Karst features and remnant dune systems on the Nullarbor Plain, Australia

S. Burnett[1,2], J.A. Webb[1] and S. White[1,2]

[1] Environmental Geoscience Department of Agricultural Science, La Trobe University, Melbourne, VIC 3086, Australia.

[2] Victorian Speleological Association.

Abstract

The Nullarbor Plain covers an area of ~200,000 km², which makes it Australia's largest karst area and one of the world's great karst areas. This semi-arid environment is famous for its low relief, lack of vegetation and lack of surface water. This karst landscape is often considered featureless, but many karst landforms can be found including dolines, blowholes, dongas, relict river courses and caves, which contain a variety of speleothems (Davey *et al*, 1992; Lowry & Jennings, 1974).

Karst features (blowholes, dolines, shallow and deep caves) are not concentrated along the coastline, with a gradual northwards decline, as previously postulated. Instead they are concentrated in two bands running roughly parallel to the cliffed coast and the Hampton scarp (coastal scarp). A ~20km wide coastal band of features is seen only when all karst features are plotted on the one map. However the main band is a larger, higher concentration of predominantly blowholes, dolines and shallow caves between ~50-85km inland in the east and ~45-80km inland in the west. The shallow caves were probably formed by mixing corrosion associated with the seawater/freshwater interface along a Miocene coastline. Any deep caves have been formed by extensive modification by collapse processes.

Blowholes are the most numerous karst feature on the Nullarbor; they have an average density of 0.11/km^2 in the intensely searched areas, giving possibly ~22,000 blowholes for the entire area of the Nullarbor.

Introduction

The undulating landscape known typically as the Nullarbor Plain covers an area of ~200,000 km², which makes it Australia's largest karst area (Fig. 1). This semi-arid environment is famous for its low relief, lack of vegetation and lack of surface water. While often considered featureless, there are many karst landforms that can be found including dolines, blowholes, dongas, relict river courses and caves, which contain a variety of speleothems (Davey *et al*, 1992; Lowry & Jennings, 1974).

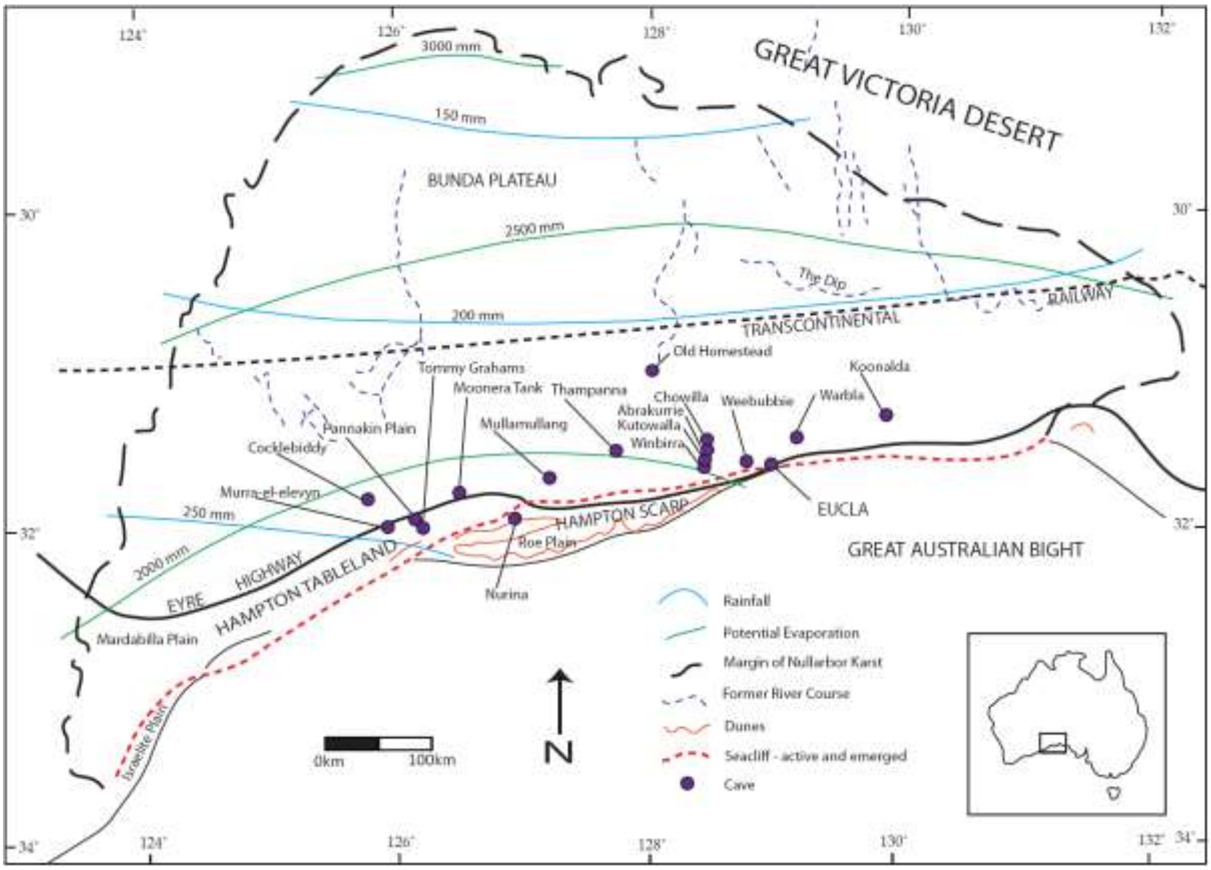

Figure 1 Map of the Nullarbor Plain area, showing location of main caves, rainfall, potential evaporation, margin of Nullarbor karst, relict river courses, dunes and seacliffs (after James, 1992).

