

**Strato-tectonic evolution of a large subsidence
structure associated with the late Proterozoic Wonoka Formation
at Wilpena Pound, central Flinders Ranges, South Australia.**

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ABSTRACT

The coincidence between the timing of the subsidence of a trough-like structure adjacent to Wilpena Pound and the initiation of canyons associated with the late Proterozoic Wonoka Formation in other parts of the Flinders Ranges provides circumstantial but not necessarily compelling evidence for a tectonic control being involved with the formation of the canyons. The trough, here termed The Wilpena Trough, is characterised by the presence of a deep central sag and shoulder sags bounded by steep north-easterly trending faults. Other canyons may have marginal faults; and the numerous reversals of current indicators within them, rather than simple unidirectional current trends such as expected with turbidite erosion, substantiate a tectonic influence in their generation.

Small scale faulting in the Wearing Dolomite Member of the Wonoka Formation reflects the dominantly extensional regime in which the Wilpena Trough was formed. A phase of warping prior to deposition of the Wonoka Formation may have provided the necessary trigger to produce stress zones in strata, where growth faults controlling the sedimentation in the Wilpena Trough were initiated.

After deposition of the Wearing Dolomite Member in a shallow water palaeoenvironment, Units 2 and 3 of the Wonoka Formation were deposited in deeper water settings on a shelfal slope. This idea supports a submarine environment prior to subsidence of the Trough. Measured stratigraphic thickness changes give a precise timing for the initiation of fault movement that caused thickened packages of sediments. Major fault movement and corresponding sediment subsidence became active near the Unit 2 / Unit 3 transition and dominated the deposition of Unit 3 through to Unit 7. Units 4 to 9 represent a wedge of prograding shelf sediments. Unit 10 is a shallow transgressional sequence and a sequence boundary has been proposed for the base of this unit, due to the marked change in sedimentary style.

Stable carbon and oxygen isotopic data from the sediments of the Wonoka Formation in the central Flinders Ranges shows an initial low negative plot which is succeeded by an interval showing a strong negative excursion which then makes a shift back to low negative values. A possible correlation between late Proterozoic units in the

Adelaide Fold Belt and the eastern Officer Basin enables the data from the Wonoka Formation to be added to information which Pell (1989) obtained from the Rodda Beds to show a continuous trend from the negative excursion to a broad positive one. Comparison with corresponding overseas data provides a potential tool for late Proterozoic inter-regional basin correlation.

CHAPTER ONE

INTRODUCTION

Reference by various authors (e.g. Coats 1964; von der Borch et al. 1982; Jenkins 1990) to faulting associated with the formation of canyons initiated during the time of the Wonoka Formation poses the possibility that tectonic movements played a major role in their generation. Recognition of a fault-controlled trough on the eastern side of Wilpena Pound, formed during Wonoka time, and of similar magnitude to many canyons raises the possibility of studying preserved structures that may have been related to canyon initiation. Elsewhere these structures are generally eroded or otherwise modified during subsequent canyon development. For these reasons, the Wilpena Trough gives important control relevant to any consideration of canyon genesis.

Mapping and measurements of stratigraphic thickness changes of sediments from the Wilpena Group associated with the Wilpena Trough enabled determination of precise timing for initiation of the structure.

Elucidation of the depositional environments provided additional control in discriminating between sequence stratigraphic events and local subsidence of sediments in the Wilpena Group.

Carbon isotope data from the Wonoka Formation at Bunyeroo Gorge were obtained to provide an added perspective on the controlling influences on sedimentation, and a search was made for microfossils.

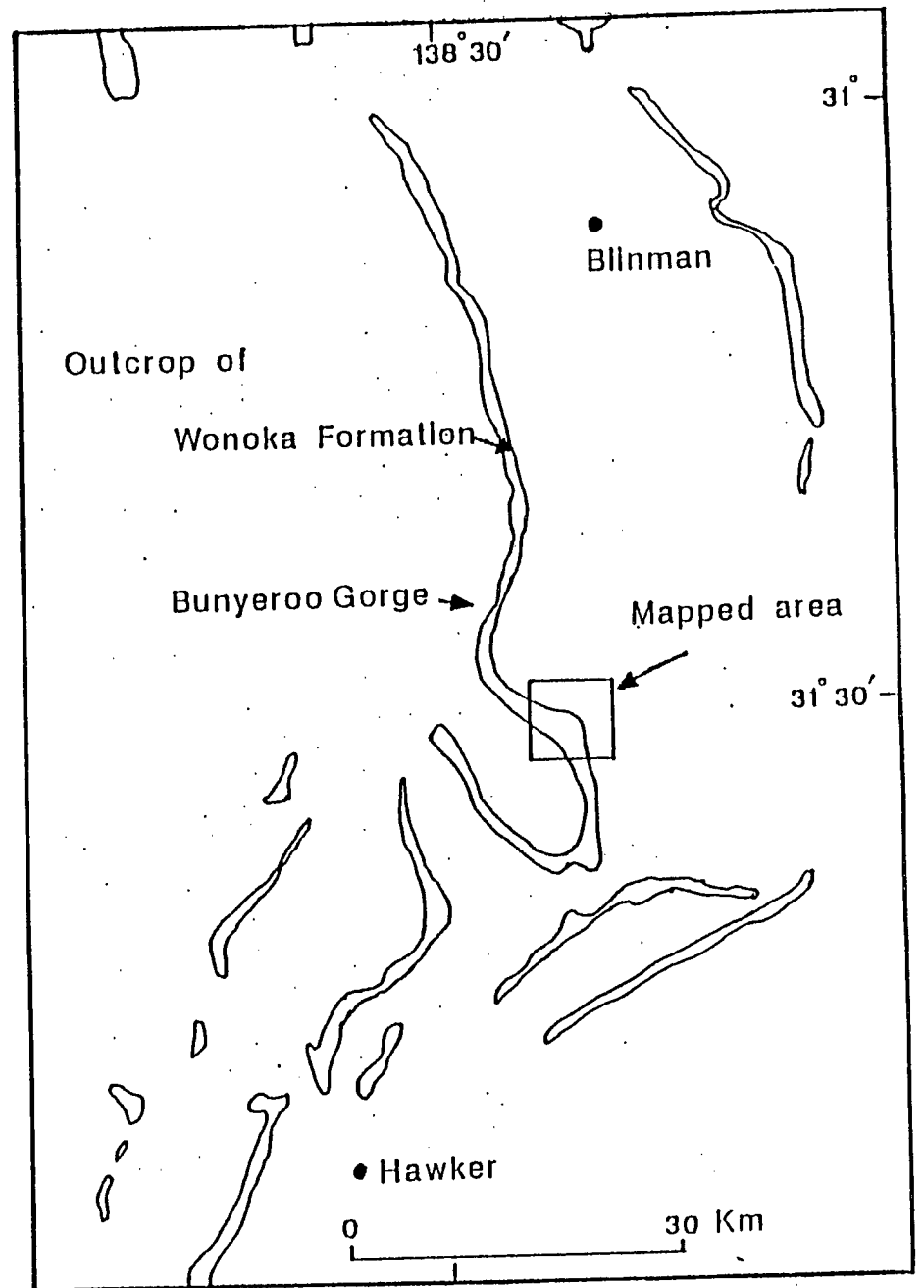
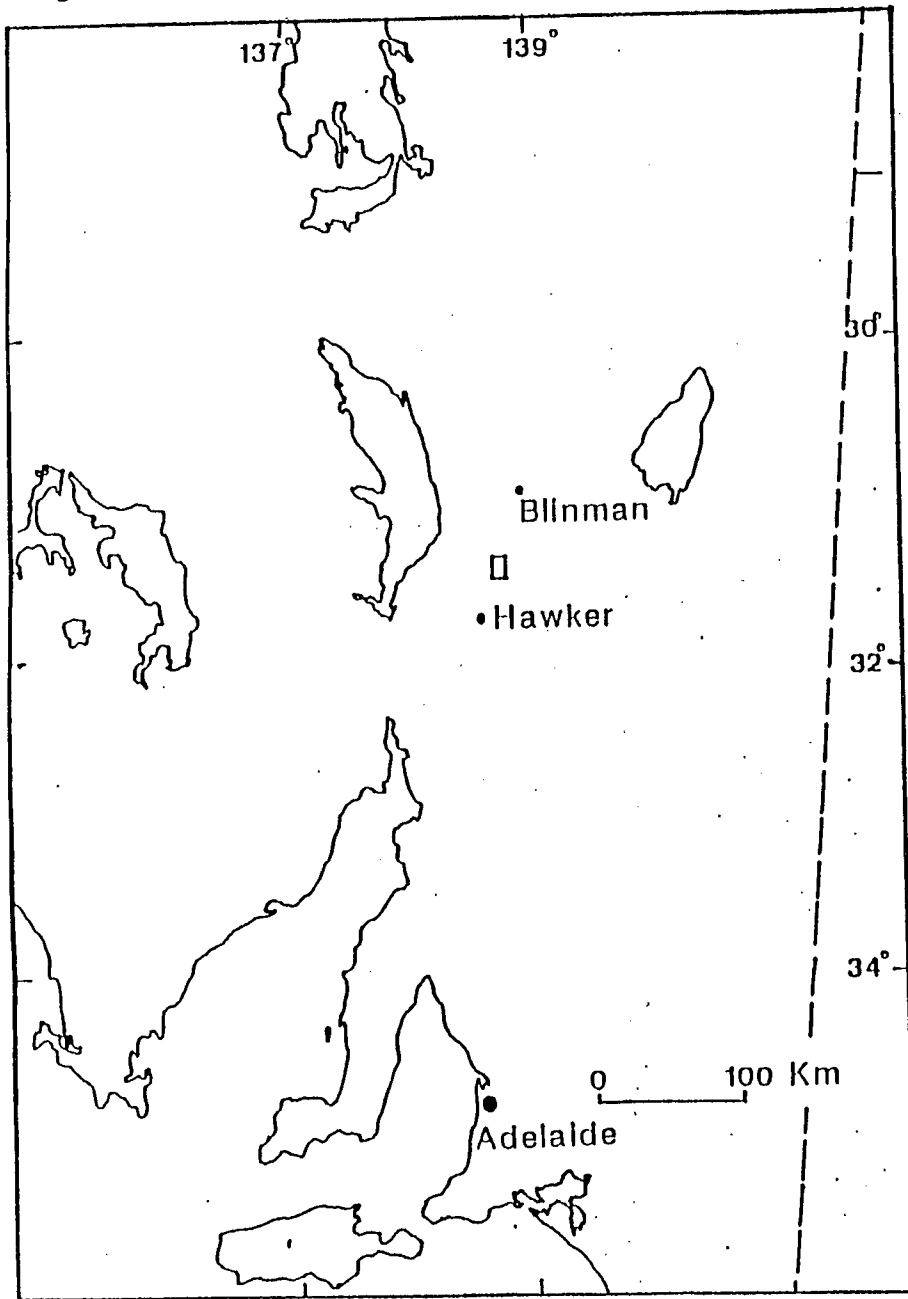
REGIONAL GEOLOGICAL SETTING AND PREVIOUS INVESTIGATIONS

