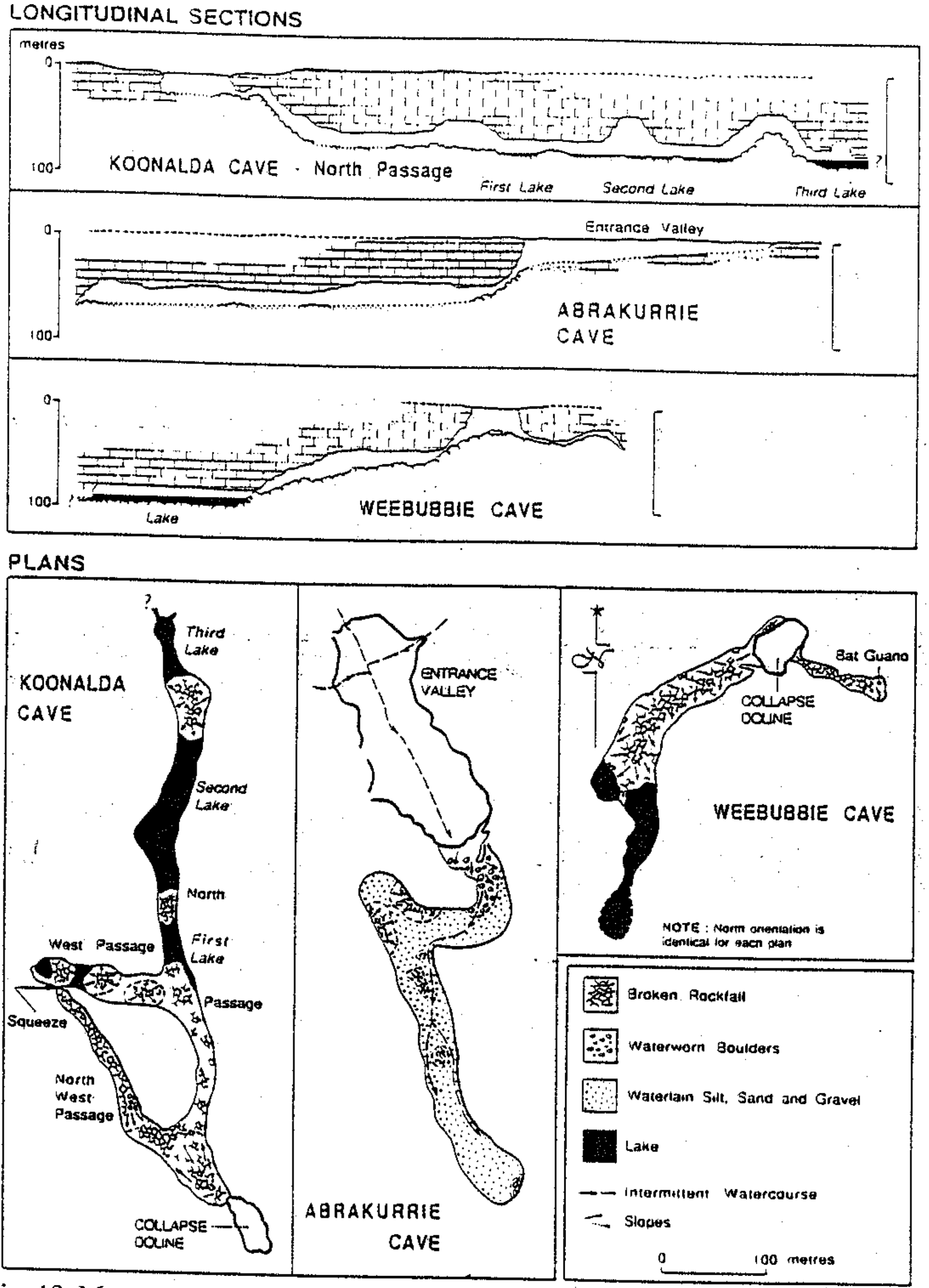


Fig. 18. Maps and cross-sections of Koonalda, Abrakurrie and Weebubbie Caves; for locations, see Fig. 2 (from Gillieson and Spate 1992)