Studies on the spatial relationships of the karst features of the Nullarbor Plain have been extremely limited to date, especially for studies utilising remote sensing. However, in the last few years, remote sensing studies have been undertaken, which includes work on the distributions of various karst features (Devine, 2010a; Devine, 2010b; Doerr *et al*, in prep). The physical characteristics of the different karst features found on the Nullarbor have undergone much more scrutiny than the spatial relationships; previous studies by authors such as Lowry & Jennings (1974) have had a rather limited sample size. This paper aims to investigate the spatial relationships and physical characteristics of the karst features on the Nullarbor Plain, while further investigating geomorphological processes involved in the evolution of these karst features.

Geology

The Tertiary limestones of the Eucla Basin comprise three main units of relatively flat lying limestone, which are partially covered with Pleistocene sediments (Benbow *et al,* 1995). During the Middle-Late Eocene marine transgression, up to 300m of the Wilson Bluff Limestone was deposited (Alley et al, 1999; Benbow *et al,* 1995; Gillieson & Spate, 1992). This is a fine grained, poorly sorted bryozoan calcarenite with high primary porosity but low permeability (James & Bone, 1992; Lowry & Jennings, 1974; Webb & James, 2006). It is partially overlain by a lens of minor grainy bryozoal Toolinna Limestone (Benbow *et al,* 1995). The Oligo-Miocene marine regressions and transgressions (Gillieson & Spate, 1992) resulted in the deposition of up to 100m of Abrakurrie Limestone in the Miocene (Benbow *et al*, 1995). This is a well sorted "yellow, coarse-grained bryozoan calcarenite and calcirudite" with both high porosity and permeability (Lowry & Jennings, 1974: 42). "The unit is composed of metre-scale subtidal cycles, each of which is capped by an erosion surface", despite the hard upper sections of the cycles the limestone is generally soft (James & Bone, 1992: 860). The short (less than 1m.y.) Miocene regression was probably a period of erosion and was followed by a transgression when the extensive 20-35m thick Nullarbor Limestone was deposited (Webb & James, 2006). This is a very fine to very coarse, poorly sorted grey-yellow calcarenite with low porosity and permeability (Benbow *et al*, 1995; Gillieson & Spate, 1992; James & Bone, 1992; Lowry & Jennings, 1974). During the Mid-Miocene, uplift, tilting and a global lowering of sea level exposed the surface of the Nullarbor (Gillieson & Spate, 1992; Hou *et al*, 2008). The Hampton Tableland and Scarp, an area on the southern edge of the Nullarbor Plain, shows denudation of the Nullarbor Limestone resulting in the Abrakurrie Limestone being exposed (Davey *et al*, 1992; Lowry & Jennings, 1974).

Geomorphology

The relatively flat "surface of the Nullarbor slopes very gently seaward" (Webb & James, 2006: 66). In the north-west region the surface of the Nullarbor Plain is 240m above sea level, sloping to 40-90m above sea level at the coastal cliffs (Davey *et al*, 1992; Webb & James, 2006). These vertical cliffs are 40-90m in height and are unbroken for some hundreds of kilometres along the coastline, except along the coasts of the Roe Plain (Fig. 1) and the Israelite Plain (Lowry, 1970; Webb & James, 2006).

Ridges and Swales are the undulating pattern that is found across the Nullarbor, especially south of the train line. A "donga" has been considered to be specific type of common doline, typically found in the north and east areas of the Nullarbor Plain (Davey *et al*, 1992; Gillieson & Spate, 1992). However, the physical characteristics and patterning of "dongas" suggest that they are the swale component of the ridge and swale landscape, which has not been previously recognised in the literature. “Dongas” are very shallow sub circular closed depressions with clay floors, 1.5-3m deep, and are up to 2km in diameter (Davey *et al*, 1992; Ford & Williams, 2007; Gillieson & Spate, 1992). “Dongas” will often carry rainfall runoff into blowholes and collapse dolines (Ford & Williams, 2007). In this study, “dongas” will be referred to as swales.

On the Roe Plain, Pleistocene sand dunes reach up to 91m high and the dune systems extend up to 96km inland (Lowry, 1970). Pleistocene sand dunes are also found on the Israelite Plain, which has well developed active dunes at its northern end; older dunes are more inland and are well vegetated (Lowry, 1970; Lowry & Jennings, 1974). There are also clifftop dunes that have formed when wind piles up sand to form a ramp, which will eventually reach clifftop and create dunes (Davey *et al*, 1992; Lowry & Jennings, 1974).