The Adelaide Fold Belt (Adelaide Geosyncline) consists of a thick sequence of late Proterozoic and Cambrian syn- and post-rift sediments and rare volcanics forming a north/south trending zone within South Australia. Current ideas indicate that the Adelaide Fold Belt resembles a passive continental margin setting in the south, and an intracontinental rift or aulocogen in the central and northern regions of the Flinders Ranges (von der Borch 1980; von der Borch et al. 1982). A somewhat different model proposed by Jenkins (1990) relates deposition of the Adelaide Fold Belt to repeated cycles of lithospheric extension and thermal subsidence. This study focuses primarily on sediments belonging to the Wilpena Group, originally defined by Dalgarno and Johnson (in Thomson et al. 1964).

The Wilpena Group has been recognised as a post-glacial sequence and is the most widespread group in the Adelaide Fold Belt (Preiss 1987). Sediments of the Wilpena Group extend across the Adelaide Fold Belt and onto the Stuart Shelf of the Gawler Platform in the west, as well as to the Curnamona Cratonic Nucleus in the east. The Wilpena Group is so extensive that the geology of the north-western Officer Basin, and the Amadeus Basin of central Australia can be stratigraphically correlated with it by way of lithological similarities and isotopic studies. This illustrates the degree to which controlling sedimentary conditions (and possibly the tectonic regime) were remarkably constant over the whole area.

The north-easterly orientated Wilpena Trough is located on the eastern side of Wilpena Pound in the central Flinders Ranges (Fig. 1). It follows on directly from other north-easterly faulted structures on the PARACHILNA (1:250 000) sheet, such as the Oraparinna Trough in the east (Fig 8). Aerial photographs show an apparent continuation of the structure on the western side of Wilpena Pound.

Figure 1- LOCATION OF STUDY AREA



Coats (1964), first recognised an unusually large scale, late Proterozoic slump structure in the Patsy Springs area, east of Copley (northern Flinders Ranges). He described the slump as showing faulted margins and being eroded to varying degrees into the underlying Bunyeroo Formation and ABC Range Quartzite, and filled with thick sequences of the Wonoka Formation. Thomson (1969) and Coats (1973) identified the erosional structure at Patsy Springs as a deep submarine canyon. Various workers (von der Borch et al. 1982, 1983, 1985, 1989; von der Borch and Grady 1983; Eickhoff et al. 1988; Di Bona et al. 1990; Haines 1987) have since made detailed studies of these structures in various parts of the Flinders Ranges.

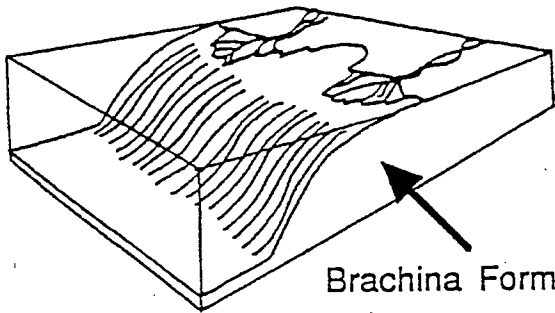
The Wonoka Formation is primarily a storm-dominated, mixed carbonate-siliciclastic shelf sequence (Haines 1988, 1989). Haines (1987) found the shelf sequence to grade laterally towards tectonically controlled, shelf-edge sediments and slope facies which passed into a shale-dominated basin. The 'submarine' canyons were cut through the shelf edge and are deepest in the northern regions of the Flinders Ranges.

Von der Borch et al. (1982) noted the presence of axial conglomerates and thick bedded turbidites within the basal canyon fill of the Patsy Springs Canyon. The axial conglomerates were interpreted as being of fluvial origin possibly sited in a river gorge formed during a low-stand of sea level. Alternatively, they may represent a deep water setting. This latter hypothesis implies that an original fluvial valley existed but was removed by subaqueous erosive action of abrasive sands, which scoured out a deep ravine (Fig. 2). The mass movement of sandflows could also have been triggered by slumping. An abrasive action was preferred due to the unusual wall steepness of canyons. However the Patsy Springs Canyon was found to occur in close association with a local synclinal structure (von der Borch et al. 1982) which may have exaggerated the wall steepness. In order to interpret its history, a correction was made to remove the superimposed tectonic folding of the canyon, possibly obscuring important fault structures. This early submarine model had considerable drawbacks because it implied a significant fall in relative sea level, to allow for fluvial systems to unload abrasive

FIGURE 2

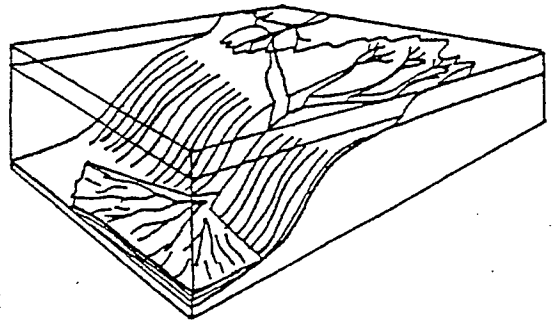
The following are models for canyon formation suggested by von der Borch et al. (1982).

- A. Prograding Brachina Formation and ABC Range Quartzite sediments.
- B. Sea level fall and initial subaerial or submarine incision of canyons.
- C. Sea level rise accompanied with progradation of Wonoka Formation delta or slope facies.
- D. Submarine-fan sequence (Billy Springs Formation and Wonoka Formation) onlaps slope and progressively backfills the canyon. Delta or slope facies continue to prograde, finally burying the filled canyon.

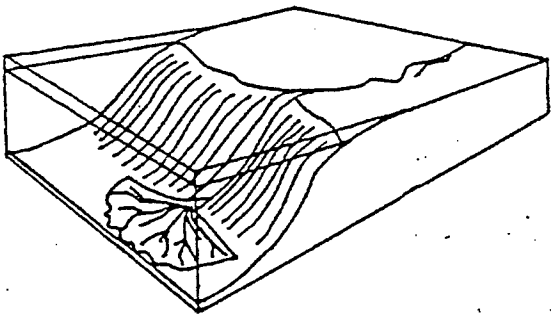


Brachina Formation
and ABC Range Quartzite

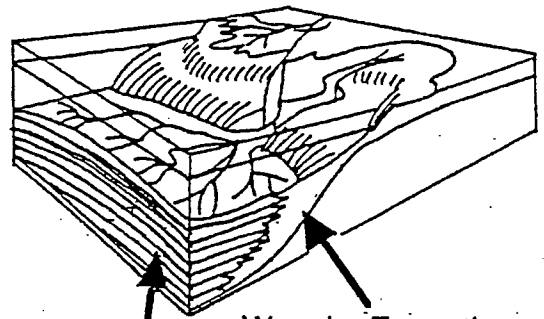
A



C



B



Wonoka Formation

Billy Springs Formation

D

sediments onto the basin slope (von der Borch et al. 1982). A significant rise in sea level was needed to account for prograding marine sediments forming the canyon fill.