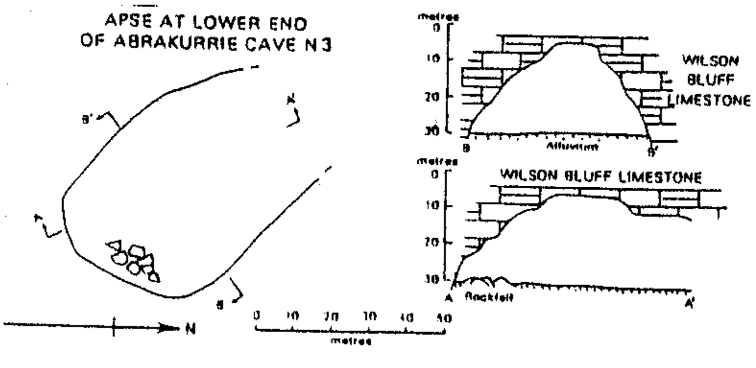


Fig. 19. Collapse form of Abrakurrie Cave; for location, see Fig. 2 (from Lowry and Jennings 1974)

time). The cave formed along joint planes, its overall north-south orientation determined by the coastwards flow of the groundwater. The cave drained when the water table dropped (due to uplift of the plain or a sea level fall), and collapse probably began almost immediately, forming breakdown chambers within the cave. In one of these chambers collapse continued until it breached the surface, creating the doline that is now the cave entrance.

A different, larger form of phreatic passage is present in Cocklebiddy Cave (Fig. 22). This cave is also entered through a collapse doline; a steep talus slope leads to a large breakdown chamber, at the far end of which is a lake of clear, salty, blue-green water. The water-filled passage beyond this has been shown by divers to extend over 6.5 km; parts have collapsed, but some sections represent a large phreatic tube, up to 40 m across and 30 m high, with a subcircular cross-section and large wall scallops (Grodzicki 1985, although James et al. in press regard the scallops as tafoni produced by salt wedging of the limestone). This passage formed by dynamic phreatic processes, i.e. slow continuous movement of large volumes of water. It is substantially larger than the phreatic passages in Old Homestead Cave, perhaps because it is closer to the coast (Fig. 2), and may represent a trunk system that had several tributary systems of the size of Old Homestead Cave. A drop in the water table has partially drained the passage, removing roof support and probably causing most of the collapse.

The caves described so far are all deep caves, extending 50-120 m below the surface of the plain; some are deep enough to reach the water table, and contain lakes of saline water (Fig. 17). They are almost all formed in the Wilson Bluff Limestone, although the entrances are generally within the Nullarbor Limestone (Lowry and Jennings 1974; Fig. 7).

There are also a number of shallow caves, less than 30 m deep. Some have formed entirely within the Nullarbor Limestone, others extend downwards into the underlying limestones. They are common on the eastern end of the plain and there are several north of Mundrabilla Homestead. Most are low collapse chambers, and their most notable feature is the presence of abundant dark brown to black calcite stalactites, stalagmites and flowstone. The Nullarbor is the only area in Australia where calcite decoration of this colour is so common. Stegamites, vertical shields of black calcite growing upwards from cracks in flowstone on the floor, are found in a few caves (Webb 1991). Their humped shape and rounded spines supposedly resemble a Stegosaurus, a dinosaur from the Cretaceous. The black calcite speleothems have been dated as more than 400,000 years old; at present they are being broken down by salt crystallising in cracks. Chemical studies have shown that the black colour is due to an intensely coloured humic compound, only milligrams of which are required to generate the black colour in kilograms of the Nullarbor calcite (James in press). The humic material is similar to the organic compounds, produced by the breakdown of vegetation, that stain swamp water a tea colour. This may indicate the presence of swamps on the plain at the time; perhaps the wet climatic phase about 3 to 5 million years ago could have been responsible for the black calcite deposition. Until the black calcite can be dated accurately, this remains very speculative. Black calcite is also present in a few of the deep caves, but most of these are almost devoid of calcite decoration.