Older linear vegetated dunes, each up to ~7.5km long and up to 1km apart can be found ~2km directly west of Thampanna Cave (N206). Red aeolian sands have been found in numerous caves in the south-east part of the Nullarbor Plain, and are composed of sub-rounded to rounded quartz sand grains with minor amounts of calcareous fragments from the host limestone (Spate *et al*, 1984). Linear dune formation is thought to be due to either ‘parallel counter-rotating helical roll atmospheric vortices in unimodal wind regimes’ (Hanna, 1969; Lancaster, 1994; Thomas, 1997), or in response to bidirectional winds or wide unimodal winds (Lancaster, 1994; Thomas, 1997).

Although the Nullarbor Plain has quite a number of karst landforms, most are subdued in nature and found within 60km of the coast (Webb & James, 2006). Over 150 collapse dolines are known on the plain, many of which are heavily eroded and show evidence of significant collapse. Much smaller in size (1-2m in diameter and 1.5-10.5m deep) but more numerous are blowholes (Lowry, 1968; Webb & James, 2006). Both shallow and deep caves are found and can be typically accessed through collapse dolines or blowholes (Webb & James, 2006). Shallow caves less than 40m deep may have speleothems present (Lowry & Jennings, 1974). However, speleothems are considered scarce on the Nullarbor Plain (Lowry & Jennings, 1974; Webb & James, 2006). The deep caves can extend up to 150 m below the present surface and intersect the water table, forming lakes (Lowry & Jennings, 1974; Webb & James, 2006). The deep caves all terminate in boulder blockages due to extensive collapse activity (Webb & James, 2006). Surface solution features such as karren are either absent or very poorly developed on the Nullarbor, but limestone pavements are extensive (Davey *et al*, 1992).

A number of meandering relict stream channels are located on the northern and western boundaries of the Nullarbor Plain (Gillieson, 2003; Webb *et al,* 2003). These relict river channels first formed in the Cretaceous, and have been inactive since the Middle Miocene emergence of the plain and now are infilled with alluvium and aeolian deposits (Alley *et al*, 1999; Devine, 2010a; Gillieson, 2003). These relict streams expanded onto the

Nullarbor Plain after its emergence in the Miocene (Devine, 2010a). Relict streams on the limestone have their headwaters in the north of the plain (Devine, 2010a; Jennings, 1967b; Lowry & Jennings, 1974). The Dip, is the longest and largest of these at 130km long, and is a chain of depressions, each up to 6-9m deep and 7km in length (Jennings, 1967b; Lowry & Jennings, 1974). All these relict river channels terminate well north of the coast (Lowry & Jennings, 1974).

Methods

Field data from various expeditions to the Nullarbor were entered into a spreadsheet; sites were split up into two data sets. Firstly a detailed data set containing 1412 sites from VSA led expeditions and N1-N225 was used in the analysis of the physical characteristics. A second less detailed data set containing 3948 sites was then used in the analysis of the spatial relationships of the karst features (except karst site position relative to ridges and swales), analysis was done in the Global Mapper 9 program.

Results and Discussion

Blowhole Physical Characteristics

Blowholes are by far the most common karst features on the Nullarbor except for rockholes. 1140 blowholes have been recorded; 62.4% occur in dolines and 39.5% are entrances into shallow caves. Therefore vertical blowhole entrances are the most common cave entrance type (~73%) (Table 1). Many blowholes interconnect with each other through small voids and shallow caves, and a high number have extensions that end in inaccessible squeezes (Davey *et* al 1992; Gillieson & Spate, 1992), that may connect into unentered caves (Webb & James, 2006)

Table 1 The different feature entrance types and the number of each

Entrance Type	Number of Sites	Percentage of total sites
Collapse	13	1.00%
Horizontal entry	50	3.85%
Horizontal blowhole	5	0.38%
Inclined entry	52	4.00%
Inclined blowhole	56	4.31%
Inclined slot entry	2	0.15%
Vertical blowhole	930	71.70%
Vertical entry (non-blowhole)	174	13.41%
Vertical slot entry	15	1.15%

Blowholes were previously described as circular in section, ranging from tens of centimetres in diameter and 2m in depth, to 1.8m in diameter and 10.5m in depth (Lowry, 1968; Lowry & Jennings, 1974; Webb & James, 2006). However, the present data analysis shows that blowholes are generally subcircular, with long axes ranging from 0.05m to 15m (median is 0.60m) and short axes ranging from 0.1m to 15m (median 0.45m). Blowhole depth ranges from 0.1m to 35m (median 2.6m). Blowhole entrances may occasionally be narrow slots.

Shallow Cave Physical Characteristics

Of the documented Nullarbor caves, 529 (86.6%) are shallow (<40m in depth) with a median depth of only 4m. Most entrances to these shallow caves (75%) are located in a doline, this characteristic is much more common than previously stated e.g. Davey *et al*, (1992). The most common entrance type is a vertical blowhole; 81% of shallow Nullarbor caves have some sort of blowhole entrance.

The median length for shallow caves is only 7m, and only a few caves are > 100m in length; the longest, Nurina Cave (N46), is 505m long. The generally short cave length may be a result of extensive collapse (Webb & James, 2006).

There is a significant relationship between length and depth for shallow caves <50m long (Figure 5.6), i.e. short caves are also very shallow. However, no relationship exists between depth and length for caves longer than ~80m, and 5 shallow caves including Nurina Cave (N46) and Webb's Cave (N132) are ~500m in long.