The presence of a grey limestone crust, or wall veneer plastered onto the sides of the structures, may support notions for the subaerial formation of canyons (Eickhoff et al. 1988; von der Borch et al. 1989). Stable isotope measurements on carbon ($\delta^{13}\text{C}$ -8.89‰ PDB) and oxygen ($\delta^{18}\text{O}$ -15.43‰ PDB) in the wall veneer from the Taylors' Gorge area (Eickhoff et al. 1988) show strong negative values suggestive of a subaerial origin.

A current working hypothesis (von der Borch et al. 1989) is for a Messinian-style evaporitic lowering, and subsequent raising of sea level. Large channels below Israel and the Rhone and Nile Valleys are thought to have been formed subaerially when the Mediterranean dried out in the mid-Tertiary 'Messinian event', and then filled gradually by the sea. However, in respect of the Wonoka Formation, there is no evidence for correlative salt deposits usually to be expected in association with large scale evaporitic drawdown and there are no substantive external lines of evidence for eustatic sea level falls in the order of 1500 metres for this period of time.

Alternatively, canyon incision may have been triggered by a warping phase near the termination of the Bunyeroo Formation and initiation of 'flyschoid' type sedimentation of the Wonoka Formation (Jenkins and Gostin 1983). Von der Borch et al. (1982) agreed that canyon incision was related to a major tectono-sedimentary cycle, but they stated that canyons were not obviously fault controlled.

The Patsy Springs and Fortress Hill Canyon Complexes are separated by 40 km and are believed to be a single sinuous incised channel (von der Borch et al. 1983, 1985; von der Borch and Grady 1983). This was supported by the fact that palaeocurrent directions in adjacent canyons altered by 180°. V. A. Gostin and R. J. F. Jenkins (pers. comm.) note evidence of oscillation ripples and hummocky cross stratification at deep levels in the fill and suggest an upwards deepening facies-succession in certain canyons. Remnants of canyons in southern regions also appear to represent a meander incised into a southerly dipping palaeoslope (Preiss 1987).

Yet another proposed mechanism (von der Borch et al. 1989) is the production of uplift by diapirism, leading to locally focussed erosive processes. There is clear evidence of diapiric movement during Wonoka Formation deposition (Haines 1986), but no direct evidence of diapirism in the Wilpena area itself.

CHAPTER TWO

STRATIGRAPHY

The purpose of mapping the Wilpena area was to measure tectonic changes in the thickness of units, thus establishing a time frame for tectonic movements relating to the formation of the Wilpena Trough.

Nuccaleena Formation

The Nuccaleena Formation, defined by Coats (in Thomson et al. 1964), represents the basal unit of the Wilpena Group. It consists of a remarkably persistent cream to yellow, weathering dolomite with minor shales and forms a useful marker horizon. The dolomite consists of thin laminae with minor low angle cross-bedding. Its thickness remains relatively constant in the Wilpena area, averaging approximately 10 metres. Thickness variations are common in this widespread unit, ranging from 5 to 50 metres across the Adelaide Fold Belt (Preiss 1987). Formation of dolomitic concretions 10 cms in diameter occur at the lowest levels of the Brachina Formation on the southern side of the Woolshed Fault, and are presumed to be related to solutions introduced along the fault (Plate 1b). Concretions of dolomite within the Nuccaleena Formation are also common across the Flinders Ranges (N.M. Lemon, pers. comm.). Although it is generally considered that dolomites are a reprecipitation of original CaCO_3 , the Nuccaleena Formation is interpreted by Williams (1979) as representing primary micritic dolomite deposited in a shallow marine environment. Plummer (1979) noted that some nodular dolomites within the Formation were of secondary origin. Therefore, late Proterozoic dolomites such as the Nuccaleena Formation and the Wearing Dolomite Member of the basal Wonoka Formation may, in fact, represent true primary dolomites, with minor secondary alteration due to diagenesis.

Brachina Formation

Boundaries between members of the Brachina Formation are gradational and accurately mappable contacts between the Moolooloo, Moorilah and Bailey Range Members were not defined. It is evident that the Brachina Formation is a fining and then a coarsening upwards sequence, culminating with deposition of the conformable ABC Range Quartzite. The fining upwards sequence of the Brachina Formation represent a high stand systems tract. Thinly laminated, basal shales indicate an initial transgression after deposition of the Nuccaleena Formation. Sediments grade into pale green to khaki weathering, finely laminated shales, with upward increasing silty shales and thin clastic storm deposits; these represent a regressive systems tract.

Continued regression is represented by the increasing sand component of upper members of the Brachina Formation. Scotford (1984) implies a complete storm domination of the upper succession due to the presence of rippled siltstones, and fine to coarse storm sandstones showing hummocky cross-stratification, cross-bedding, and interference rippled tops.

Sedimentation of the Brachina Formation appears to have occurred initially below storm wave base, and then shallowed to reach fair-weather wave base.

ABC Range Quartzite

The ABC Range Quartzite is composed of pink to grey, medium grained quartzites with minor siltstone and fine sandstone interbeds. A common characteristic of the lower quartzites is their heavy mineral lamination. Upper ABC Range Quartzites show particularly well preserved, three dimensional oscillation ripples and tabular cross bedding, representing shallow marine to tidal flat environments (with occasional drying out of sediments evidenced by the presence of mudcracks and intraclasts: Preiss 1987). The ABC Range Quartzite also contains occasional conglomeratic layers (sedimentary breccias), particularly near the Woolshed and Wilpena Faults, indicating a reworking of sediments. It is noteworthy that Scotford (1984) also recognised local conglomerates in the Warraweena area, northern Flinders Ranges, where he related them to diapiric

activity. Because these conglomerates occur close to faults in the Wilpena area, it may be assumed that they are related to faulting. In later discussion it is suggested that movement on the faults was most prominent during Wonoka Formation time. However Preiss (1987) suggests that syndepositional faulting allowed considerable thicknesses of the ABC Range Quartzite to accumulate in a region east of the Torrens Hinge Zone. Extensional movement and hence formation of the basin for deposition of the Bunyeroo Formation could possibly have been initiated at this stage, but the ABC Range Quartzite shows no great thickness variation across the Wilpena area such as would be needed to support this model.

Bunyeroo Formation

The base of the Bunyeroo Formation is clearly evident as a sharp colour change from the coarse quartzites of the ABC Range to maroon 'pencil' shales. At the base of the Bunyeroo Formation, small interbeds of sandstone (up to 5cm thick) are present. Similar sandstones were also recognised in Brachina Gorge by Haines (1987), who interprets them as storm deposits. Although the Acraman impact ejecta layer (Gostin et al. 1986) occurs at the correct stratigraphic level (approximately 95 metres above the base of the Bunyeroo Formation), it outcrops poorly (Plate 1c). It contains Gawler Range Volcanic fragments up to 3cm in diameter in a bed of coarse sandstone approximately 15 cm thick (Plate 1d). At Bunyeroo and Brachina Gorges, volcanic and coarse fragments within this layer show evidence of shock metamorphic features such as shock lamellae in quartz, and small scale shatter cones. Gostin et al. (1986) interpreted the horizon as evidence of a major meteoric impact event, with the impact site occurring in Lake Acraman, 300 km west of the Flinders Ranges (Williams 1979).

Wonoka Formation: introduction

Haines (1986, 1987) subdivided the Wonoka Formation into eleven mappable units on the basis of lithological differences. Field mapping and interpretation of the Wonoka Formation in this study follows Haines' classification. The original basal boundary of

the Wonoka Formation proposed by Dalgarno and Johnson (1966) excludes Units 1 and 2, which remain within the Bunyeroo Formation. A revised boundary for the Wonoka Formation defined as corresponding to the start of the Ediacaran Period (Jenkins 1981) has now been adopted by many authors (Gostin and Jenkins 1983; Jenkins and Gostin 1983; Scotford 1984; Haines 1986, 1987, 1988, 1990; von der Borch et al. 1988; Di Bona et al. 1990; Jenkins 1990) because it represents a basin-wide marker horizon. However, there is still caution in acceptance of this new boundary (Priess 1987, 1990) although it defines an abrupt sedimentological change, from carbonate-poor sedimentation to sediments of increasing carbonate content (Plate 1e).