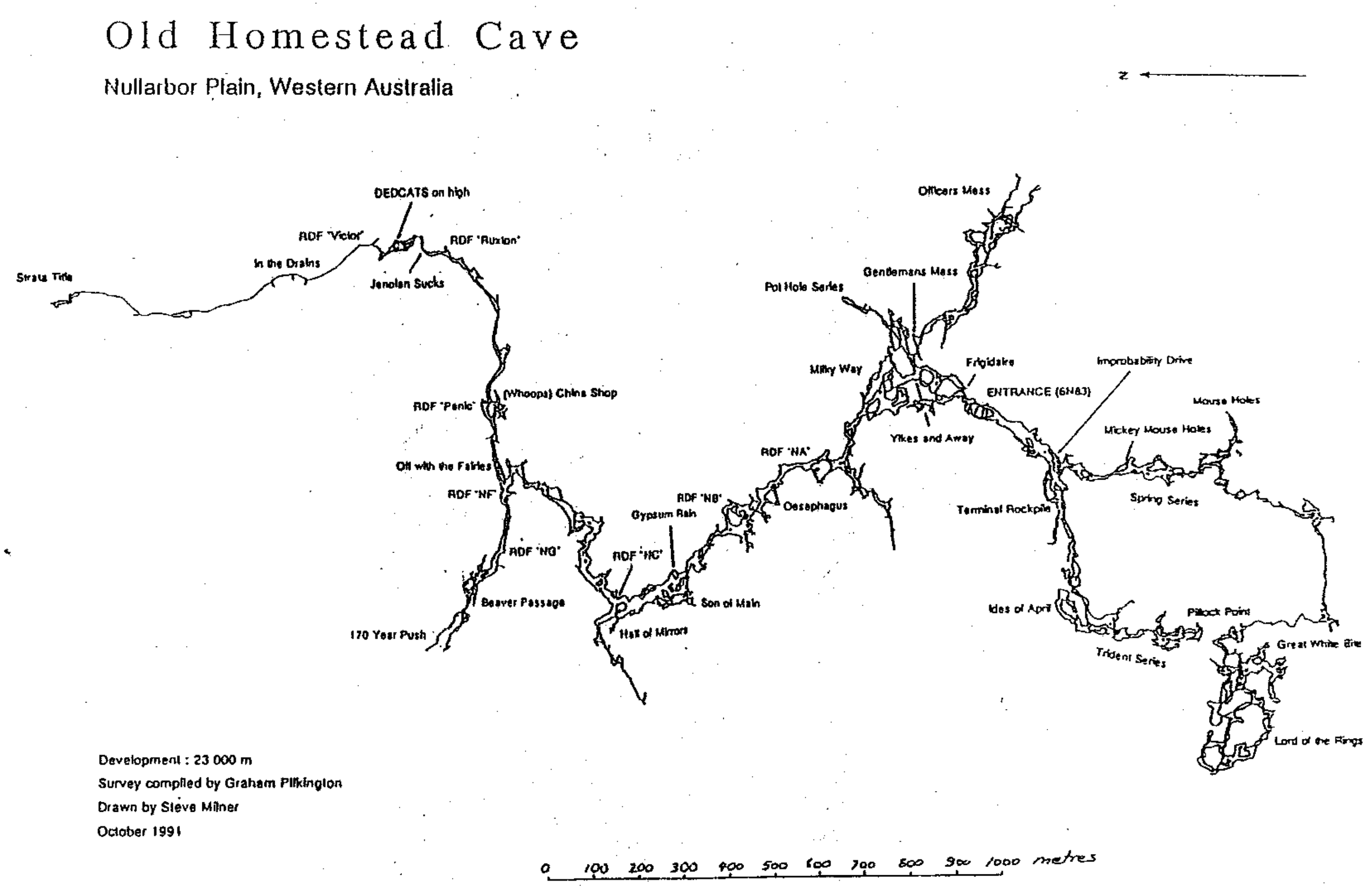


Fig. 20. Map of Old Homestead Cave; for location, see Fig. 2 (supplied by P.J. Ackroyd)

