GEOLOGY AND CAVES OF THE FLINDERS RANGES

by

Ruth E Lawrence
Department of Geography, University of Adelaide, South Australia, 5005
rlawrence@arts.adelaide.edu au

I. INTRODUCTION

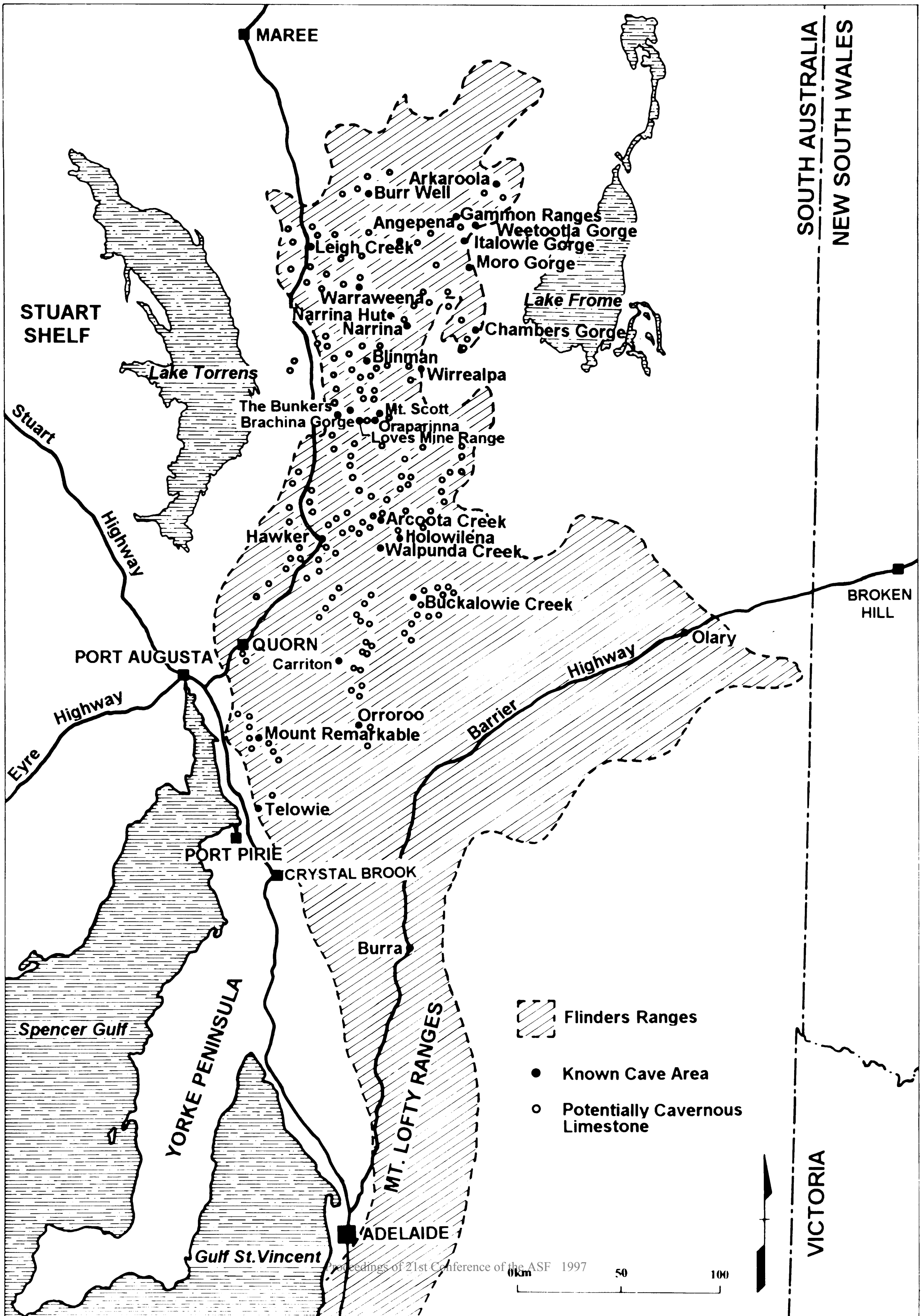
The Flinders Ranges are a spectacular place in which to go caving. The geology of the Flinders Ranges is the main scenic attraction of the area, and allures many people to the region. Imposing mountain ranges, upturned layers of rock and hidden gorges provide a strong aesthetic appeal to visitors. Quartzite, sandstone and siltstone tends to dominate the landscape, but there are also some areas of limestone. The focus of this paper is the limestone outcrops throughout the Flinders Ranges, and the caves within that limestone are described.

The Flinders Ranges constitute the northern component of the geological feature known as the Adelaide Geosyncline. The mountains of the northern part of the Flinders Ranges known as the Gammon Ranges, the Flinders Ranges themselves, the Mount Lofty Ranges, the Fleurieu Peninsula, and the underlying geology on Kangaroo Island are all part of the Adelaide Geosyncline. In fact, the same rocks which constitute the Flinders Ranges also outcrop in the Officer and Amadeus Basins in central Australia, the Barrier Ranges in New South Wales, and the Ross Orogen region in Antarctica (Preiss 1987).

The Flinders Ranges are generally regarded to be those mountain ranges north of Crystal Brook and Burra in South Australia (Figure 1), and include the Gammon Ranges. The Australian Speleological Federation have classified all caves north of the roads linking Port Pirie, Crystal Brook and Burra to belong to the 'Flinders Ranges' cave region, and are allocated 5Fx numbers (Matthews 1985).

The majority of the Flinders Ranges are above 200 metres elevation, with some parts in the vicinity of Wilpena Pound and the Gammon Ranges rising to over 1000 metres. The distribution of native vegetation is closely related to climate and landform. Low open woodlands of native pine (*Callitris columellaris*) and black oak (*Casuarina cristata*) often occur in the ridge areas, mallee species dominate the lowland country, native grasses tend to grow on the rounded ridges, river red gums (*Eucalyptus camaldulensis*) line all the major water courses, and saltbush (*Artiplex* spp.) and bluebush (*Marieana* spp.) occupy the plains and alluvial fans (Gell & Bickford 1996). The variety and distribution of vegetation against the backdrop of colourful mountain ranges adds to the scenic appeal of the Flinders Ranges, especially when seasonal rains result in spectacular wildflower displays including the Sturt's desert pea (*Swainsona formosa*).

FIGURE 1 Known and potentially cavernous areas in the Flinders Ranges. Source: Author's research based on records held by the Cave Exploration Group of South Australia.



Mean annual precipitation for the Flinders Ranges varies from over 500 mm in the Mount Remarkable area in the south to less than 200 mm on the northern slopes (Schewerdtfeger & Curran 1996). Most rainfall falls during the winter months, and there is a strong east-west gradient, with those areas to the east subject to the rainshadow effect. Surface water in the Flinders Ranges is scarce, and is usually restricted to a few deep water holes along the main river valleys. These water holes are replenished only after infrequent and intense storm events, such as the one which occurred in February 1997, when major road and valley features were realigned. The paucity of readily available water in the Flinders Ranges severely restricts the movement of visitors away from base camp areas, which are usually located along the creek lines.