Unit 1

Unit 1 is a thin, banded, cupriferous dolomite horizon equivalent to the Wearing Dolomite Member of Thomson (1965) and Priess (1987). It is present throughout the study area but appears as a brecciated crust-like deposit on the margin of the Wilpena Trough, adjacent to the Woolshed Fault and on the southern faulted margin (Plate 1f). Its average thickness is approximately 80 cm. However, it may vary from as thin as 5 cm in the northern Flinders Ranges to a maximum thickness of approximately 10 metres in the southwest (Haines 1987). In the Wilpena area, Unit 1 consists of thin, cream dolomite beds (1cm) which have sharp bases and gradational tops, representing rhythmic deposition (Plate 2a). Some exposures show erosional scouring topped by reworked intraclastic dolomite material in a shale matrix. This may reflect minor local slumping. In Bunyeroo Gorge, Unit 1 is about two metres in thickness and also consists of thin beds of cream dolomite. Here there is more evidence of reworking of dolomite to produce beds of intraformational conglomerate.

Unit 1 shows distinct green malachite staining in outcrop and Haines (1987) noted the occasional presence of pyrite and chalcopyrite in fresh samples.

Discussion of Unit 1

A precise model for the environment of deposition of Unit 1 is very uncertain. Dolomite deposition is generally associated with shallow water conditions. Staining of sections (following a method used by Dickson 1984) shows a ferroan calcite cement, and also non-ferroan calcite thought to reflect an early secondary alteration component. The ferroan calcite may represent seafloor cementation of the dolomite intraclasts. The calcite suggests a primary origin for the dolomite, or very early diagenetic replacement (Haines 1987). Haines (1987) observed that dolomite beds had gradational bases and sharp tops, and interprets this as a function of seafloor dolomitization during periods of non-deposition or following minor erosive events.

Generally, it is considered that primary dolomites indicate a supratidal depositional environment (von der Borch and Lock 1979). But Baker and Burns (cited in Haines 1987) give evidence that modern dolomite formation on continental shelves is a function of relatively low rates of sedimentation and a high organic carbon content (>0.5 wt% TOC). Conditions that allowed for a condensed interval of dolomite deposition during a time of very slow sedimentation were favoured because at higher rates of sedimentation the dolomite becomes diluted (Haines 1987; von der Borch et al. 1988; Di Bona et al. 1990). Such conditions are low energy and commonly reducing, and thus should favour the preservation of organic matter. Associated green shales and sulphides may indicate the temporary reducing conditions necessary (Haines 1987). The organic carbon content of Unit 1 is very low (0.011wt% TOC) consistent with a shallow water, oxidising environment. This may have permitted episodic current reworking responsible for the intraclastic bands. Most Proterozoic carbonates have low organic carbon contents reflecting a shallow water, oxic environment (Ronov 1958). Therefore a suggested suitable environment for Unit 1 is a shallow water oxidising environment with occasional pulses of incoming sediment, and fewer energetic currents ripping up and depositing intraclasts. A supratidal environment is ruled out by the lack of mud cracks, ripples or truncation of layers. Beach conglomerates and stromatolites have in fact been reported

for this unit (Gostin and Jenkins 1983). A more favourable shallow environment is that of a shelf at the time of reduced sea level, just below fair weather wave base.

Unit 2

The base of Unit 2 is characterised by thin storm sandstone beds (up to 10 cm thick) alternating with maroon shales (Plate 2c). The calcareous content of the quartz-rich sandstones and shales increases up section. The thickness of the storm sandstones reaches a maximum 50 to 60 metres above the base of the unit, with some beds ranging up to 90 cm thick. An amalgamation of beds is common. These sandstones show both sharp and gradational bases, and flute marks (Plate 2e) give an average palaeocurrent trend of 060° (implying a northeast current direction consistent with currents in several known canyons). These beds also show characteristics which are indicative of Bouma turbidites (Bouma 1962), particularly Bouma $T_{A,B,C,E}$ divisions. Haines (1987) found that the graded T_A division was generally absent, and regards the beds as 'tempestites'. In the Wilpena area, the T_A is commonly present in a $T_{A,B,C}$ (Plate 2b). Thicker sets (40 to 90 cm) are composed of a massive T_A division grading into the planar laminated T_B division and the rippled T_C division (with sharp wavy tops, Plate 2d). Small scale hummocky cross stratification is also commonly present. Towards the top of the unit, sandstone tempestite beds become thin (< 30 cm) and alternate with calcareous shales forming a transition into Unit 3. Hummocky cross stratification and ripple features indicate some storm reworking of sediments (Haines 1987, 1988, 1990; Di Bona et al. 1990) and unidirectional currents indicate deposition down palaeoslope, away from a presumed source near the Torrens Hinge Zone. The observation of relatively rapid thinning of beds at the top of Unit 2 and the transition into Unit 3 may suggest a continuing rise in sea level, or raising of depositional base level and truncation of coarse sediment supply. This correlates with initiation of subsidence of the Wilpena Trough structure and canyon formation in other areas of the Flinders Ranges.

Unit 3

Fine, planar laminated bands of thin limestone which occur as sets in surrounding red, silty shales characterise Unit 3 (Plate 2f). This unit has a recessive topographic expression. The pink, micritic limestones are less than 4 cm thick and first appear several metres above the base of Unit 3, but are known to occur up to 40 metres above the base (Haines 1987). The limestones show little evidence of current activity and represent a return to deposition in deep starved conditions, much like the muds of the Bunyeroo Formation. Thick intraformational conglomerates have been observed elsewhere within this unit (Scotford 1984, Haines 1987) and this suggest episodic slumping and density currents possibly related to active tectonism during this phase. Local synsedimentary slumping occurs adjacent to faults in the Wilpena area, but is less pronounced in Bunyeroo Gorge, where the unit is considerably thicker (approximately 150 metres).

Unit 4

The passage up into Unit 4 is gradational at Bunyeroo Gorge and in the Wilpena area, where it forms small rounded hills. Outcrops of weathered, pale green shales/limestones are interbedded with sets of calcareous siltstones and minor maroon shales. Malachite staining appears near the base of Unit 4. The sets of green limestones and shales show Bouma T_{C,E} and T_{B,C,E} divisions (Plate 3a). Unit 4 is predominantly storm dominated (Scotford 1984). Intraformational conglomerates as observed in the mid-northern Flinders Ranges (Scotford 1984) were not present in outcrop, and this may reflect exclusion of coarse material from the Wilpena Trough, indicating a general offshore setting. The distinct green coloration of the storm beds and associated limestone turbidites may suggest reducing conditions similar to those of the green sulphide-rich shales in the mid-Bunyeroo Formation. There is also evidence of diapirism in central northern areas of the Flinders Ranges late during deposition of Unit 4 (Scotford 1984). Synsedimentary slumping common within Unit 4 may reflect movement of local diapirs.

Unit 5

The thin bedded, green sediments of Unit 4 grade rapidly into thicker beds of silty limestones and red, sandy limestones. Hummocky cross stratification, planar bedding and climbing ripples are common. Thinly laminated shale interbeds (possibly turbidites) may represent periods of suspension sedimentation. Stylonodular texture is present in gritty limestones upsection. Small scale, soft-sediment deformation in the form of truncated bedding occurs and is particularly obvious in reddened limestones (Plate 3b). Staining of sections (following the method in Dickson 1984) shows the red sandy limestones to be particularly ferroan, hence accounting for the coloration. Thinner (< 3 cm), but coarser beds of sandy carbonate show greater ferruginous coloration which Haines (1987) related to haematite coating of grains. The increase in the sandy component in Unit 5 from Unit 4 reflects shallowing and infilling of the Wilpena Trough. Unit 5 also shows spectacular syndepositional slumping and related tight, zig-zag folding corresponding to a time of increased fault movement (Plate 3c, 3d).

Unit 6

Medium to thick sets of fine grained sandstones and interbedded grey shales define Unit 6. Hummocky cross stratification and some wave ripple structures are present in the calcareous sandstone towards the top of Unit 5, and appear to indicate continued shallowing. Syn-depositional slumping occurs near the main faulted margin (Woolshed Fault) of the Wilpena Trough.

Unit 7

Unit 7 predominantly consists of relatively clean, grey limestones and finer silty micritic limestones along with minor amounts of interbedded shale. Intraformational conglomerates and concretions are present. Abundant hummocky cross stratification,

planar lamination, climbing and interference ripples are easily identifiable. Stylonodular bedding is well developed along bedding planes and provides evidence for some secondary alteration by meteoric waters. A stromatolitic horizon, identified by Haines (1987) in upper Unit 7, appears to be absent in the Wilpena area. Occurrence of tuffaceous intervals are a notable aspect of Unit 7. The red coloration of limestones enveloping the tuff beds is due to iron oxides leaching into the surrounding sediments. The source of the volcanics is unknown.

Units 6 and 7 represent the thickest wedge of sediments within the Wilpena Trough, reflecting fault-induced subsidence.