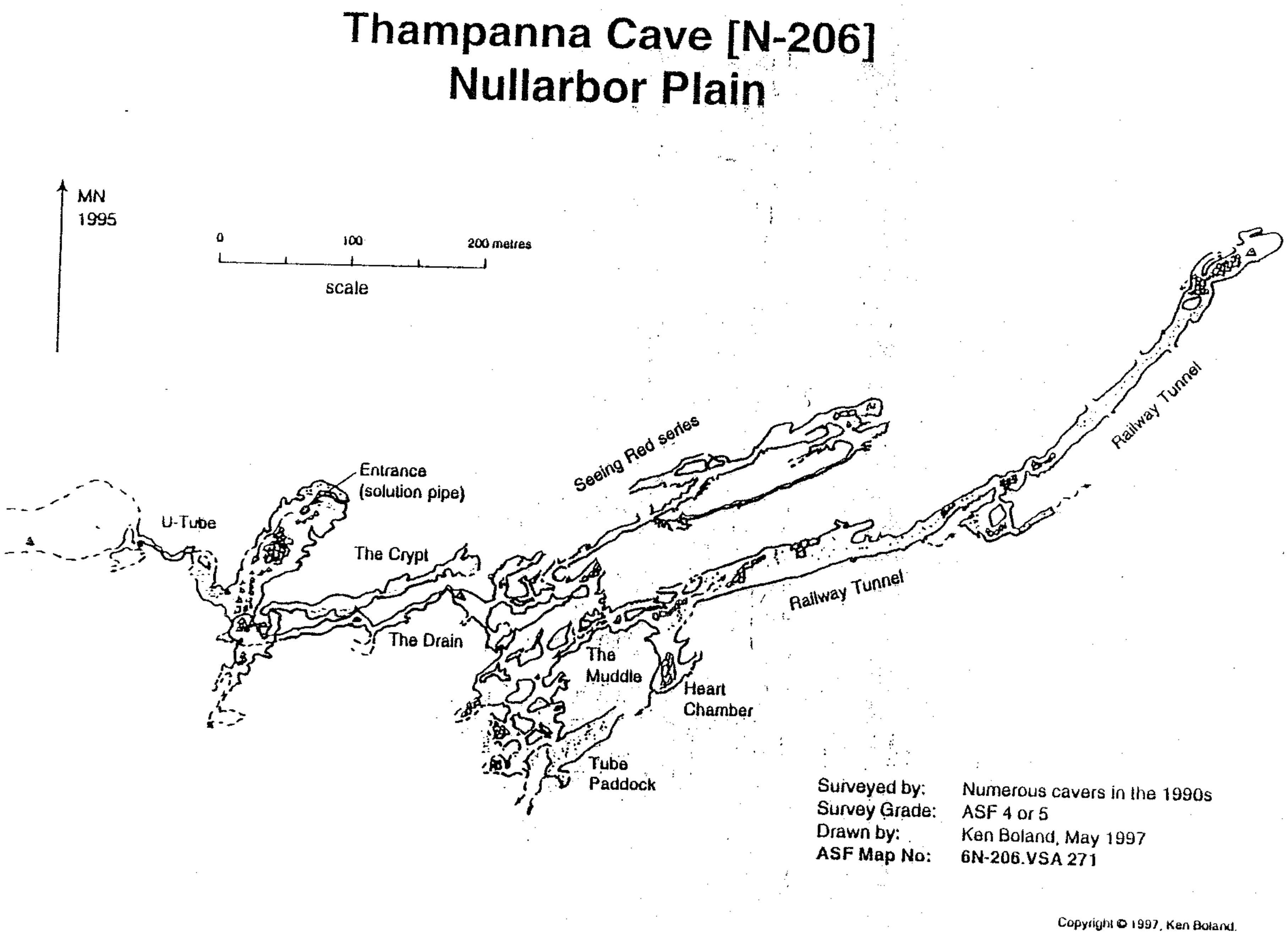


Fig. 21. Map of Thampanna Cave; for location, see Fig. 2 (from Boland 1997)

The limestone close to the surface of the plain is honeycombed with small irregularly shaped cavities generally less than 20 cm in diameter, as well as narrow sinuous tubes that are mostly concentrated along bedding planes and joint surfaces (Lowry and Jennings 1974). These tubes may fork and rejoin to form a complex anastomosing pattern. In Webb's Cave these tubes also occur along a fracture plane through a large flowstone boss of black calcite. The tubes may have formed due to solution beneath the present limestone surface (James et al. in press). Intense storms will dissolve the salts deposited by light rain and salt spray in the soil and near-surface limestone; the resulting saline water is more aggressive than fresh water (this is sometimes called the ionic strength effect) and can dissolve small cavities as it seeps down through the limestone.

Also present in the near-surface limestone of the Nullarbor are perhaps 100,000 blowholes, smooth-walled vertical tubes within the limestone, tens of centimeters to one meter across, and generally only a few meters deep, although occasionally they may be deeper (Lowry and Jennings 1974; Fig. 23). They are so-called because air draughts blow in and out of them, often strong enough to blow a hat into the air, or make a flag held across the hole flutter vertically; wind speeds of up to 70 km/hr have been recorded (James et al. in press). When the weather changes because a low or high pressure system moves across the plain, the surface air pressure decreases or increases, forcing air to blow out of or suck into the blowholes respectively. Some blowholes lead into large caves (at least 30 blowholes above Old Homestead Cave connect with the cave below), but most connect with the numerous small voids mentioned above. Many blowholes resemble the solution pipes in Quaternary limestones, and could have formed in a similar manner, i.e. beneath trees (see Quaternary section). Alternatively, blowholes may form by upward doming from the small underlying cavities, due to erosion of the limestone by salt wedging (Lowry 1968).