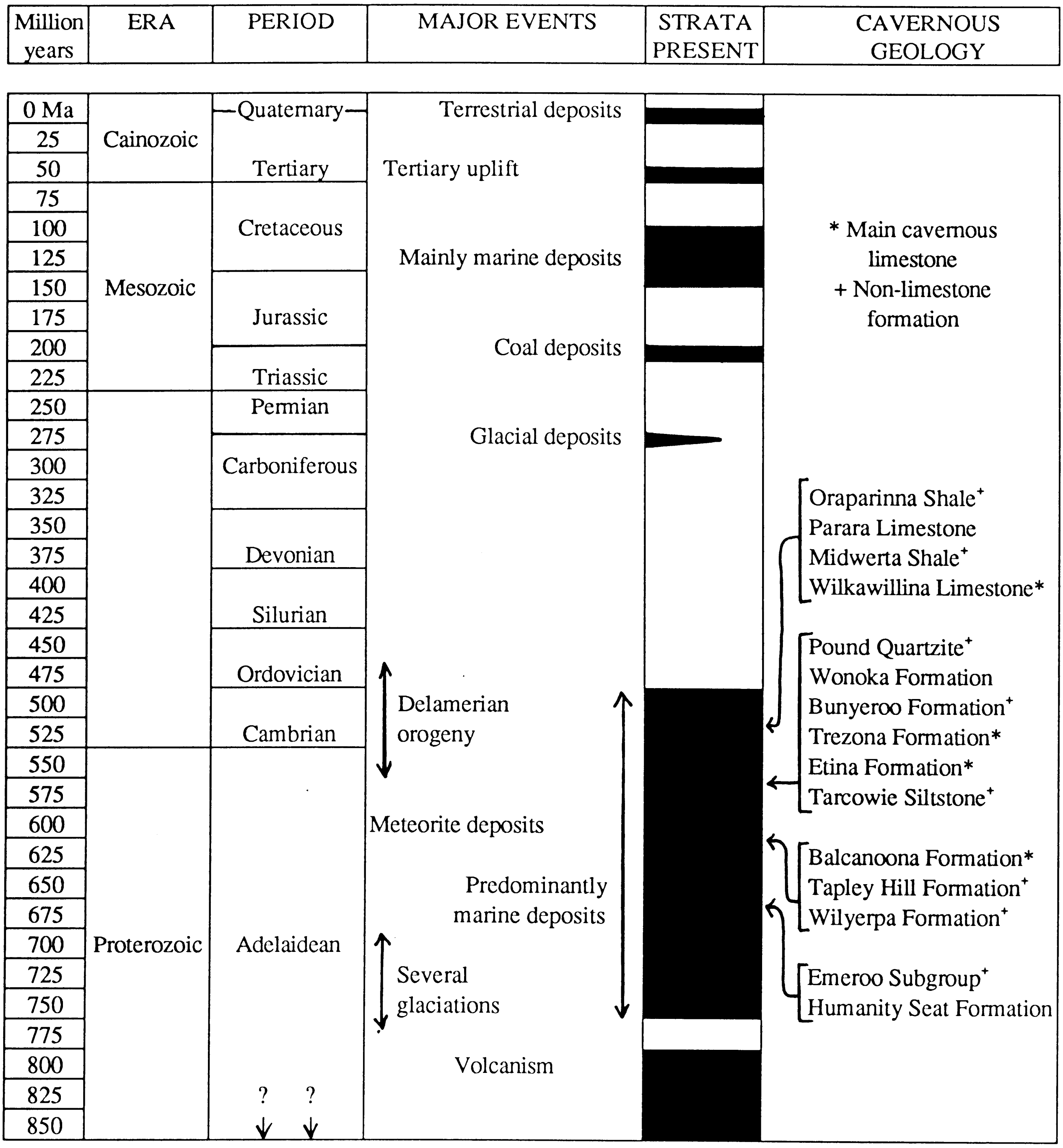
Contemporary land uses range from grazing and arable land in southern areas where rainfall exceeds 300 mm, to sheep grazing on leasehold land in the northern sector. There are several National Parks in the Flinders Ranges, the most notable of which are the Gammon Ranges National Park, Flinders Ranges National Park (encompassing Wilpena Pound) and the Mount Remarkable National Park (Bonython 1996). There is also a large segment of the north-central Flinders Ranges around Nepabunna and Mount Serle which belongs to the Adnyamathanha Aboriginal people (Jones & McEntee 1996). Thus, access to caves in the Flinders Ranges is not automatic, and permission with the relevant land owner or lease holder should always be sought before entering each karst area.

II. GEOLOGICAL HISTORY OF THE FLINDERS RANGES

The rocks which underlie the Flinders Ranges and Adelaide Geosyncline are considered to be a basement of the earth's crust comprised of metamorphic and granitic rocks. These do not outcrop anywhere, but are known from extensive drilling operations conducted in the area, and are also inferred from the composition of the numerous diapirs in the region (Preiss 1987). Associated ancient crustal rocks occur west of the Flinders Ranges in the Gawler Craton, and to the east in the Curnamona Craton. The formation of the present day Flinders Ranges commenced when the earth's crust in this area thinned due to extension at the western and eastern perimeters. This resulted in faulting, so that the basement became a series of linear, fault-controlled downthrown areas, or a rift zone (Lemon 1996). Selby (1990) considered this to occur during the Proterozoic Era.

Being a low point in the landscape, the area was then suitable for the deposition of sedimentary material which began to infill the rift zone. Initial deposition took the form of alluvial fans, fluvial deposits, and lacustrine sediments, and was accompanied by the extrusion of volcanics in the Arkaroola area. This deposition phase resulted in subsidence of the area until the rift dropped to below sea level. Once this happened, the sea flooded in and resulted in the deposition of marine deposits, which forms the vast bulk of the sedimentary sequence seen in the Flinders Ranges today. Most deposition occurred during 'Adelaidean' Period (Figure 2), which can be divided into the Willouran, Torrensian, Sturtian, Marinoan and Ediacaran Epochs. Preiss (1987) has identified 45 major time periods within the Adelaidean Period, and more than 165 distinct sedimentary units. Preiss (1987) should be consulted for details of these periods and units. Suffice to say here that the maximum thickness of sedimentary layers is fifteen kilometres, and that the sediments are composed of a variety of muds, silts, sands, quartzite, conglomerates and dolomite, and that stromatolites commonly accompany the dolomite formations.

FIGURE 2 GEOLOGICAL TIME LINE SHOWING MAJOR GEOLOGICAL EVENTS AND CAVERNOUS STRATA IN THE FLINDERS RANGES. Source: time line adapted from Lemon (1996) and supplemented from data held by the Cave Exploration Group of South Australia



Even though the majority of the sediments which now constitute the Flinders Ranges are of marine origin, there are a few notable exceptions. There is evidence of glacial activity in the Arkaroola and Holowilena areas, where distinctive glacial deposits known as tillite have been found. In fact, at the glacial maximum during Appila time (Preiss 1987), the entire depression was covered with an extensive ice sheet, and the surrounding peaks in the Gawler and Curnamona Craton areas were permanently covered with snow. Also, there exists a continuous layer of volcanic rock debris throughout much of the Flinders Ranges which is considered to be of meteoritic origin (Gostin *et al.* 1986). Williams (1986) demonstrated that these deposits originated from a meteorite impact at a site known as 'Lake Acraman' north of Gawler Ranges hundreds of kilometres to the west of the Flinders Ranges.