Unit 8/9

Units 8 and 9 are thinned relative to other areas and were mapped as one unit on the basis of their intergradation, and the poor representation of Unit 9 in the Wilpena area. The base of Unit 8 is characterised by grey limestones which grade into olive green calcareous shales and siltstones. Hummocky cross stratification is generally absent, except for small scale examples in the Unit 7 to Unit 8 transition. Unit 9 is less than one metre thick at Bunyeroo Gorge and does not occur at localities further south (Haines 1987). The occurrence of a thin purple coloured horizon in Unit 8, including possible fine thigmotactic trace fossils, is considered to represent a significant time line (Haines 1987).

Unit 10

Unit 10 consists of medium grained quartzose sandstones with sandwaves and cross bedding. Basal yellow sandstones pass into an interval of red, silty sandstone similar to that of the Bonney Sandstone. The red sandstone grades into a thin accumulation of weathered shale. A sequence boundary is suggested to occur at the base of Unit 10 on the basis of a change in the style of sedimentation. This sequence boundary may correlate with the base of Sequence 5 of Di Bona et al. (1990). Unit 10 represents a shallowing

transgression above the surface marking the sequence boundary, and grades into an overlying lagoonal facies in the central Flinders Ranges area.

Unit 11

Haines (1987) reported that Unit 11 thickens rapidly southwards towards the central regions of the Flinders Ranges and further south it is not recognised. However, above an interval of little exposure, Unit 11 appears as an ooid-rich, grey to silty thin bedded limestone. This passes into an interval (approximately two metres thick) of columnar stromatolites (Plate 3e, 3f). Grey to black micritic limestones and minor thin dolomites complete sedimentation of the Wonoka Formation, which passes transitionally into red feldspathic sandstones of the Bonney Sandstone, implying continuous deposition.

CHAPTER THREE

MICROFOSSIL EXAMINATION

Samples 931-08, 931-18, 931-24 from Bunyeroo Gorge (Appendix 1) and sample BR-01 from Brachina Gorge (collected by D.M.McKirdy) were analysed for acritarchs using the hydrofluoric acid rock digestion method (Phipps and Playford 1984). Results proved negative and only varying amounts of amorphous organic matter (kerogen) were microscopically identifiable. The amount of kerogen present varied through the section (c.f. Appendix 1 TOC values).

A positive result was obtained from cut sections prepared from the most organic-rich samples (based on Total Organic Carbon data, see Appendix 1). Thin sections were cut parallel to bedding in samples BR-01 and 931-08. Careful inspection revealed two major groups of microfossils, which were particularly well preserved in sample BR-01. Large spheroid acritarchs varying from 100 μm to 250 μm in diameter, and filamentous microfossils (approximately 50 - 90 μm in width) were present in a fine micritic matrix. Due to low grade metamorphism, thermal alteration of microfossils has occurred. Cell walls have been carbonised and probably replaced by blebs of pyrite. Only the cell outlines are recognisable. Negative results obtained from the hydrofluoric acid method probably reflect the degree of metamorphism (lower greenschist facies) and clotting of the original carbon. Hydrofluoric acid dissolves the carbonate matrix which holds the carbonaceous residues in the shape of filaments and spheroids. Therefore, all that remains is unstructured kerogen and blebs of pyrite.

The occurrence of microfossils within certain units (e.g. Unit 8/9) of the Wonoka Formation closely relates to the particular facies. Unit 11, a black lagoonal carbonaceous silt, should appear to be relatively prospective for microfossils. Stromatolitic assemblages are also identifiable in this unit and they mark the major appearance of biotic activity within the Wonoka Formation (Plate 3e, 3f). This accords with carbon isotope data for this unit taking a sharper shift towards the positive side indicating increased burial of carbon (the silts/shales of Unit 11 were deposited under low energy reducing

conditions which favoured the preservation of organic matter). However, sample BR-01 was collected from the Unit 8/9 level which also occurs above a prominent stromatolitic marker horizon (Haines 1987).

TOTAL ORGANIC CARBON CONTENT

Several important factors which may have governed the TOC content of Proterozoic sediments include

- a) the primary productivity in the overlying water column;
- b) the rate and kind of accumulating sediment; and
- c) the degree of oxidation of dead organic matter in the water column (or the extent to which the dead organic matter is attacked by aerobic bacteria) prior to burial in bottom sediments.

Post-depositional effects, such as high temperature alteration during metamorphism and reworking of the buried organic matter should also be considered when interpreting TOC data.

The group of samples tested for TOC are from the measured section of Wonoka Formation in Bunyerroo Gorge (see Appendix 2). Pell (1989) placed his data from the Wonoka and Billy Springs Formation into two distinct groups; altered and unaltered sediments. TOC values from Bunyerroo Gorge are very low (0.00 - 0.057wt% TOC, Appendix 1) but show a direct correlation with individual units of the Wonoka Formation. The low values tend to suggest thermal alteration of organic matter.

Samples from the Flinders Ranges (including Pell's (1989) data) have lower TOC values than those of correlative units in the Officer Basin. The Rodda Beds were deposited in an environment which favoured incorporation of organic matter into the sediments and escaped severe thermal alteration (Pell 1989).

STABLE ISOTOPES

Determination of the inorganic carbon isotopic composition and total organic carbon content of sedimentary carbonates provides a potentially useful tool for stratigraphic correlation providing there is close understanding of secondary alteration processes. Secular variation of the carbon isotope composition of carbonates has been recorded for much of the Phanerozoic geological record, but until recently, data for the Proterozoic interval were sparse. Based on $\delta^{13}\text{C}$ variations, new information suggests correlations between sequences in Svalbard and East Greenland (Knoll et al. 1986), and Brasier et al. (1990) describe potential correlations between sections in China, Iran, India, Siberia, Morocco, as well as Australia. However, these studies pertain mainly to a positive global carbon isotope excursion below the Precambrian-Cambrian boundary. Recently, Pell (1989) successfully showed similarities in beds in the Officer Basin and those of the Adelaide Fold Belt. Caution must be taken when conclusions are drawn solely on the basis of variation within the isotopic record as resetting of isotopic ratios may occur with diagenesis and thermal overprinting, and any form of metasomatic alteration. Therefore comparisons should be supported by lithological and sedimentological evidence, as well as an understanding of post-depositional processes involved.

THE ISOTOPIC RECORD AT BUNYEROO GORGE

Samples were collected at 30 metre tape intervals through the Wonoka Formation in Bunyeroo Gorge. These were analysed for carbon and oxygen isotope ratios as well as total organic carbon (TOC). Obviously weathered samples were avoided.

Oxygen isotopes provide a less reliable source of information because ratios in sea water are affected by temperature, evaporation and dilution and incorporated ratios in carbonates are also readily altered by a variety of processes. Commonly, Proterozoic oxygen isotopes values show negative trends which may result from the isotopic

exchange with fresh waters during meteoric diagenesis, or exchange involving warm waters at the time of burial (Brasier et al. 1990). Carbon isotopes are generally expected to remain near the composition of the precipitating solution but are sensitive to factors such as mineralogy (eg. calcite, dolomite) and fresh water diagenesis (such as in Bunyeroo Gorge). Brasier et al (1990) state carbon isotopes can provide an indication of the isotopic composition of seawater because circulating pore water solutions contain much less carbon compared with oxygen. A strong positive correlation is found between the $\delta^{18}\text{O}$ and $\delta^{13}\text{C}$ curves from Bunyeroo Gorge, and this suggests true secular variations in the record (Fig. 3).

ISOTOPIC COMPOSITION AND MINERALOGY

Carbonate phases were difficult to determine in samples due to the micritic nature of the sediments. XRD techniques were used to determine approximate dolomite to calcite ratios of the samples. On average, samples contained mixed dolomite /calcite mineralogy, giving rise to more negative $\delta^{13}\text{C}$ values. Minor variations in the trend of the carbon and oxygen profiles can be explained partly by the mineralogy, such as the negative shift above the maximum flooding surface (lower part of Unit 3). Samples of a mixed carbonate mineralogy from drillcore in the Officer Basin also show enrichment in the light isotope (Pell 1989).

The initial plot (see Fig. 3) is of values obtained from Unit 1, the Wearing Dolomite Member, and shows a marked shift relative to values from the overlying mixed carbonates (Fig. 1). Dolomites are more likely to reflect their true $\delta^{18}\text{O}$ and $\delta^{13}\text{C}$ signatures because they are less affected by circulating meteoric waters (Degens et al. 1964). Fine grained shallow water dolomites maintain $\delta^{13}\text{C}$ values close to original CaCO_3 and sea water bicarbonate (Margaritz and Holser 1986). A considerable shift (of the $\delta^{13}\text{C}$ signature) into low negative values beyond 610 metres (base of Unit 10) appears to mark the beginning of a new carbon isotope cycle and correlates with the proposed sequence boundary at this stratigraphic level.