Decoration in the caves, apart from the black calcite already mentioned, is largely restricted to formations composed of gypsum and salt (halite). Gypsum forms golden yellow stalactites, as well as encrustations and curving crystal clusters ('flowers'). Salt occurs as white or clear crusts, straws and columns, often with smooth glassy surfaces from which project tiny cubic crystal shapes, as well as curving, wire- or hair-like helictites. A 2.7m long fallen column of salt, christened Big Salty, was found in one cave. The abundance of these minerals reflects the current arid climate; salt speleothems, in particular, will only form when the cave atmosphere is very dry. Dating of a gypsum and two salt speleothems gave ages of ~185,000 years and less than 40,000 years respectively (Goede et al. 1990, 1992), providing independent evidence that the present level of dryness in the Nullarbor caves was reached within the last million years (only recently in geological terms).

There is very little decoration below water level within the cave lakes. However, recent underwater exploration of one lake in Mullamullang Cave discovered a series of generally low, oval underwater phreatic passages at -4.5m. The walls are encrusted with brilliant white, short, sharp crystals; each crystal point is hollow. This is reputed to be one of the most beautiful submerged passages in Australia.

In Weebubbie Cave a very unusual speleothem type was discovered by cave divers. It consists of ordered concentric rings of microcrystalline calcite around gelatinous 'dreadlocks' produced by bacterial colonies, which festoon the walls and roofs of the water-filled passages (Contos 2001; James in press; James et al. in press). The floors below are snowfields of tiny calcite crystals or pavements of cemented calcite.