Once the sedimentary units were deposited, a period of folding and faulting followed. Preiss (1987) recorded that this occurred principally during the late Cambrian era, during an event known as the Delamerian Orogeny (Figure 2). This event was preceded by extensive diapir intrusions, where multiple domes or anticlinal folds of underlying soft and plastic rocks were squeezed upwards, rupturing the overlying rocks, and often producing breccia. The Delamerian Orogeny then operated in two phases. The early phase produced linear north-south folds in the southern and central Flinders region, and was responsible for the essentially linear mountain ranges between the Fleurieu Peninsula in the south and the area east of Port Pirie. The second phase of the Delamerian Orogeny affected mainly the northern Flinders area, and resulted in strong east-west folds in that area and relatively tight northeast-tending folds in the eastern central zone of the Flinders Ranges. Fault line activity in places such as the Northwest Fault, west of Leigh Creek, occurred during this phase.

Since the deposition of the main sedimentary deposits, other geological events have occurred, including a minor glacial event, the formation of coal deposits in four small circular basins in the Leigh Creek area, deposition of marine sediments in the northern part of the Flinders Ranges associated with the inland Cretaceous sea, and uplift of the mountain ranges during the Tertiary period.

The uplift which occurred during the Tertiary period resulted in the present relief of the Flinders Ranges. Initially, the uplift occurred gradually, and resulted in sedimentation of lacustrine and fluvial material around the margins of the ranges. The major phase of uplift of both the Flinders and Mount Lofty Ranges took place towards the end of the Tertiary and beginning of the Quaternary period. Associated with the uplift, the top layers of the sedimentary sequence were eroded, exposing the 165 geological units identified by Preiss (1987), and resulting in the present elevation of the ranges and their current rugged character (Lemon 1996). The geological units can be seen in cross-section along many roads in the Flinders Ranges. For example, twelve main geological units are exposed along the Brachina Gorge Road ranging from the older Enorama Shale in the east to the younger Wirrealpa Limestone to the west (Selby 1990).

A feature of the geology of the Flinders Ranges today is that outcrops of specific rock types are scattered and discontinuous. Most rock strata are dipping quite steeply, which is a function of the high frequency of folds and faults in the area. Rock outcrops frequently occur in couplets and there is often a mirror image of the same sequence on either side of anticlinal ridge or synclinal depression. For example, the Pound Quartzite, which is resistant to erosion and thus often constitutes the high points in the landscape, forms the perimeter of the wall of Wilpena Pound and the main ridgeline of the Elder, Chase and Druid Ranges (Selby 1990).

Much of the material that was eroded from the Flinders Ranges during the Tertiary Uplift has since been reworked and deposited beneath the plains to the west, north and east, or as alluvial fans along the boundaries of the Ranges. Today, the dominant process throughout the Flinders Ranges is erosion, with sedimentation restricted to the flanking areas.

Thus, the distinguishing features of the Adelaide Geosyncline are threefold. Firstly, the rocks are sedimentary in nature. There are the usual assortment of sandstones, limestones, mudstones and quartzite, but there are also scattered layers of glacial deposits and ash from an asteroid impact. The majority of the sediments are of marine origin. Secondly, the rocks are very old. The vast majority of the rocks of the Flinders Ranges are considered to date from the Pre-Cambrian (or Adelaidean) era, with some rocks being of Cambrian age (Preiss 1987). This implies that considerable time has been available for cave development in the Flinders Ranges. Thirdly, the Flinders Ranges have been subject to extensive folding and faulting. Much of the top layers of rocks have been sheared off over time resulting in massive amounts of erosion of the uplifted material and associated deposition in the adjacent lowland plains.

III. THE LOCATION AND USE OF CAVES IN THE FLINDERS RANGES

There are 115 known caves scattered throughout Flinders Ranges (Kraehenbuehl *et al.* 1997). The best known caves are as follows: 5F3 Mairs Cave and 5F4 Clara St Dora Cave in the Buckalowie Creek area; 5F15 Eyrie Cave in the Bunkers Range; 5F1 Mt Remarkable Blowhole at Mount Remarkable; 5F11 Woodendinna Cave on Narrina Station; 5F8 Oraparinna Cave, 5F29 Thunderdrum Cave and 5F33 Yellow Foot Rock Wallaby Cave in the Oraparinna area; 5F5 Arcoota Creek Cave, 5F6 Good Friday Cave and 5F7 Mt Simms Cave in the Walpunda Creek and Holowilena region; and 5F9 Wooltana Cave on Wooltana Station. In fact, caves are found at all the locations shown in Figure 1.

To the casual observer, there is no apparent pattern to the distribution of caves in the Flinders Ranges. Indeed, caves occur in a variety of locations (Figure 1) and many different rock types (Table 1). The scattered nature of cave locations is due to the geological history of the region outlined above, where the same geological unit may outcrop at multiple sites. As with other rock types, the distribution of limestone in the Flinders Ranges is scattered and discontinuous. Hence, the Flinders Ranges are not a typical karst region of more or less continuous limestone, but limestone outcrops occur in elongated strips or semi-circular bands. However, there are four main limestone units in which the majority of the caves of the Flinders Ranges are found, and these are detailed in the following section.

As with other geological units, couplets of outcropping limestone often occurs. For example, in the Buckalowie Creek area north-east of Orroroo, there are two parallel bands of limestone running north-east to south-west. Two caves in the northern outcrop, 5F3 Mairs Cave and 5F4 Clara St Dora Cave, have been known for many years, and there are three other smaller caves in the same outcrop: 5F27 Lizard Cave, 5F28 Chimney Cleft Cave, and 5F35 False Wall Cave (Kraehenbuehl *et al.* 1997). The southern outcrop of limestone has the same potential to be cavernous, although its remoteness from access tracks has so far precluded investigation of that area for caves.

However, only about 70 percent of the known caves in the Flinders Ranges are found in limestone. Other caves are found in quartzite, sandstone, shale or siltstone (Table 1). For example, 5F99 Yourambulla Cave, which is famous for its Aboriginal art work, is found in Pound Quartzite. Most caves in non-limestone are small, being little more than large rock shelters, and some do not have zones of permanent darkness.

Past Aboriginal interactions with caves in the Flinders Ranges were significant. The Adnyamathanha, Walypi, Ngadjuri and Nukunu languages were spoken by the original inhabitants of the Flinders Ranges, although the Adnyamathanha tradition dominates the area today (Jones & McEntee 1996). Karst areas such as Chambers Gorge and Moro Gorge feature extensively in Adnyamathanha mythology (Tunbridge 1988), on account of the presence of permanent water holes in the vicinity of caves. Some caves such as 5F84 Wild Dog Cave and 5F99 Yourambulla Cave show evidence of Aboriginal art work (Kraehenbuehl *et al.* 1997), and it is likely that many caves and shelters were known and visited for the purposes of hunting euros and wallabies which lived there. Other caves in the Flinders Ranges were taboo. For example, 'Yamuti', the name of a large mammal-like being, was said to have originated from 5F9 Wooltana Cave, and indeed Tunbridge (1988) claimed that the entrance to that cave lends itself to the idea that it was made and inhabited by a prehistoric creature.