Bonney Sandstone

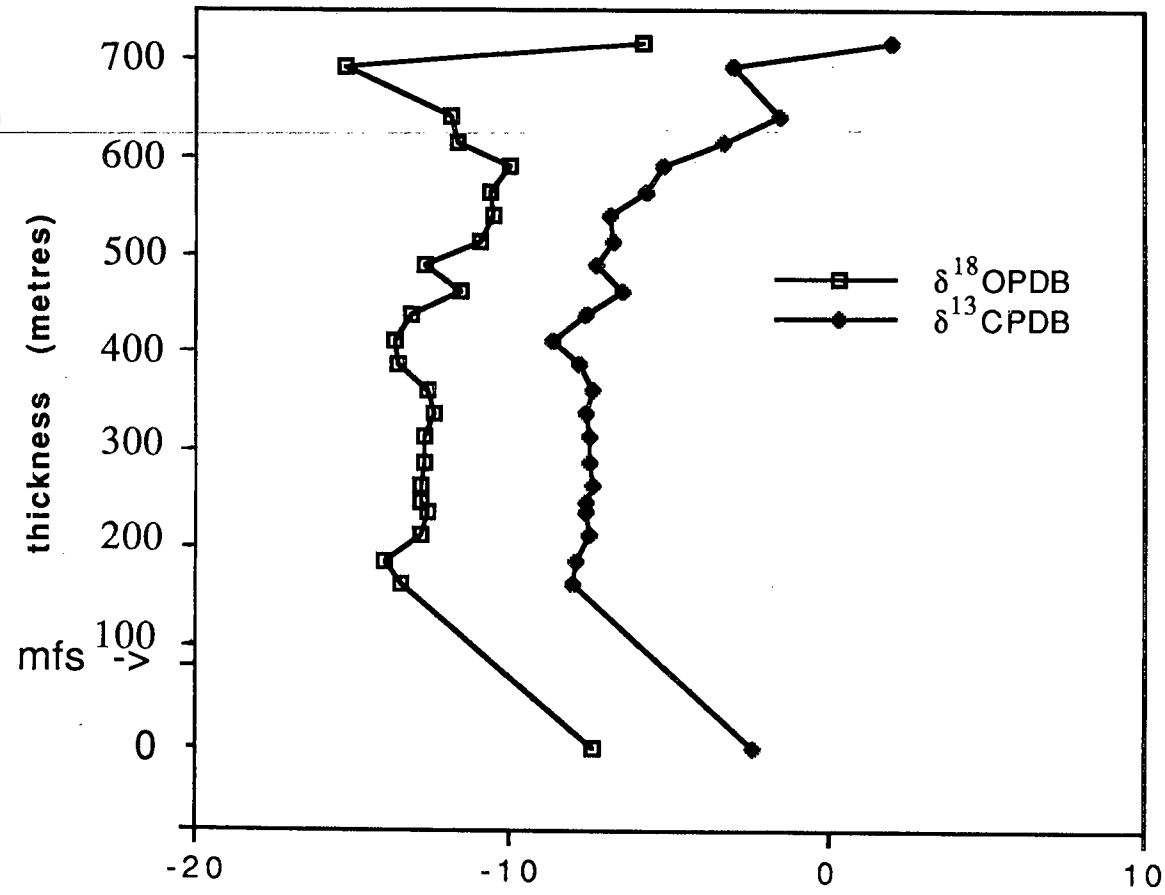
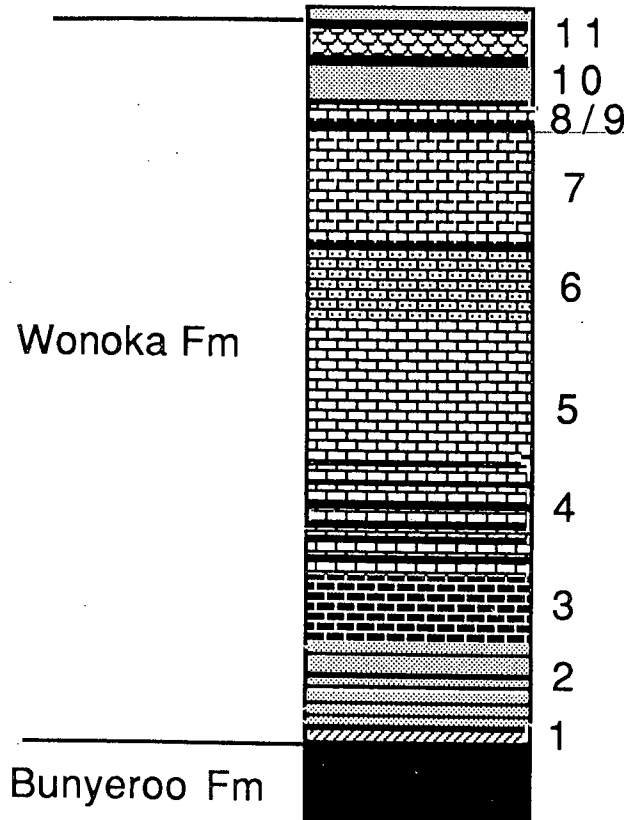


Figure 3. $\delta^{18}\text{O}$ and $\delta^{13}\text{C}$ profiles through the Wonoka Formation at Bunyerroo Gorge, Central Finders Ranges.

COMPARISON WITH THE EASTERN OFFICER BASIN

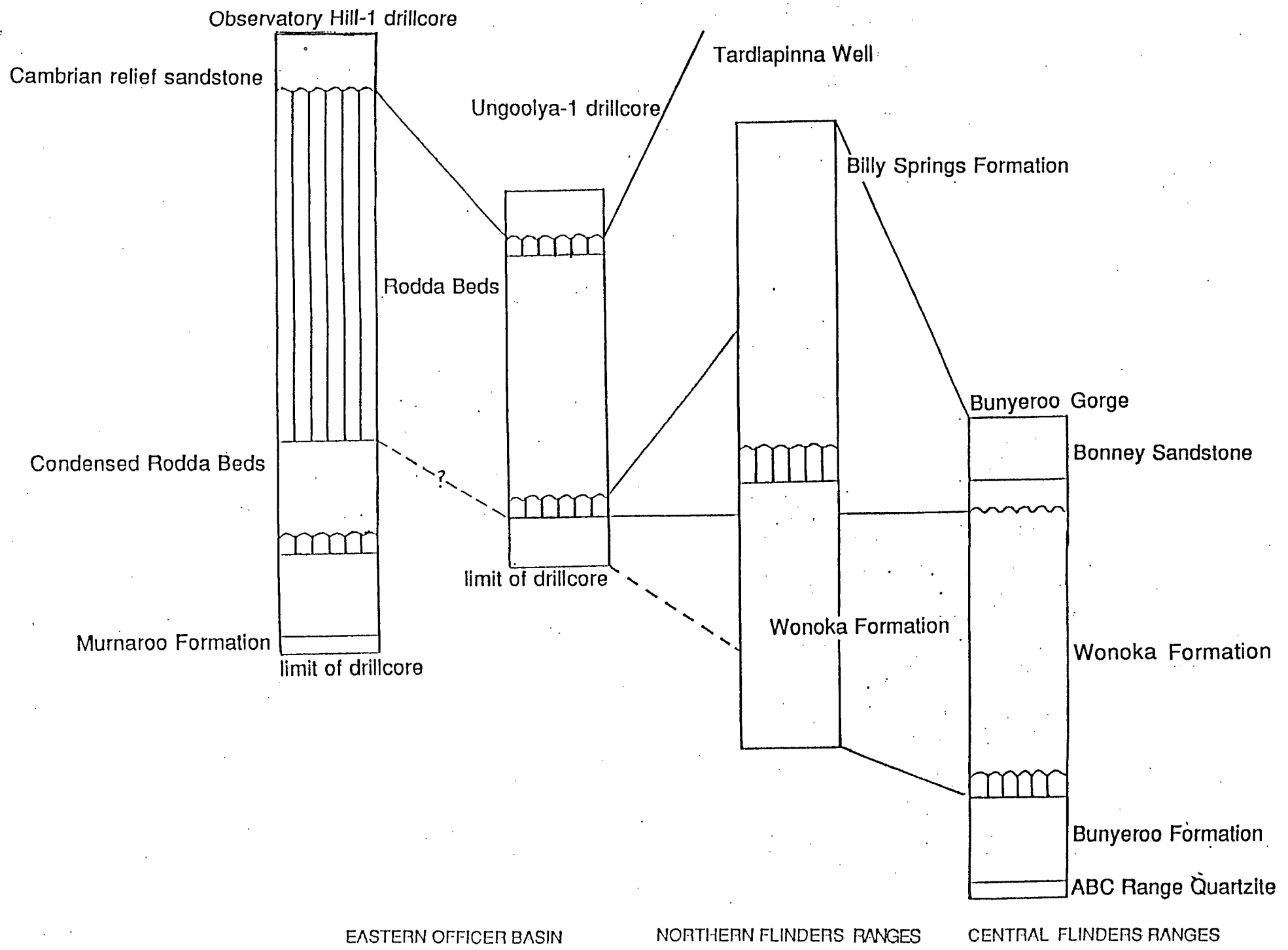
The Officer Basin, which contains a thick sequence of sediments of late Proterozoic and early Palaeozoic age, occupies an area between the Gawler Craton to the south, and the Musgrave Block to the north and extends across Western and South Australia. Sequences of the eastern Officer Basin (South Australia) resemble those of similar age in the Adelaide Fold Belt, in particular the Bunyeroo, Wonoka and Billy Springs Formations. The Rodda Beds overlie the late Proterozoic Murnaroo Formation and consist of red siltstones and thick intervals of grey, laminated calcareous and dolomitic siltstones, limestones and sandstones (Pell 1989; Thomas 1990). Stainton et al. (in Thomas 1990) suggest that the Rodda Beds mainly show characteristics of deep-water sediments. The Rodda Beds are unconformably overlain by Cambrian units.