Shallow caves commonly consist of a blowhole entry with a single chamber or passage at the bottom of the shaft. Although cave chambers and passages are not recorded consistently in the database, 48.4% of shallow caves are recorded as containing "chambers", and 7.75% have more than one chamber; 68.6% of shallow caves have "passages" and 13.5% have multiple "passages". Shallow cave chambers and passages on the Nullarbor are usually quite small (Table 2). However, there are a few exceptions; Kangaroo Cave (N4156) has a chamber 350m long, and Witches Cave (N193) has a chamber 150m wide (wider than any chamber recorded in a deep cave) and 16.1m in height. Shallow caves are slightly longer and deeper in Western Australia (median length 8.8m, median depth 5m) than South Australia (6.6m and 3.9m respectively).

Table 2 Shallow cave chamber characteristics

Characteristic	Dimensions
Minimum length	0.52m
Maximum length	350m
Median length	7.3m
Minimum width	0.48m
Maximum width	150m
Median width	4m
Minimum height	0.3m
Maximum height	16.1m
Median height	1.85m

Deep Caves

Of the documented Nullarbor caves, only 27 (13.4%) are deep caves (>40m depth); 86.9% of entrances to these caves are located in a doline, often collapse dolines (Webb & James, 2006), particularly for large caves, e.g. Weebubbie Cave (N2). Even though many collapse dolines do not lead to accessible deep caves (Gillieson and Spate, 1992), there may be significant numbers of caves with no surface entrances underneath these dolines. Unlike shallow caves, the most common deep cave entrance type is not a vertical blowhole but a horizontal/inclined cave entrance, due to collapse of cave roofs. Deep cave entrances are typically located in the sides of large collapse dolines.

For deep caves, the median length is 227.5m and the depth is 91m, including the depth of any doline; the deepest is Mullamullang Cave (N37) at 143m depth. The median cave length is 227.5m; the longest, Old Homestead (N83), is 28,460m long. The generally short length compared to deep caves elsewhere in the world is probably a result of extensive collapse, due at least partly to crystallization of evaporite minerals within the cracks and intergranular porosity of the limestone (Webb & James, 2006). The collapse materials would have infilled the caves, reducing both their overall size and their accessible depth. There is a no relationship between deep cave length and depth, as the 14 caves with depths > 80m are deeper than the longest Nullarbor cave (Old Homestead).

Passages are quite large in deep Nullarbor caves, and deep cave chambers are significantly larger than for shallow caves (Table 3), e.g. Cocklebiddy Cave (N48) has a chamber 360m long. Deep caves can have very simple passage plans such as shallow caves e.g. Cocklebiddy Cave (N48), or very complex plans, such as Old Homestead (N83), and may be maze like and cover multiple levels.

Table 3 **Deep cave chamber characteristics**

Characteristic	Chamber
Minimum length	30m
Maximum length	360m
Median length	80m
Minimum width	14m
Maximum width	45m
Median width	30m
Minimum height	2m
Maximum height	5m
Median height	3m

Speleothems

Speleothems are generally uncommon and are only recorded in 8% of Nullarbor caves. Speleothems are more likely to be present in caves that contain chambers, e.g. shallow caves such as Webb's Cave (N132) and deep caves such as Weebubbie Cave (N2). Speleothems are occasionally present in blowholes, e.g. 5N4533 or 5N4622. The black/ brown calcite speleothems have been regarded as the most common form (Davey *et al*, 1992; Webb & James, 2006), but this is not supported by the data, as only 8 out of 30 calcite speleothem sites had black/brown calcite. The most common type of speleothem is stalagmites, recorded at 17 sites. Current dating methods have dated Nullarbor speleothems as old as 4Ma and ~8Ma (Prideaux *et al*, 2007; Woodhead *et al,* 2006; Woodhead, 2010, personal commun.).

Dolines

Most caves in the Nullarbor are located in a doline (74.4%). However, the data did not allow for differentiation between the different types of dolines. Previously it was thought that many dolines do not contain any features such as caves (Davey *et al*, 1992; Gillieson & Spate, 1992), but this is not true, as 45.2% of dolines contain caves. Dolines are sites of ground water recharge to the water table (Commander, 1990; Gillieson & Spate, 1992; Gillieson *et al,* 1994); water that flows into dolines can also erode any infilled or plugged features and enlarge existing features.

Dolines that contain caves are on average deeper, wider and longer than dolines that contain just blowholes or no significant features (Table 4). What is not expected is that dolines with no significant features, scattered across the Nullarbor, are actually the largest in terms of length, width and depth on average than the dolines with blowholes or caves

(Table 4). These may be collapse dolines that have been infilled with clay and have undergone erosion. Dolines containing just blowholes had the smallest median length, width and depth (Table 4). This may be evidence of solutional processes, as if collapse processes had occurred, these dolines would be larger. Dolines containing caves or insignificant features are typically sub-circular in shape, but dolines with blowholes are typically much more circular.

Table 4 Physical measurements of different types of dolines. *Note: insignificant features refer to pavement and rockholes.