Many of the more popular and well-known caves in the Flinders Ranges were mined for bat guano by Europeans early this century. Before the advent of superphosphate, bat guano provided a valuable fertiliser for the generally nutrient-poor soils in Australia. This land use activity had a deleterious effect on the bat populations of the Flinders Ranges, but did ensure vehicular access to the site of some caves, and easy access into other caves via adits. Caves thus affected included 5F9 Wooltana Cave (Winton 1920a), 5F26 Burr Well Cave (Winton 1920b), 5F3 Mairs Cave, 5F4 Clara St Dora Cave (Winton 1922), 5F8 Oraparinna Cave (Segnit 1933a) and 5F6 Good Friday Cave (Segnit 1933b).

IV. THE FOUR MAIN LIMESTONE FORMATIONS IN THE FLINDERS RANGES

The four main formations in which caves are found in the Flinders Ranges are the Balcanoona Formation, Etina Formation, Trezona Formation, and the Wilkawillina Limestone. About 70% of the known caves in the Flinders Ranges occur in one or other of these formations, and details of each are described below based on the work of Preiss (1987).

The Balcanoona Formation

This is the oldest of the limestones in the Flinders Ranges, being deposited early in the Proterozoic era. This formation is equivalent to the Brighton Limestone of the Mount Lofty Ranges, and comprises material of a sandy limestone with flat shale pebbles and fragments of stromatolites. It is up to 75 metres thick and is overlain by a dark grey massive limestone that is usually 60 metres in thickness. Stromatolites are domical or columnar structures produced by cyanobacteria which trap, bind and precipitate sediment such as calcium carbonate. There are about 240 square kilometres of outcrops of the Balcanoona Formation, mainly in the eastern and northern parts of the Flinders Ranges.

TABLE 1 LOCATION OF CAVERNOUS ROCK STRATA AND CAVES IN THE FLINDERS RANGES. Source: strata information adapted from Preiss (1987) and cave location information based on records held by the Cave Exploration Group of South Australia

ERA (PERIOD)	EPOCH	FORMATION CONTAINING CAVES		LOCATION OF OUTCROPS	SPECIFIC SITES WHERE CAVES ARE FOUND IN EACH FORMATION
Palaeozoic (Cambrian)	Lower	Oraparinna Shale	Cho	Northern Flinders Ranges	Angepena
		Parara Limestone	Chr	Central & northern Flinders Ranges	Narrina, Wirrealpa
		Midwerta Shale	Chd	South-central Flinders Ranges	Narrina Hut
		Wilkawillina Formation	Chw	Central & northern Flinders Ranges	Angepena, Brachina Gorge, Moro Gorge, Narrina, Oraparinna, Wirrealpa
Proterozoic (Adelaidean)	Marinoan	Pound Quartzite	Pwp	Central and northern Flinders Ranges	Gammon Ranges, Hawker, Italowie Gorge, Narrina
		Wonoka Formation	Pww	Throughout the entire Flinders Ranges	Leigh Creek, Wirrealpa
		Bunyeroo Formation	Pwb	Throughout the entire Flinders Ranges	Narrina Hut
		Trezona Formation	Phz	Central & northern Flinders Ranges	Arcoota Creek, Buckalowie Creek, Chambers Gorge, Oraparinna, The Bunkers, Trezona, Walpunda Creek, Warraweena
		Etina Formation	Phe	Central & northern Flinders Ranges	Arcoota Creek, Blinman, Buckalowie Creek, Holowilena, Mt Scott, Oraparinna, Orroroo, The Bunkers, Walpunda Creek
		Tarcowie Siltstone	Pu	Southern Flinders Ranges	Carrieton
	Sturtian	Balcanoona Formation	Pfb	Extreme western & north-eastern parts of the Flinders Ranges	Arkaroola, Burr Well, Chambers Gorge, Mt Remarkable, North Flinders, Warraweena, Weetootla Gorge
		Tapley Hill Formation	Pft	Throughout the entire Flinders Ranges	Walpunda Creek
		Wilyerpa Formation	Puw	Central & northern Flinders Ranges	Loves Mine Range
	Torrensian	Emeroo Subgroup	Po	Throughout the entire Flinders Ranges	Telowie
		Humanity Seat Formation	Por	North-eastern Flinders Ranges	Arkaroola, Italowie Gorge

Caves in this formation have been found in the Mount Remarkable, Chambers Gorge, Burr Well and Arkaroola areas (Figure 1). It is probable that both 5F1 Mt Remarkable Blowhole and 5F9 Wooltana Cave are found in this formation, and both have near vertical entrance pitches of 40 or 50 metres (Kraehenbuehl *et al.* 1997). Other caves found in this formation do not show any vertical control. Most caves in the Balcanoona Formation are small - generally having less than 50 metres of main passage, which is a reflection of the limited thickness of the limestone laid down at the time of deposition. Very little speleothem development is evident in these caves.

The Etina Formation

Occurring mainly around the central Flinders Ranges region, the Etina Formation consists of grey oolitic and sandy limestone with interbedded green dolomitic siltstone and shale. The oolitic component comprises spherical or ellipsoidal ooid grainstones of quartz and feldspar cemented by calcite. This is the most common limestone formation in the Flinders Ranges, and outcrops in about 760 square kilometres and is up to 700 metres in thickness.

Due to the extent and thickness of the Etina Formation, many significant caves have been found in this limestone deposit. In fact, 30% of all known caves in the Flinders Ranges have developed in the Etina Formation. Caves have been found at Orroroo, Buckalowie Creek, Wulpunda Creek, Arcoota Creek, Holowilena, Oraparinna, The Bunkers, Blinman and Mt Scott (Figure 1). The most well known caves in this formation are 5F3 Mairs Cave and 5F4 Clara St Dora Cave at Buckalowie Creek, 5F5 Arcoota Cave at Arcoota Creek, 5F6 Good Friday Cave and 5F7 Mt Sims Cave at Holowilena, 5F8 Oraparinna Cave at Oraparinna, and 5F15 Eyrie Cave in The Bunkers Range.

The largest caves in the Flinders Ranges are all found in the Etina Formation, and most display a strong structural control. Flinders Ranges caves are generally not noted for speleothem development, but most caves in the Etina Formation are well decorated. Both Mairs and Clara St Dora Caves have examples of unusual calcite formations (Kraehenbuehl *et al.* 1997). Some speleothems in these caves are active, but the majority are not. The relic speleothems tend to be very large.

The Trezona Formation

The Trezona Range north of Wilpena Pound is named for the alternating limestone and shale beds of the Trezona Formation where a series of terraces have formed. Located mainly in the central Flinders Ranges, this formation is comprised of pale red and grey fine-grained limestones alternating with greenish grey laminated shale and siltstone. The content of the limestone is up to 92% carbonate, and the shale is up to 32% calcite. There is about 250 square kilometres of outcropping Trezona Formation in the Flinders Ranges, and the depth of the formation may reach 240 metres.

Caves in the Trezona Formation have been found at Arcoota Creek, Oraparinna, the Trezona Range, and the Walpunda Creek areas (Figure 1). Thunderdrum Cave (5F29) and Yellow Foot Rock Wallaby Cave (5F33) in the Trezona Range near Oraparinna are two well-known caves in this formation. Some caves developed in the Trezona Formation have multiple passages that are parallel to each other and linked by smaller squeezes perpendicular to the dominant passages (Kraehenbuehl *et al.* 1997). Cave passages tend to be horizontal or slightly dipping, following the orientation of laminations. Many caves in the Trezona Formation have developed at creek level, and very few display speleothem development.