The lower unit of the Rodda Beds can be correlated with the Bunyeroo Formation based on the presence of the Acraman impact ejecta horizon in the Officer Basin (Wallace et al. 1989). The equivalents of the Bunyeroo Formation constitute approximately 140 metres of the 'lower' Rodda Beds in drillcore at Observatory Hill-1, Officer Basin. However, at Ungoolya-1, the interval of Rodda Beds intersected equates principally with the Billy Springs Formation of the northern Flinders Ranges. An overlying thin interval correlates with the Wonoka Formation. The Billy Springs Formation post-dates the Wonoka Formation.

Recent seismic studies in the eastern Officer Basin (Thomas 1990) show that the Rodda Beds include several prominent marker horizons which provide further evidence that several of the intervening intervals of sediment may correlate with the Bunyeroo and Wonoka Formations. Thomas' classification (1990) of the seismic horizons in the Officer Basin is adopted to make a comparison with particular sediments of the Adelaide Fold Belt (Fig. 4).

FIGURE 4

A correlation of stratigraphic sections from the Officer Basin and the Adelaide Fold Belt. Sections are not to true scale.



Coring in wells indicates seismic horizon 'F₅' (a sequence boundary), is coincident with the Bunyeroo/Wonoka Formation transition, and marks a time of regional extensional faulting. The horizon 'F' sequence boundary is an erosional surface which incised canyons several hundreds of metres deep through the underlying rocks of the 'F₅-F' sequence. The canyon cutting event does not appear to be equivalent to that in the Adelaide Fold Belt because the interval 'F₅ -F' shows a considerably thickened syntectonic sequence, most likely correlating with Wonoka Units 2 to 9. Horizon 'F' may be equivalent to the newly proposed sequence boundary at the base of Wonoka Formation Unit 10, and coincident with the erosional event at the base of the Billy Springs Formation of the northern Flinders Ranges. Therefore, seismic information suggests that the lowermost part of the intersection of the Rodda Beds in Ungoolya-1 is equivalent to part of the Wonoka Formation (R.J.F. Jenkins pers. comm.). Carbonate carbon isotopic evidence presented by Pell (1989) supports this correlation. Negative carbon isotopic values are recorded for both regions (Ungoolya-1 $\delta^{13}\text{C}$ -0.49‰ PDB, $\delta^{18}\text{O}$ -6.41‰ PDB after Pell (1989); Bunyeroo Gorge $\delta^{13}\text{C}$ -6.13‰ PDB, $\delta^{18}\text{O}$ -12.03‰ PDB).

Haines (1987) found petrographic evidence for parts of the Wonoka Formation (Units 2 and 5) to have undergone metamorphic alteration to the chlorite grade and hence data obtained may show some re-equilibration. Samples from the Officer Basin do not appear to show alteration of primary $\delta^{13}\text{C}$ organic values (Pell 1989).

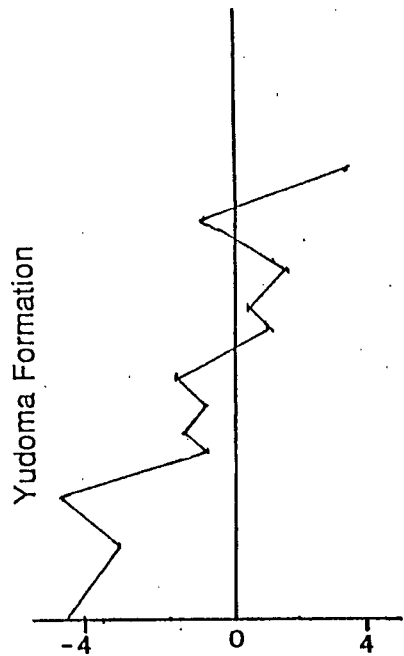
GLOBAL COMPARISONS IN THE ISOTOPIC RECORD

Available isotope data ordered with respect to possible correlations with information from the Officer Basin are presented in Figure 5. An initial negative excursion followed by a broad, weakly positive excursion shows similarities with isotopic profiles of sequences of comparable age in Siberia and Svalbard, hinting at the potential for interregional correlation based on such information.

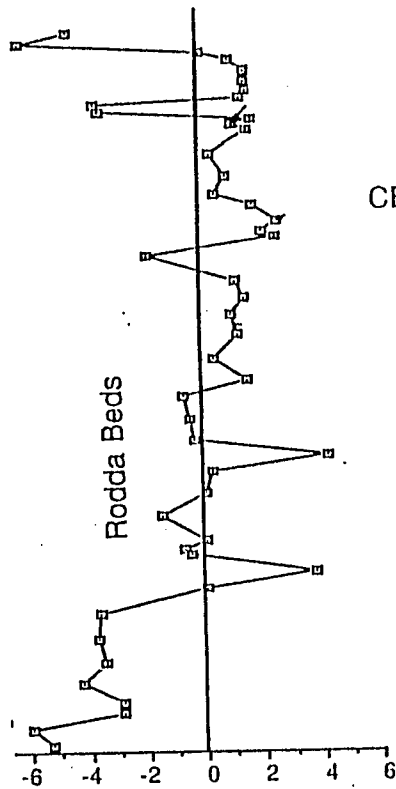
FIGURE 5

A possible correlation of $\delta^{13}\text{C}$ (‰ PDB) profiles from Officer Basin (after Pell 1989), Svalbard and Siberia (after Brasier et al. 1990) with the Bunyeroo Gorge (central Flinders Ranges) profile.

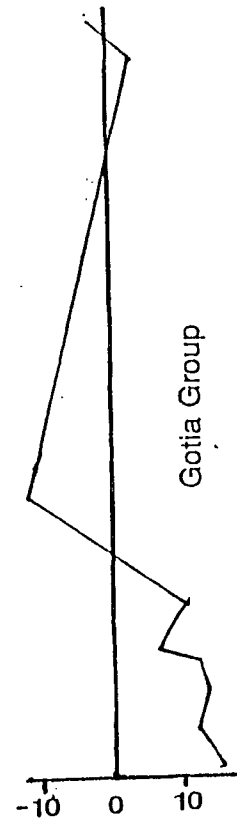
SIBERIAN PLATFORM



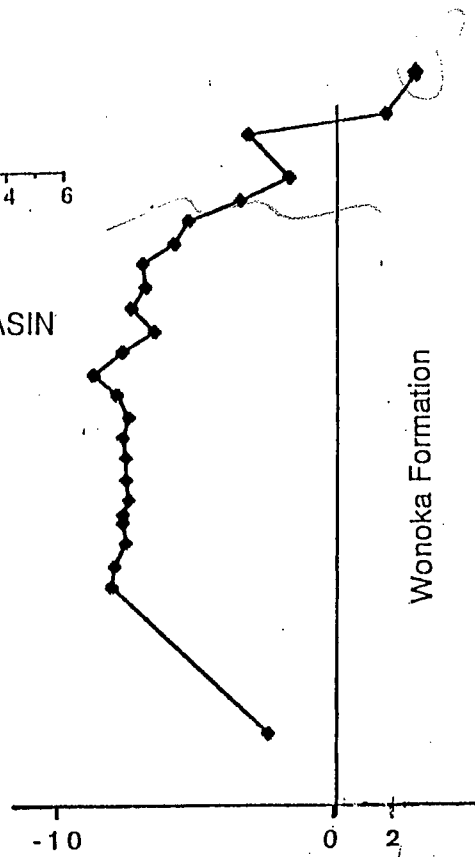
CENTRAL FLINDERS RANGES



SVALBARD



EASTERN OFFICER BASIN



CHAPTER FOUR

DISCUSSION

The Wilpena Group has been divided into two major transgressive-regressive cycles which complete Proterozoic deposition in the Adelaide Fold Belt. The lower cycle begins with the Nuccaleena Formation, a post-glacial capping dolostone of shallow water origin. This is conformably overlain by basinal shales and clastic turbidites or storm beds of the Brachina Formation (Gostin and Jenkins 1983). The shallow marine (beach) to tidal deltaic sandstones of the ABC Range Quartzite overlie the Brachina Formation.