Characteristic	**Dolines with cave(s)**	**Dolines with blowhole(s)**	**Dolines with insignificant feature(s)***
Minimum length	0.7m	0.5m	1.5m
Maximum length	290m	105m	240m
Median length	10.3m	8m	25m
Minimum width	0.7m	0.5m	1m
Maximum width	100m	85m	210m
Median width	8.5m	5.5m	19m
Minimum depth	0.05m	0.1m	0.3m
Maximum depth	43m	23m	18m
Median depth	1m	0.70m	1.6m

Karst Feature Distribution

Previous workers have recognised that there is a concentration of karst sites along the Nullarbor coastline and a general decrease in the number of features further inland (Gillieson & Spate, 1992; Jennings 1967b; Lowry & Jennings, 1974; Webb & James, 2006). Shallow surface depressions were reported to be extensive by Gillieson *et al*, (1992), but deep caves are mostly found within 60km of the coast (Webb & James, 2006), and Lowry and Jennings (1974) noted that collapse dolines also mainly occur within 60km of the coast.

The present study has shown that most karst sites are found south of the Trans-Continental Railway, 102km north of the coast, although the most northerly karst site (5N320) is 233km from the coast. There is no gradual northwards decrease in karst sites (Figure 2). A relatively high concentration band of karst sites runs parallel to the coastal scarp, inland of the Hampton Scarp backing onto the Roe Plain (Figure 2); in the far east and west of the Nullarbor Plain this band is up to ~40km from the coast (Figure 2). Most deep caves are located in this band. However, the highest concentration of karst features forms another band further inland, roughly parallel to the coast and between ~50-85km inland in the east and ~45-80km inland in the west (Figure 2). Both bands are parallel to the coastal Scarp (old shoreline) rather than the present coastline.

These two bands are not clearly identifiable in the far west of the Nullarbor (Figure 2), but this may just reflect the limited exploration in this area. Remote sensing work on the Mardabilla Plain in the south west of the Nullarbor using Google Earth has identified over 1000 previously unknown karst features in an area of ~7000km^2 (Devine, 2010b), and the far west of the Nullarbor may be shown to have a similar number of karst sites to the central and eastern Nullarbor if appropriate analysis were done. The total density of karst sites on the Nullarbor is 0.12 per km^2 (1 site per 8.3km^2). There is a density of 0.11 blowholes per km^2 (1 blowhole per 9.1km^2). Applying this figure to the ~200,000km^2 area of the Nullarbor, assuming uniform density across the plain, gives an estimated ~22,000 blowholes.