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Wilkawillina Limestone

This is the youngest of the limestones in the Flinders Ranges, being of Early Cambrian age. This limestone is oolitic, stromatolitic, often dolomitised, and contains fossil archaeocyathans. Over 500 square kilometres of outcropping Wilkawillina Limestone has been mapped, and most of that is located in the central-western and north-eastern Flinders Ranges. Caves in the Wilkawillina Limestone have been found in the Brachina Gorge, Oraparinna, Wirrealpa, Angepena and Moro Gorge areas (Figure 1). Bunyeroo Cave (5F13) at Oraparinna and Anticline Cave (5F24) at Wirrealpa are two notable caves in this unit. Some caves in Wilkawillina Limestone have developed reasonably-sized chambers and some also display speleothem development (Kraehenbuehl *et al.* 1997).

V. CHARACTERISTICS OF LIMESTONE CAVES IN THE FLINDERS RANGES

Due to the non-uniformity of the rock type and the scattered nature of the limestone outcrops, no unifying hydrological or geomorphological process can be invoked to account for the caves of the Flinders Ranges. It is probable that some caves have formed under current climatic conditions, and that others are relic of past eras. This section is intended to highlight some of the major processes which have contributed to the development of the cave systems in the Flinders Ranges, so as to stimulate further work in the area.

Structural control shown in caves

The most obvious factor contributing to cave development in the Flinders Ranges is that of the structure of the rocks themselves. Due to the tectonic activity associated with both the Delamerian Orogeny and the Tertiary uplift, the dip of the sedimentary rocks ranges anywhere from 0° to 90°, with most around 30° to 40°, as at Brachina Gorge (Selby 1990).

Caves in both the Etina and Trezona Formations display structural control, with the most pronounced effect being seen in the larger caves in the Etina Formation. For example, 5F3 Mairs Cave has developed along the contact between the Etina Formation and an adjacent shale member. First-time observers of a map of Mairs Cave (Kraehenbuehl *et al.* 1997) often conclude there is something wrong with the plan, as the north-western boundary of most of the cave is a straight line. However, the map is accurate, as the cave features a near-vertical wall for about 100 metres in length, which reaches a height of at least ten metres in some parts. It is likely that the Buckalowie Creek was responsible for the formation of this cave, as it gradually lowered the land surface over time. Standing water is still occasionally observed in Mairs Cave, as the cave extends ten metres below the current creek level. A three-metre deep pool formed at the bottom of the entrance shaft following the 1974 rains.

Both 5F8 Oraparinna Cave and 5F17 Arcoota Creek Cave are maze systems where the joints and slightly-dipping bedding planes have been enlarged by the action of water on limestone to produce hundreds of metres of cave passage (Kraehenbuehl *et al.* 1997). Gillieson (1996) writes that maze caves often form where flat-lying well-bedded limestones are invaded by floodwaters, and Segnit (1933a) reported that at least three distinct phases of water erosion are evident in Oraparinna Cave. These three phases are represented by the three distinct levels found there: during the first phase the channels were formed in a direct plane with the north-westerly dip of the beds; during the second phase, which was the period of greatest cave formation, the channels were eroded in a general north-south and east-west direction; and channel development was similar during the third phase (Segnit

1933a). The third phase operates at the present time, and evidence of water having moved through the third (lowest) level of the cave was seen following the flood events of February 1997.

Not only do bedding planes play a role in the development of the Flinders Ranges caves, but some of the larger caves occur where fault lines are present. This can be seen for the two caves at Buckalowie Creek (5F3 Mairs Cave and 5F4 Clara St Dora Cave), 5F11 Woodendinna Cave on Narrina Station, and several caves in the Mt Scott area (Kraehenbuehl *et al.* 1997).

Surface hydrological influences

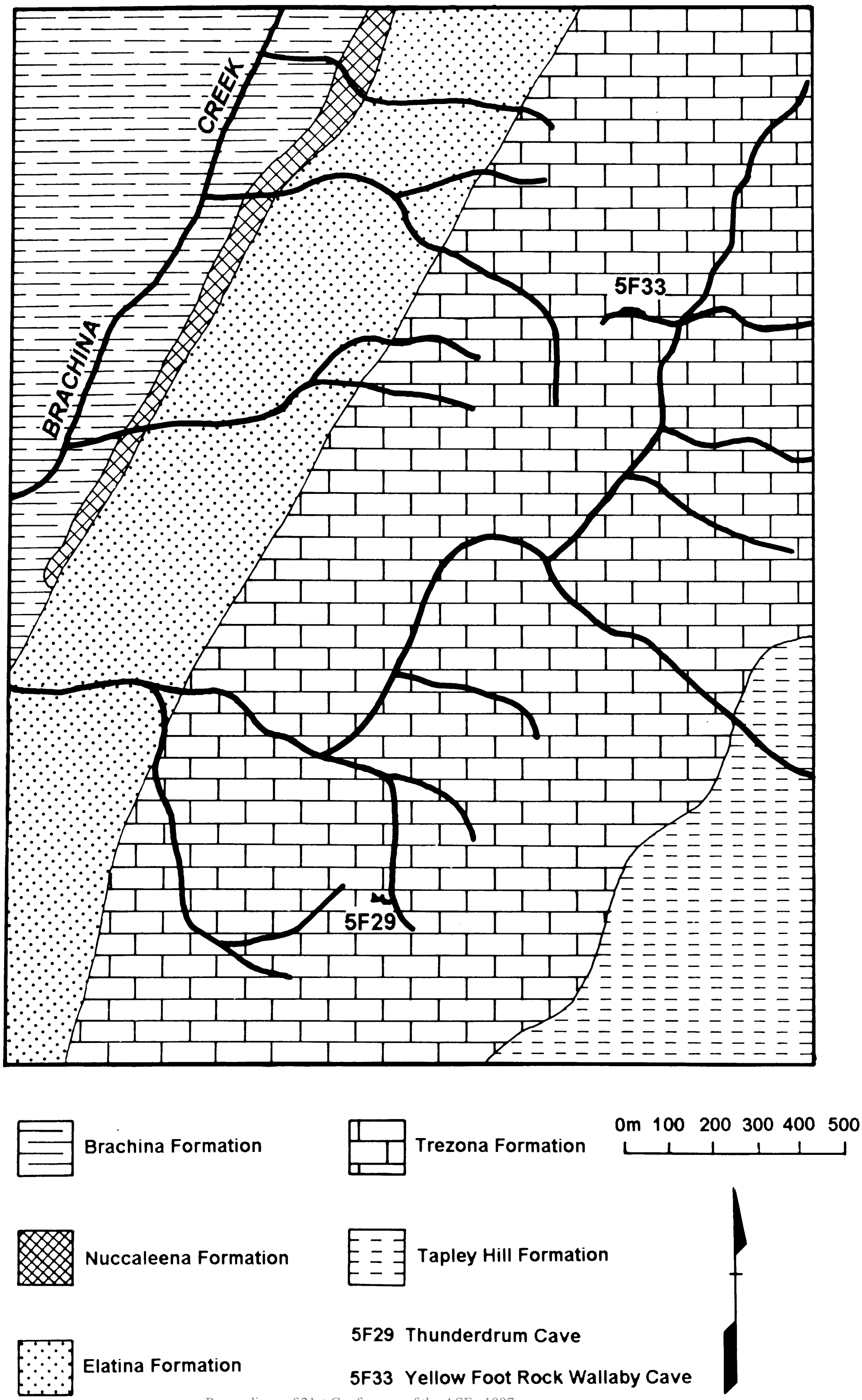
As one moves northwards through the Flinders Ranges, the amount of rainfall received diminishes. Parts of the southern Flinders Ranges receive 500 mm per annum, whereas the far northern slopes average about 200 mm per annum (Schewerdtfeger & Curran 1996). Local variation in incident rainfall does occur, with western peak areas receiving more annual rainfall than the eastern rainshadow areas.