Some caves contain interesting phosphate and organic minerals, e.g. stercorite, aphthitalite, mundrabillite, archerite (Bridge 1973; Bridge and Clarke 1983; Martini 2002). These have formed by chemical reactions between the phosphate leached from piles of bat guano with the saline groundwater and the limestone of the cave floor. One species of bat, *Chalinobus morio*, has been recorded roosting in a number of Nullarbor caves, and Murra-el-elevyn may be the site of a maternity colony (Hamilton-Smith 1967).

The Nullarbor caves have a moderately diverse fauna, including a number of troglophile insect species, mainly cockroaches, beetles and crickets, and a troglobitic cockroach (Hamilton-Smith 1967). Peregrine falcons are known to nest in some caves. There is an almost complete absence of aquatic fauna, with only a troglobitic amphipod crustacean recorded from the very saline water of Nurina Cave (James et al. in press).

The very dry atmosphere of the caves has resulted in excellent preservation of some fossil remains. Mummified Tasmanian Tiger carcases, one dated to 4600BP, have been recorded in several caves (e.g. Lowry and Lowry 1967), as well as bones of the Tasmanian Devil. Both species were extinct on the mainland prior to European settlement. Other caves contain bones of Pleistocene megafauna, including giant kangaroos. A recently discovered cave contained a complete skeleton of the marsupial lion *Thylacoleo*. Around the large rockpile near White Lake in Mullamullang, some 2.5km into the cave, the desiccated remains of two people were found several years ago; the skeletons were about 70 years old.

Aboriginal usage of caves throughout Australia was generally restricted to camping, artwork and rituals in the entrance sections or overhangs; dark zones were avoided. However, one of the Nullarbor caves, Koonalda, was the site of extensive mining by aborigines of flint nodules from the cave walls, well within the dark zone, and spanning approximately 30,000 years (Frank 1971; Wright 1971). The flint breaks to give a sharp edge, and was used for stone tool manufacture. The cave walls also show early artwork, in the form of wavy lines and other patterns created by dragging the fingers over the soft limestone.

History of cave formation

There is some cave formation on the Nullarbor occurring at present; in particular there are periodic collapses within the caves, aided by salt crystallisation due to the current arid climate. In addition, small cavities just below the surface may be actively dissolving (as described above). However, there is probably little active dissolution of large caves going on at the moment, because groundwaters and cave waters are all saturated with respect to calcite, i.e. they cannot dissolve more limestone. Rainwater floods into the caves after heavy storms, and although this water can dissolve calcite, its effect is apparently relatively small, as shown by Old Homestead Cave. In this cave a system of small passages, often only tens of centimeters high and wide, slope gently away from the entrance (G. Pilkington pers. comm.); these are superimposed