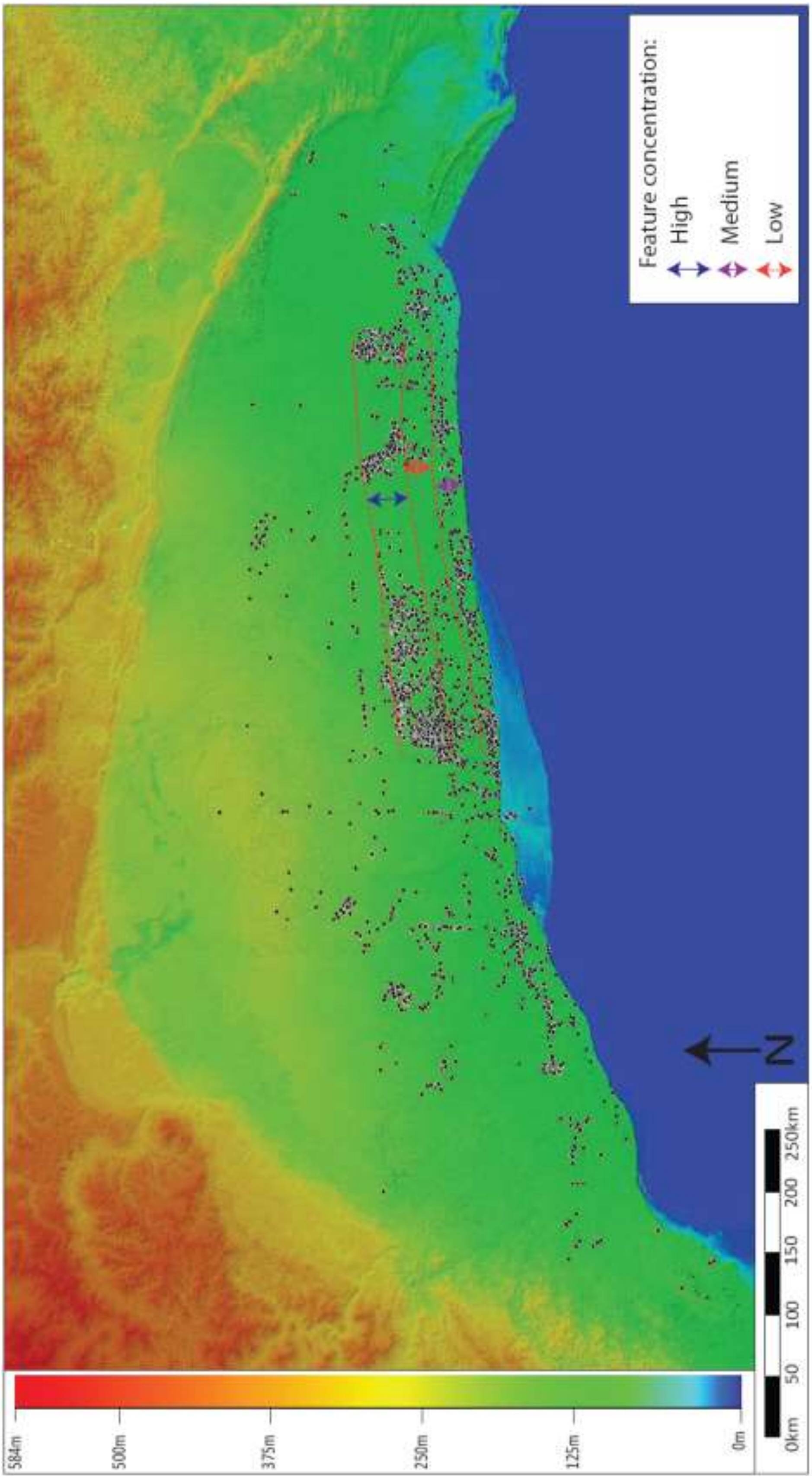

Figure 2 **Distribution of karst sites on the Nullarbor Plain, including: blowholes, caves and dolines.**

Blowhole, Shallow Cave and Deep Cave Formation

The high concentration band of shallow caves and blowholes is probably parallel to, and just inland, of an old shoreline (coastal scarp), and formed during a sea level stillstand, explaining the lack of a gradual inland decrease in density of karst sites. This stillstand may have occurred ~15Ma, during the regression that first exposed the surface of the Nullarbor Limestone, when the shoreline probably lay at the southern edge of the band of highest karst concentration. In order to form parallel to the shoreline, the shallow caves and blowholes must have formed before the Miocene tilting (Hou *et al,* 2008) of the plain occurred. At this time the climate was relatively humid, and there were perhaps streams on the ground surface (Alley *et al,* 1999; Benbow *et al*, 1995; Webb and James; 2006). The watertable would have been shallow and ground water may have been much less saline than present. Mixing corrosion could have occurred at the top of the fresh water lens and at the halocline at the base of the freshwater lens, as explained by the Ghyben-Herzberg Principle, making the water aggressive and increasing its ability for dissolution (Ford & Williams, 2007; Mylroie and Carew, 2000; White, 2005).

The relative lack of shallow caves and blowholes south of the high concentration band represents the area that was inundated with sea water when the shallow caves were developing. As sea water is saturated with respect to calcite, dissolution of limestone seaward of the shoreline is inhibited (Ford & Williams, 2007).

A fresh water/salt water interface presently occurs on the Nullarbor in flooded passages and lakes of caves, after heavy rainfall events when fresh inflow forms a layer on top of the saline lake (James, 1992). However, this plays only a minor role in cave development. The deep caves probably formed by conduit development in the Oligocene and collapse in the Miocene. This is significantly different from the development of small shallow caves close to the shoreline, which were probably associated with the seawater/freshwater interface.

The low number of deep caves probably reflects restricted karst development on the Nullarbor, due to the flatness of the ground surface, porosity and permeability of the limestone, and lack of jointing (Webb & James, 2006). The flatness of the ground surface and lack of jointing causes uniform infiltration of rainwater, rather than concentrating groundwater preferentially along the jointing, causing dissolution and cave development (Lowry & Jennings, 1794; Webb & James, 2006). The relative weakness and high porosity of both the Wilsons Bluff and Abrakurrie Limestones contributed to the collapse and breakdown of larger caves (Lowry & Jennings, 1794; Webb & James, 2006). The lack of inception horizons also inhibits karst development (Webb & James, 2006).

Karst Site Position Relative to Ridges and Swales

The number of sites on a ridge is always greater than that in a swale, although the ratio of sites on a ridge compared to a swale changes depending on location and there is no clear pattern. The search areas in Western Australia do not have significantly more features either on a ridge or in a swale, than the areas in South Australia (Table 5). The west of the Nullarbor has greater relative relief than the east, so the amount of relative relief is not related to the position of sites.

Table 5 Number of karst sites located on a ridge or in a swale

	South Australia	Western Australia
Sites on ridges	602	436
Sites in swales	66	83
Total number of sites	668	519

The relative lack of sites in swales can be explained by the infilling of features or plugging of entrances, so it is possible that the swales contain a similar number of karst sites as the ridges. Many caves (e.g. 5N4663) have significant amounts of aeolian sediment infill (Spate *et al*, 1984), which over time may completely plug entrances, e.g. the three so called '*Thylacoleo* caves', famous for their Pleistocene vertebrate fossils, relatively recently lost their entrance plugs (Prideaux *et al*, 2007; White, 2010, personal commun.) Features in swales are also commonly blocked by clay which is an efficient entrance plug, as it resists the abrasive power of the wind (Brady & Weil, 2008). Clay soil dispersion can seal the ground surface, limiting groundwater recharge into the blocked features (Brady & Weil, 2008; Commander, 1990). The sediment in the features may be washed into the underlying network of channels, cracks, conduits and voids (Worthington, *et al,* 2000) and infill the entire feature.

Ridge and Swales

The ridges and swales described earlier are up to a kilometre wide with a relative relief of 1.5-3m in the east increasing to 3-6m in the west. From west to east across the plain the ridge and swale corridors change orientation from north-south, to southwest-northeast, east-west, then northwest-southeast. This pattern of ridges and swales has previously been attributed to joint control (Lowry & Jennings, 1974).