The monthly distribution of rainfall throughout the Flinders Ranges is variable. Generally reliable rainfall occurs in the south between May and September as a result of cold fronts embedded in westerly air streams moving across the southern part of the continent. Alternatively, rain-bearing cloud banks from the tropical north may move into the Flinders Ranges at any time of the year, and often result in afternoon or evening thunderstorms and associated flash flooding (Schewerdtfeger & Curran 1996). Such an event occurred between 6 and 10 February 1997, when a tropical depression moved through the area resulting in a two-hour downpour every afternoon for five days. The most severe thunderstorm occurred on 7 February 1997, when 52.4 mm and 72 mm of rain fell in two hours at Blinman and Wilpena Pound respectively. This event was determined by the Bureau of Meteorology to have been a 1 in 100 year rainfall event (Burrows, pers. comm.).

The sporadic rainfall of the Flinders Ranges results in even greater sporadic runoff events. Surface drainage from the Ranges flows either west to Spencer Gulf or Lake Torrens, north to Lake Eyre, or east to Lake Frome. The influence of present rainfall and runoff regimes on cave development is seen in the Oraparinna area, where two caves have developed in the Trezona Formation. Both 5F29 Thunderdrum Cave and 5F33 Yellow Foot Rock Wallaby Cave are located at creek level and act as stream swallows (Figure 3). The surface catchment area for these two caves are small - 3.9 ha and 1.5 ha for Thunderdrum Cave and 5F33 Yellow Foot Rock Wallaby Cave respectively. Yet the orientation of Thunderdrum Cave is perpendicular to the surface stream, and Yellow Foot Rock Wallaby Cave runs parallel to the surface gully but slopes away from the land surface. Both caves appear to be reorienting runoff in a more direct line to the local base level of Brachina Creek.

The recent heavy rains have interacted with the caves in a number of ways. In the case of Thunderdrum Cave, the silt and boulder floor which was present throughout most of the cave until January 1997 was washed clean during the February 1997 storm event and the main passage was extended beyond that mapped in Kraehenbuehl *et al.* (1997). In all probability, subsequent smaller rainfall events will replenish the supply of sediment to the floor of the cave. At Chambers Gorge, even more dramatic changes occurred, when 5F115 Waterfall Cave, which was located at creek level, completely disappeared! Obviously, current hydrological conditions play an important role in some caves in the Flinders Ranges.

FIGURE 3 Geological setting of 5F29 Thunderdrum Cave and 5F33 Yellow Foot Rock Wallaby Cave in the Oraparinna area of the Flinders Ranges. Source: adapted from published topographic and geological maps and supplemented by data collected by the Cave Exploration Group of South Australia.



Groundwater influences

The Flinders Ranges are not noted for having abundant groundwater supplies. This is because the fractured rock nature of the geology of the Adelaide Geosyncline precludes the storage of large volumes of water. Where groundwater is present, salinity levels are commonly around 3000 mg/l (Shepherd 1983). It seems that the groundwaters in the fractured rock aquifers rarely interact with the caves of the Flinders Ranges.

However, scattered throughout the Flinders Ranges are several sedimentary groundwater basins. There are three groundwater basins of agricultural and pastoral significance in the Flinders Ranges: the Pirie Torrens Basin on the extreme western edge of the Flinders Ranges, and the small Willochra and Walloway Basins east of Port Augusta (Shepherd 1983). Also, there is another unnamed groundwater basin in the Narrina area (Figure 1) which is highly significant in explaining the presence of 5F11 Woodendinna (Narrina Lake) Cave.

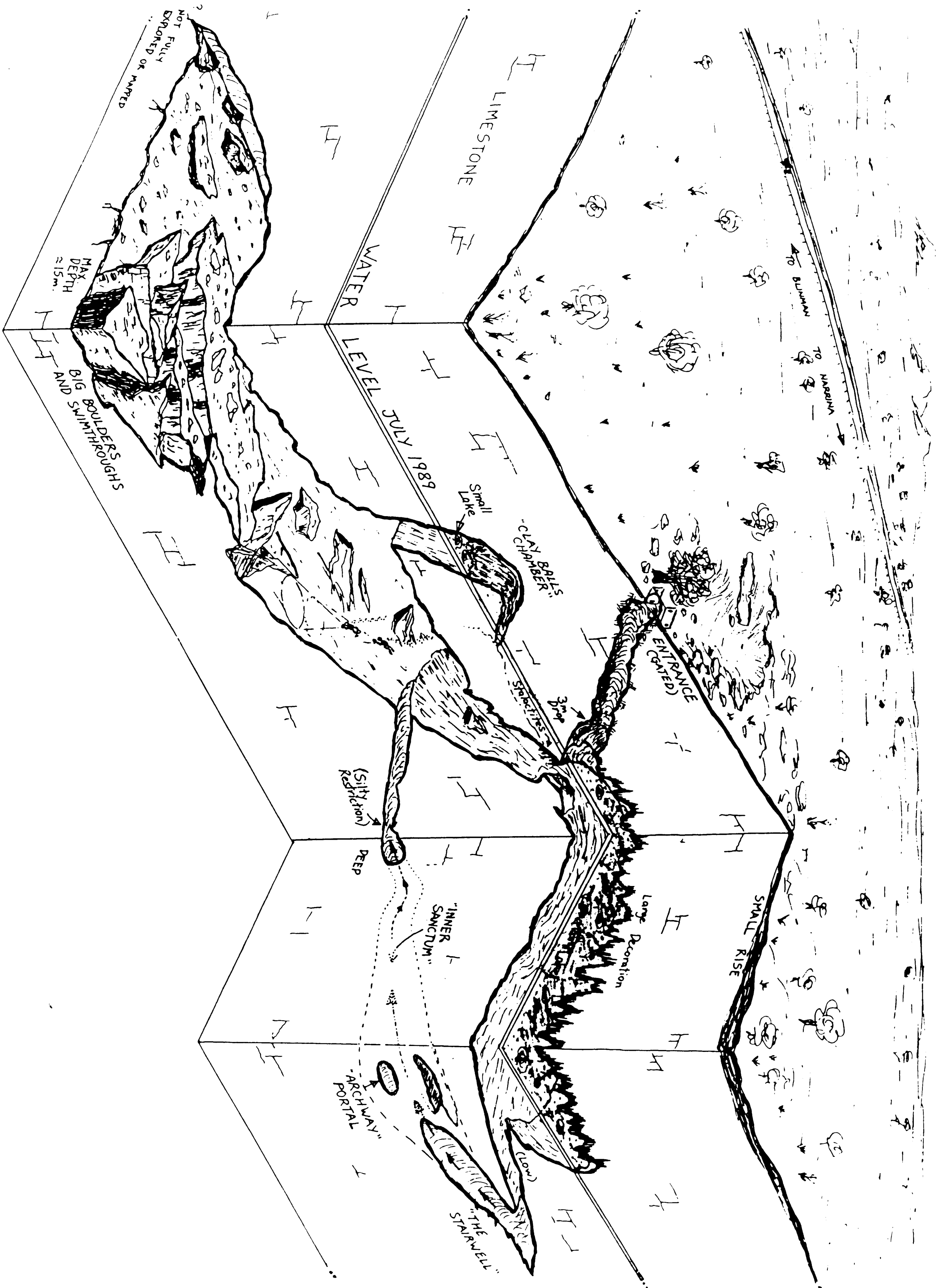
Woodendinna Cave is located in Wilkawillina Limestone in the north-central region of the Flinders Ranges. It is the only cave in the Flinders Ranges with permanent standing water, and provides a unique cave diving opportunity in a region usually devoid of permanent surface and groundwater. The watertable is located about ten metres below the surrounding land surface and the water-filled section of the cave extends to a depth of about fifteen metres (Figure 4). No other caves in either the Wilkawillina Limestone or other formations are permanently water-filled, and indeed Woodendinna Cave only exists because of the relationship between the limestone and the underlying Pound Quartzite. The Narrina area forms a pound similar to that of Wilpena Pound, where the Wilkawillina Limestone is underlain by the impervious Pound Quartzite in a saucer-shaped depression. This has resulted in a groundwater catchment area of approximately 700 square kilometres and the development of a perched aquifer. Woodendinna Cave has formed in the middle of the pound within this perched aquifer at a point where a faultline crosses the pound.