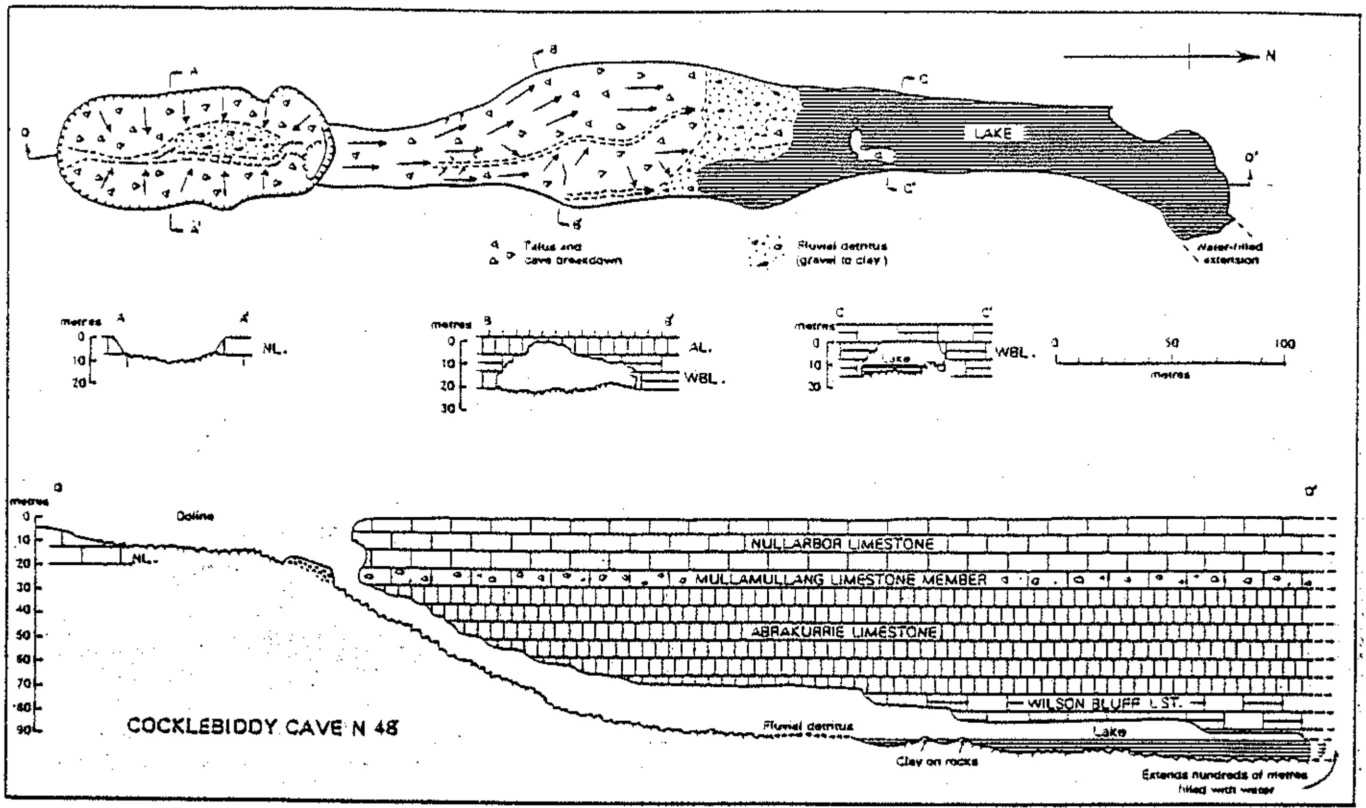


Fig. 22. Map and cross-sections of Cocklebiddy Cave; for location, see Fig. 2 (from Lowry and Jennings 1974)

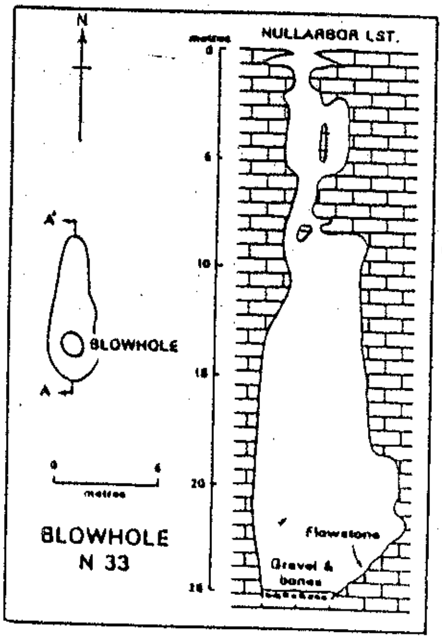


Fig. 23. Map and cross-sections of blowhole; for location, see Fig. 16 (from Lowry and Jennings 1974)

on the larger, horizontal phreatic system. It seems likely that these small passages formed due to rainwater input into the cave after the doline entrance had collapsed.