Analysis suggests these ridges and swales are the footprints of an extensive dune system. The ridges and swales have the characteristics of linear sand dunes; they are parallel, regularly spaced and have spurs that connect the ridges, and generally fork northwards in the western most north-south dune set. A previously undescribed well-vegetated linear group of dunes with an east-west orientation, each up to ~7.5 km long and up to 1 km apart have been found ~2km directly west of Thampanna Cave (5N206). The ridges and swales of this remnant dune system align with the nearby ridges and swales on the surface of the plain. The ridges and swales formed from the increased dissolution of the limestone of the plain beneath the swales, due to water collecting in the swales of the dunes. The remnant dunes are yet to be ground truthed.

Conclusion

Known karst sites (features) on the Nullarbor Plain are almost all located south of the trains-continental railway. No gradual northwards decrease in concentration is evident and two bands of high karst site concentrations occur, roughly parallel to the present cliffed coast and Hampton Scarp (coastal scarp). The previously recognised ~20km wide coastal high concentration band is present only when all karst features are plotted on the one map. This is not the highest karst site concentration on the Nullarbor. The main band is a larger and higher concentration band of predominantly blowholes, dolines and shallow caves ~50-85km inland from the coastal scarp in the east and ~45-80km inland the coastal scarp in the west. Despite the higher density in the two bands of high concentration, the overall density of sites is only 0.12 per km^2 (1 site per 8.3km^2).

The shallow caves probably formed as a result of mixing corrosion related to the coastal Ghyben-Herzberg freshwater/seawater interface. Deep caves have been modified by collapse processes. Deep caves are generally all close to the coast, and deep caves typically do not have a blowhole entrance.

Almost all caves on the Nullarbor are small shallow caves, which have a blowhole entrance and have a median length of 7m. Shallow caves generally consist of a single chamber or passage at the bottom of a blowhole shaft. Blowholes are subcircular, varying in size from 0.05m to 15m in width and from 0.1 to 35m in depth. Blowholes are the most common karst feature 0.11 per km^2 (1 site per 9.1km^2), with an estimated ~22,000 across the Nullarbor.

The surface of the Nullarbor is covered by an undulating landscape of relatively low relief ridges and swales; the swales are commonly known as dongas. These ridges and swales are not a result of joint control as previously stated, but instead represent the footprints of eroded dune systems. The swales formed from incision due to dissolution of limestone from water collecting in the swales. One remnant dune system west of Thampanna Cave (5N206) was identified. The accessible karst features are overwhelmingly located on the apex or slope of ridges, as the karst features in the swales are infilled with clay or have entrance plugs.

References

Alley, N.F., Clarke, J.D.A., Macphail, M., and Truswell, E.M., 1999, Sedimentary infillings and development of major Tertiary palaeodrainage systems of south-central Australia: *Special Publications of the International Association of Sedimentologists*, **v. 27**, p. 337–366.

Benbow, M.C., Alley, N.F., Callen. R.A., and Greenwood, D.R., 1995, Geological history and palaeoclimate, *in* Drexel, J.F., and Preiss, W.V., eds., *The geology of South Australia. Volume 2,* The Phanerozoic: *Geological Survey of South Australia Bulletin*, **v. 54**, p. 208-218.

Brady, N.C., and Weil, R.R., 2008, *The Nature and Properties of Soils, 14th ed.*: New Jersey, Pearson Education International, 975 p.

Commander, D.P., 1991, Outline of the hydrogeology of the Eucla Basin, *in Proceedings of the International Conference on Groundwater in Large Sedimentary Basins*, Perth, 1990: Canberra, Australian Government Publication Service, p. 70–78.

Davey, A.G., Gray, M. R., Grimes, K.G., Hamilton-Smith, E., James, J.M, and Spate, A.P., 1992, *World Heritage significance of karst and other landforms in the Nullarbor region*: Canberra, Commonwealth of Australia: Department of the Arts, Sport, the Environment and Territories, 202 p.

Devine, P., 2010a, Relict Palaeorivers of the Western Nullarbor and their associated Karst Features, *in Proceedings of the 26th Biennial Conference of the Australian Speleological Federation*, Mount Gambier, 2007: South Australia, Cave Exploration Group (South Australia) Incorporated, 15 p.

Devine, P., 2010b, The Karst features of the SW Nullarbor - Mardabilla Plain & adjacent localities, *in Proceedings of the 26th Biennial Conference of the Australian Speleological Federation*, Mount Gambier, 2007: South Australia, Cave Exploration Group (South Australia) Incorporated, 20 p.

Doerr, S.H., Davies, R.R., Lewis, A., Pilkington, G., Webb, J.A., Ackroyd, P.J., and Bodger, O., in prep 2010, Origin and karst geomorphological significance of the enigmatic Australian Nullarbor Plain 'blowholes', unpublished.

Ford, D., and Williams, P., 2007, *Karst Hydrogeology and Geomorphology*: England, John. Wiley & Sons Ltd., 562 p

Gillieson, D., 2003, Nullarbor Plain, Australia, *in* Gunn J., eds., *Encyclopedia of Caves and Karst Science*: New York, Routledge, p. 544-546.

Gillieson, D., and Cochrane, J.A., and Murray, A., 1994, Surface Hydrology and soil movement in an arid karst: the Nullarbor Plain, Australia: *Environmental Geology*, **v. 23**, p. 125-133.