The water in Woodendinna Cave is of meteoric origin, as evidenced by both the water and salinity levels in the cave. The cave was first surveyed in 1970 when the water level was such that swimming access to features such as the 'Clayballs extension' of the cave was possible. When cave divers re-entered Woodendinna Cave in the early 1980s to explore and map the subterranean section, however, the 1970 map proved to be confusing and inadequate (Horne pers. comm.). It was subsequently found that heavy rainfall during 1974 had resulted in a rise in the water table of at least five metres (Kraehenbuehl *et al.* 1997). Both extended droughts periods and floods during the subsequent years have also caused fluctuations of the lake level in Woodendinna Cave, and it is thought that there is a time delay of about six months after heavy rains before the lake level responds by rising. In May 1990, salinity values of the water in the lake ranged from 1160 mg/l at the surface to 1300 mg/l at fourteen metres depth (Horne, pers. comm.). These factors seem to indicate periodic replenishment of fresh water to the lake in Woodendinna Cave after incident rainfall has percolated through the porous limestone aquifer.

Caves formed in a bygone era

One of the features of the geological history of the Flinders Ranges is that the sedimentary sequences are very old. This implies that considerable time has been available for cave development and, indeed, there is evidence that some caves could not have formed under present climatic conditions.

FIGURE 4 Three-dimensional perspective view of 5F11 Woodendinna (Narrina Lake) Cave. Sketch not to exact scale.
Source: Peter Horne of the Cave Exploration Group of South Australia.



There are many caves in the Flinders Ranges which are located just below the summit of mountain ranges. Within that subgroup of caves, there are a few caves of particular note which contain large and relic speleothems. Both 5F13 Bunyeroo Cave and 5F15 Eyrie Cave are two such examples. Eyrie Cave is noted for its decorations - it has expansive stalactities, stalagmites, columns and flowstone. In fact, one particular column is more than two metres in diameter and about four metres in height (Kraehenbuehl *et al.* 1997). Most of the speleothems in Eyrie Cave are inactive, apart from a few dripping straws deep in the cave. What makes these large and mostly relic features so remarkable is that Eyrie Cave is located 70 metres above the present creekbed, with only about eight metres of rock above it.

The size of the calcite formations in caverns such as Eyrie Cave implies two things. Firstly, at the time the speleothems were formed, there had to have been much more rock above the cave through which vadose water could percolate and dissolve the limestone before it reached the cave where degassing and deposition of calcite occurred. Eight metres of overlying limestone is not sufficient for the production of such massive columns. Secondly, a much wetter climate would also be needed to account for the size of the speleothems, as the current rainfall regime has only produced straws. These factors suggest that some of the caves in the Flinders Ranges were formed in a previously wetter climate prior to extensive erosion of the landscape. These caves were obviously formed in a bygone era, and the association of the caves with the Tertiary uplift has yet to be determined.

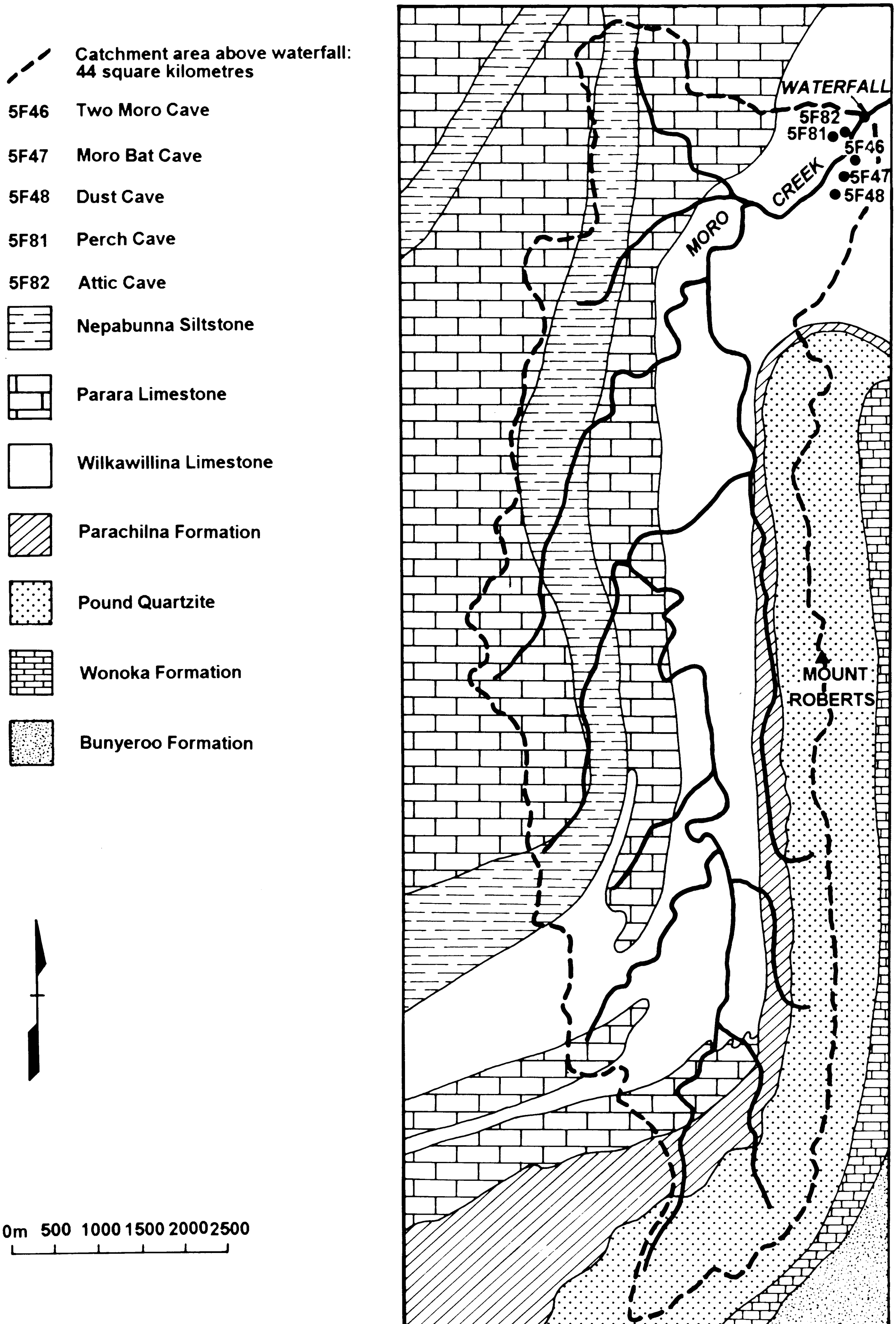
Caves that are a relic of previously bigger systems