Some cave dissolution is also occurring at present due to mixing corrosion (James et al. 1990; James 1992). When rainwater flows into a lake cave, it forms a lighter surface layer of water, up to one meter thick, on top of the heavier saline water of the underground lake. The boundary between the two layers is called the halocline. As the two different water bodies mix, they form water with a new composition that can dissolve calcite. This process (mixing corrosion) is probably responsible for the notches in the walls around some lakes, notably in Cocklebiddy Cave. However, it may be causing calcite precipitation as well as dissolution (James in press). A stratified calcite flowstone over a kilometre long covers many metres of the lower passage walls and floor in the flooded passage of Cocklebiddy. This was probably deposited below the halocline, whereas above the halocline the limestone wall rock is being eroded. Thus the effects of present-day mixing corrosion seem to be relatively small.

Thus the main phase of cave formation was in the past. Cave development could have started when falling sea level exposed the Wilson Bluff Limestone to weathering from 35 to 25 million years ago, before deposition of the Abrakurrie and Nullarbor Limestones (Fig. 6). However, it is likely that the caves formed after the last retreat of the sea and uplift of the Nullarbor Plain around 14 million years ago. Thus the caves could have been forming more or less continuously for the last 14 million years, and for a large part of this time, the climate was wetter than at present. Around 14 million years ago the Nullarbor was probably covered in eucalypt woodland and rainforest grew along nearby river valleys (Fig. 11). The present level of aridity was only reached around one million years ago. However, if the climate has been wetter in the past, why isn't there more karst development? Why are there so few caves and dolines, given the vast size of the Nullarbor? Why is the surface so flat, and why is there so little solutional sculpturing?

It may be that flat plains of porous limestone cannot readily develop extensive underground and surface karst features, no matter what the climate. The Gambier karst in South Australia and Victoria (Webb and Grimes in press) is a flat plain of porous, flat-lying limestone the same age as the Nullarbor, with very gentle groundwater gradients, and has now, and probably always has had, around double the rainfall of the Nullarbor. However, like the Nullarbor, it also has relatively few caves and karst features given its size, and little surface solution sculpture. There are probably two factors involved. Firstly, the porosity allows rainfall to seep more or less uniformly into the limestone, and although groundwater flow is concentrated along a few joints which become caves, there is still substantial flow through the porous limestone itself. By contrast, in well-cemented, low porosity limestones like those of the Palaeozoic karst areas of Australia, groundwater flow is concentrated entirely along joints and faults, allowing greater cave development. Secondly, the flat outcrops of the limestone plains are unsuitable for the extensive formation of vertical solution sculpture like fluting.

The flat roofs in the phreatic sections of caves like Old Homestead indicate that at least some and probably most cave formation on the Nullarbor occurred in the shallow phreatic zone, at and just below the water table at that time. The fact that most caves are developed at only one level indicates that the water table was stable throughout their development. However, Mullamallang shows two levels separated by about 25m vertically, and the shallow caves probably formed at a different level to the deep caves, reflecting different positions of the water table, caused by sea level fluctuations and/or uplift of the plain.

Some caves, like Old Homestead, probably started to form where old river courses sank into the porous limestone (Fig. 2). The larger caves closer to the coast may represent trunk systems that had several tributaries of the size of Old Homestead Cave.

As noted already, most caves and dolines occur within 60 km of the coast (Fig. 16). This may reflect the fact that there has always been relatively greater rainfall near the coast; the additional rainfall would probably promote cave development. However, the belt of cavernous limestone lies parallel to the coast, and this is not the region of highest rainfall. The amount of rain decreases progressively along the coastline from southwest to northeast. Instead salt spray, blown a more or less uniform distance inland from the waves breaking on the coastal cliffs, may be responsible. Salt crystallisation would weaken the limestone (as described above), making caves in the coastal region more susceptible to collapse, opening entrances into them and forming dolines. Thus there may be many caves further from the coast, but entrances into them have not been opened by collapse. It is notable that Old Homestead Cave, about 100 km from the coast, has relatively little breakdown, and also lacks the halite speleothems that are prominent in caves closer to the coast (Martini 2002).

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