Gillieson, D., and Spate, A., 1992, The Nullarbor Karst, *in* Gillieson D., ed., *Geology, climate, hydrology and karst formation: IGCP Project 299, Field symposium*: Canberra, Department of Geography and Oceanography, Australian Defence Force Academy Special Publication, **v. 4**, p. 65-99.

Hou, B., Frakes, L.A., Sandiford, M., Worrall, L., Keeling, J., and Alley, N.F., 2008, Cenozoic Eucla Basin and associated palaeovalleys, southern Australia — Climatic and tectonic influences on landscape evolution, sedimentation and heavy mineral accumulation: *Sedimentary Geology*, **v. 203**, p. 112–130.

James, J., 1992, Corrosion par mélange des eaux dans les grottes de la Plaine de Nullarbor, *in* Salomon, J.N., and Marie, R., eds., *Karst et evolutions climatiques*: Bordeaux, France, Presses Universitaires de Bordeaux, p. 333-348.

James, N.P., and Bone, Y., 1992, Synsedimentary cemented calcarenite layers in Oligo-Miocene cool-water shelf limestones, Eucla Platform, southern Australia: *Journal of Sedimentary Petrology*, **v. 62**, p. 860–872.

Jennings, J.N., 1967b, The Surface and Underground Geomorphology, *in* Dunkley, J. R., and Wigley, T. M. L, eds., *Caves of the Nullarbor*: Sydney, The Speleological Research Council Ltd, p. 13-31.

Lancaster, N., 1994, Dune morphology and dynamics, *in* Abrahams, A.D., and Parsons, A.J. eds., *Geomorphology of desert environments*: London, Chapman & Hill, p. 474-505.

Lowry, D.C., 1968, The origin of blow-holes and the development of domes by exsudation in caves of the Nullarbor Plain, *in Geological Survey of Western Australia*, Annual Report - Western Australia, Geological Survey, Report: 1967: East Perth, Geological Survey of Western Australia, p. 40-44.

Lowry, D.C., 1970, *Geology of the Western Australian part of the Eucla Basin*: Perth, Geological Survey of Western Australia, 201 p.

Lowry, D.C., and Jennings J.N., 1974, The Nullarbor karst Australia: *Zeitschrift für Geomorphologie,* **v. 18**, p. 35-81.

Mylroie, J.E., Carew, J.L., 2000, Speleogenesis in Coastal and Oceanic Settings: *in* Klimchouk, A.B., Ford, D.C., Palmer, A.N., and Dreybrodt, W., eds., *Speleogenesis: Evolution of karst aquifers*: Huntsville, Alabama, National Speleological Society, p. 226-233.

Prideaux, G.J., Long, J.A., Ayliffe, L.K., Hellstrom, J.C, Pillans, B., Boles, W.E., Hutchinson, M.N., Roberts, R.G, Cupper, M.L, Arnold, L.J., Devine, P.D., and Warburton, N.M, 2007, An arid-adapted middle Pleistocene vertebrate fauna from south-central Australia: *Nature*, **V.445**, p. 442-445.

Spate, A., Gillieson, D., and Jennings, J., 1984, Red sands of the Nullarbor, a preliminary note, *in* Pilkington, G., eds., *Proceedings of the fourteenth Australian speleological biennial conference*: Adelaide, The Australian Speleological Federation, p. 61-66.

Thomas, D.S.G., 1997, Sand seas and aeolian bedforms, *in* Thomas, D.S.G., 2nd ed., *Arid zone geomorphology*: Sussex, John Wiley & Sons Ltd, p. 373-412.

Webb, J.A., Grimes, K., and Osborne, A., 2003, Black holes: caves in the Australian landscape, *in* Finlayson, B., and Hamilton-Smith, E., eds., *Beneath the Surface*: Sydney, UNSW Press, p. 24-31.

Webb, J.A., and James, J.M., 2006, Karst evolution of the Nullarbor Plain, Australia, *in* Harmon, R.S., and Wicks, C., eds., *Perspectives on karst geomorphology, hydrology, and geochemistry—A tribute volume to Derek C. Ford and William B. White*: Geological Society of America Special Paper 404, p. 65–78.

White, N., 2010, personal communication.

White, S., 2005, *Karst and Landscape Evolution in parts of the Gambier Karst Province, Southeast South Australia and Western Victoria, Australia*: *: PhD Thesis*, Department of Earth Sciences, La Trobe University, Melbourne, 247 p.

Woodhead, J., 2010, personal communication.

Woodhead, J., Hellstrom, J., Maas, R., Drysdale, R., Zanchetta, G., Devine, P., and Taylor, E., 2006, U–Pb geochronology of speleothems by MC-ICPMS: *Quaternary Geochronology*, **v. 1(3)**, p. 208–221.

Worthington, S.R.H., Ford, D.C., and Beddows, P.A., 2000, Porosity and permeability enhancement in unconfined carbonate aquifers as a result of solution, *in* Klimchouk, A.B., Ford, D.C., Palmer, A.N., and Dreybrodt, W., eds., *Speleogenesis: Evolution of karst aquifers*: Huntsville, Alabama, National Speleological Society, p. 463–472.