In tandem with the idea that some caves in the Flinders Ranges were formed in a bygone era is certain evidence that other caves are relic of previously bigger systems. The basis of such an assertion is the presence of large tufa deposits in several places in the Flinders Ranges. Jennings (1985) claims that the most important factor producing these secondary carbonate deposits is the diffusion of carbon dioxide to the atmosphere after water emerges from caves or soil with a higher partial pressure than that of open air. However, tufa deposits in the Flinders Ranges have been found to be unassociated with current rivers and caves.

At the foot of Mt Caernarvon in the Loves Mine Range is a feature known locally as 'The Skull'. This is a twenty metre high tufa deposit which is so named because of the cavities that resemble a hairline, eyes, nose, mouth and ears in perfect symmetry. In fact, the deposit is so large that it contains two small caves. Both 5F65 Black Cave and 5F66 Out Flow Cave (which forms the mouth of the skull) have speleothems including stalactites, stalagmites, shawls, flowstone and cave coral (Kraehenbuehl *et al.* 1997). However, when the area upstream of the tufa deposit was explored for the mother cave, nothing was found. If the large tufa curtain has resulted from the deposition of calcite-rich waters at mouth of cave, there is no evidence of that cave today. It is likely that the cave through which water flowed and deposited tufa at its exit has since disappeared.

Another large tufa deposit can be found in the Moro Creek area. At this site, the tufa curtain is marked on the relevant topographic map as a waterfall, as it is immediately upstream of a large permanent water hole. Unlike The Skull, however, the Moro Creek tufa curtain is located in Wilkawillina Limestone and there are five known caves immediately upstream (Figure 5). Only one of these five caves - 5F46 Two Moro Cave - is located adjacent to the tufa waterfall, and the other four are all small and found in the cliffs on either side of Moro Creek (Kraehenbuehl *et al.* 1997). All caves appear to be oriented perpendicular to the present creek line. Could it be that these caves are the arms of a much larger system which has collapsed to form the present Moro Gorge and tufa curtain?

FIGURE 5 Geology of the catchment of the Moro Creek above the tufa waterfall in relation to the location of known caves. Source: adapted from published topographic and geological maps and supplemented by data collected by the Cave Exploration Group of South Australia.

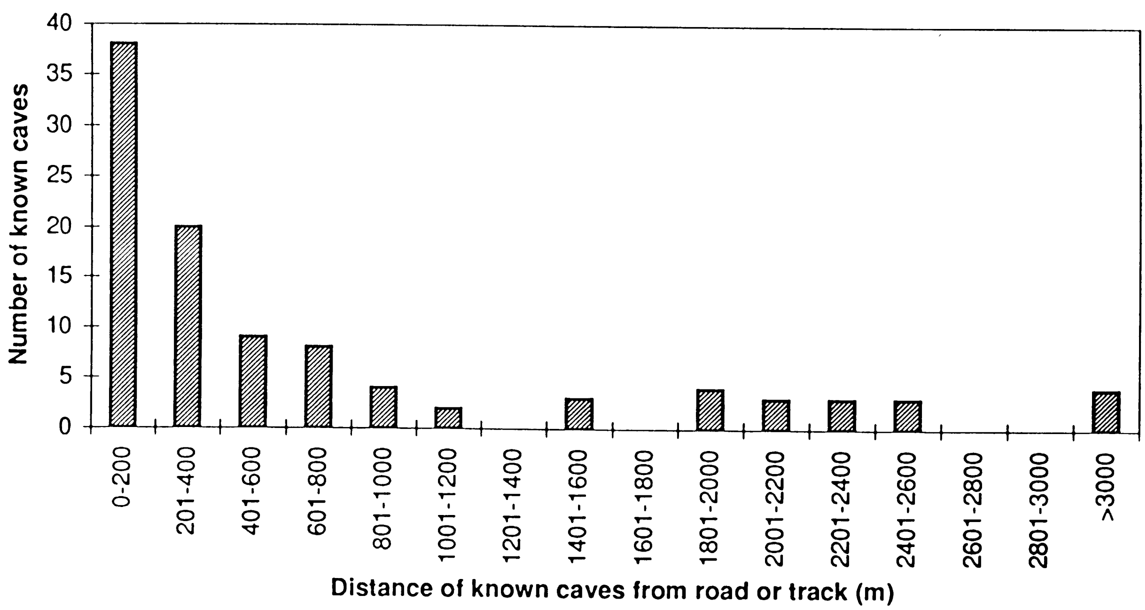


VI. CONCLUSION

There is no commonality of explanation for the caves of the Flinders Ranges. Some show a strong structural control, others are influenced by present surface and subsurface hydrological conditions, and yet others appear to be relic features of either a bygone era or a bigger system. It is possible that some caves and karst features in the Flinders Ranges may provide significant evidence of palaeo environments not available elsewhere in the landscape. These apparent relic systems deserve much more geomorphological attention than has been possible here.

And yet, for all the surmising that can result from presently known caves in the Flinders Ranges, there is still a lot of exploration to be done. Despite the fact that there is about 2000 square kilometres of outcropping limestone in the Flinders Ranges, only about five percent of that total area has been systematically explored for caves! Why? To date, the Flinders Ranges have not been regarded as a karst province of any significance, and so have not been targeted for cave exploration activities. Added to this is the difficulty of access to the bands of limestone. Due to the rugged nature of the landscape, most limestone areas have to be explored on foot (or horse? or camel?). The semi-arid and arid nature of the Flinders Ranges has meant that penetration of the region has been minimal. Most visitors are restricted to the main roads and gorges, and cave exploration across limestone outcrops are limited by both access restrictions and availability of water. These twin factors have resulted in the fact that, to date, most caves in the Flinders Ranges are found within 400 metres of either a road, track or gorge (Figure 6).

FIGURE 6 The relationship between known caves and access routes. Source: compiled by author based on records held by the Cave Exploration Group of South Australia.



The selection of the Flinders Ranges as a venue for the twenty-first conference of the Australian Speleological Federation signifies that the area is worthy of consideration as a karst region. May there be much more exploration of the area in the future! The areas of greatest potential for new cave finds are outcrops of Balcanoona, Etina, Trezona and Wilkawillina Formations in the areas shown in Figure 1. If (or when) more caves are found in the Flinders Ranges, it would be appreciated if accurate location information (preferably a GPS reading) and description details (preferably using the forms found in the 'Australian Karst Index' (Matthews 1985)) are reported to the official South Australian repository of such information. The appropriate person is:

The Records Officer
Cave Exploration Group of South Australia
PO Box 144
Rundle Mall
Adelaide
South Australia 5000

VII. ACKNOWLEDGMENTS

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