The upper cycle commences with deposition of the maroon 'starved', basinal shales of the Bunyeroo Formation which grade rapidly into a thin cupriferous dolomite believed to be the Wearing Dolomite equivalent (Thomson 1965; Preiss 1987). This commonly intraclastic dolomite unit corresponds to Unit 1 of Haines' (1986) classification of the Wonoka Formation, and marks the base of the newly redefined Wonoka Formation (and the beginning of the Ediacaran System, Jenkins and Gostin 1983; Jenkins 1984). The Wonoka Formation represents progradation after the second transgression, with an increasing component of limey sediments overlying the deep basinal shales of the Bunyeroo Formation. The second cycle is completed with the feldspathic, red sandstones of the Bonney Sandstone and the open marine deposits of tidal and shelf origin characterising the Rawnsley Quartzite. Sedimentary environments of the Wonoka Formation are believed to differ across the Flinders Ranges, with deeper basinal settings in the southern and northern regions, and shallower, shelfal environments in the central zone (Haines 1990).

DEPOSITIONAL MODELS

During deposition of the Elatina Formation and possibly the oldest parts of the Brachina Formation, coeval extension of the underlying crust was occurring (Jenkins 1990), perhaps along ancient zones of weakness, or slippage planes. Crustal depletion

caused mantle material to rise closer to the surface beneath the zones of extension. This in turn caused thermal dis-equilibrium in the mantle, leading to thermal subsidence, or sag, and the onset of a basin represented by the Brachina Formation or equivalents. The ABC Range Quartzite may represent the final fill of this basin (Jenkins 1990).

Further subsidence of the basin, possibly as the result of renewed extension and relative sea level rise, caused a marked change in appearance of sediments. This is represented by the deeper water 'starved' basinal shales of the Bunyeroo Formation. These predominantly maroon coloured Bunyeroo shales formed under starved (reducing) conditions. The sulphide-rich unit possibly represents a period of maximum transgression, or a high stand systems tract. The contact between the ABC Range Quartzite and the Bunyeroo Formation appears gradational, but has been reported as disconformable (Plummer 1978). This contact marks a Type 1 Systems Tract boundary (Vail et al 1977), representing a prograding shallow slope and shelf of an offlap cycle (Von der Borch and Grady 1983).

The thin dolomite of Unit 1 defines a sharp change in the sedimentary style and possibly represents a large sea level drop or the onset of a low stand systems tract. The lower dolomite unit grades into tempestites (interpreted storm deposits) and turbidites of Unit 2 of the Wonoka Formation. Tempestites formed as a result of rapid density deposition from storm currents which possibly originate from on-shore delta fans, deposited near or narrowly below wave base level (Haines 1987). The sediments towards the top of Unit 2, mark another change in sedimentation. This may coincide with a sequence boundary which Di Bona et al (1990) recognise at the base of Unit 3. However, a gradational contact is observed here. Unit 3 is characterised by deposits of thin 'starved' shales and red limestones.

A very important phase in depositional history is associated with Unit 3, as it represents the time of onset of tectonic movement, particularly in the eastern Wilpena area. Increased subsidence (sag) of underlying strata possibly caused oscillatory lowering and raising of depositional base level within the basin. Precise timing of events must be determined for an accurate comparison with mechanisms that may have

produced the Wonoka Formation canyons. Varying subsidence and changes in depositional slope may account for the palaeocurrent reversals observed in some canyons. Alternatively, the thin starved shales and limestones of Unit 3 may, in fact, represent only the time of maximum flooding (maximum flooding surface). Unit 3 passes gradationally into storm dominated green shales and limestones which represent the continuation of the low stand systems tract. Units 4 through to 9 were then deposited as prograding shelf wedge sediments, with maximum tectonic movements occurring during the time of Units 3 to 7 as evidenced by syn-sedimentary slumping. However, changes in thickness of facies packages indicate that tectonic activity continued well into the time of Unit 7 (Table 1).

Yet another change in sedimentary style occurs with the deposition of the relatively homogenous sandstone of Unit 10. The sequence boundary suggested to coincide with the base of this unit may correlate with one recognised by Di Bona et al (1990). Unit 10 is widespread throughout the Flinders Ranges and probably indicates a minor regressive shore phase, and likely includes tidal channel facies.

Sedimentation of the Wonoka Formation is completed by ooid and stromatolitic-rich deposits which grade into micritic muds and shales (Unit 11). This unit was deposited under very low energy conditions, possibly in a reducing environment which favoured the preservation of organic matter (however, organic matter was all but destroyed by post-depositional alteration). The environment may have been a restricted lagoon forming behind a barrier bar (Unit 10). Tidal and shelfal sands of the Bonney Sandstone were then deposited, during a major regressive phase and represent a regressive systems tract. See Figure 6 for summary models of deposition.

STRUCTURAL CONFIGURATION IN THE WILPENA AREA

Mapping shows that the Wilpena Trough has a deep central sag filled with Wonoka Formation, as well as shoulder sags on the northern and southern margins which were controlled by north-easterly trending faults (refer to map enclosure). On the northern

Thickness (metres)	Southern limb	Central Sag	Northern limb
Bunyeroo Formation	420	415	408
Stratigraphic level of the impact ejecta layer above the ABC Range Quartzite and Bunyeroo Formation contact.	96	no outcrop	95
Wonoka Formation			
Wearing Dolomite (cms)	82	80	83
Unit 2	65	82	68
Unit 3	70	124	99
Unit 4	97	156	89
Unit 5	92	140	86
Unit 6	75	460	103
Unit 7	120	534	85
Unit 8/9	59	38	43
Unit 10	20	22	17
Unit 11	39	37	32
Total thickness of the Wonoka Formation	628	1677	623

Table 1. Thickness variations of the Bunyeroo and Wonoka Formations across the Wilpena Trough (see also Enclosure 2).

shoulder, the faulted block bounded by the Wilpena and Woolshed Faults appears to have been detached from the shoulder and rotated to an unusual angle of dip (88°). Adjacent to this block is a smaller block which repeats part of the section and also represents a slide into the Trough. These rotated blocks and dislocations approach the configuration of true Wonoka Formation canyons where slide blocks dislocated from shoulder regions are apparent (von der Borch et al. 1988).

TIMING OF TECTONIC ACTIVITY

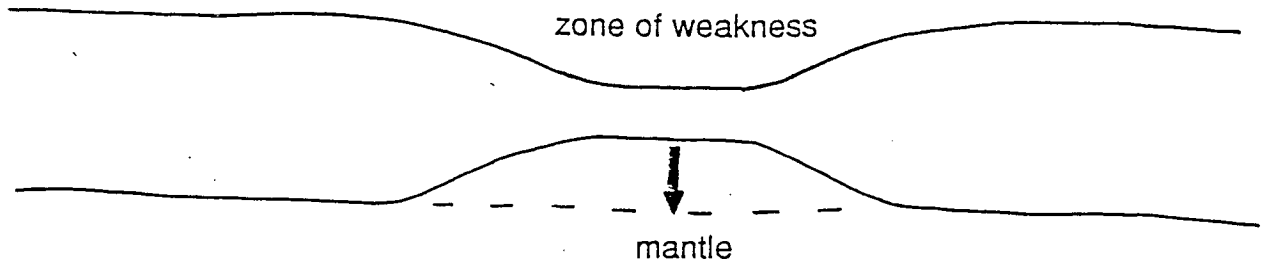
In order to correlate the mechanisms that produced the Wilpena Trough with processes that produced Wonoka Formation canyons, precise timing of the controlling tectonic factors must be established from field mapping, and measurements of changes in thickness of individual formations and units (Table 1). Stratigraphic thickness changes are not evident in strata below the Wonoka Formation and therefore any destabilising mechanisms were presumably initiated some time after the Bunyeroo Formation was deposited. The Acraman impact ejecta layer, a useful marker horizon, appears in outcrop at approximately the same stratigraphic level as reported outside this area (Gostin et al. 1983).

The cupriferous dolomite of Unit 1 remains at a constant thickness along strike. Stratigraphic sections were measured through Unit 2 tempestites where a thickness variation was evident with true thickness increasing from approximately 65 and 68 metres on the southern and northern limbs, to 82 metres in the central trough region (see Enclosure 2). Tectonic subsidence of the Wilpena Trough had therefore begun during deposition of Unit 2. Unit 3 greatly increases in thickness within the Trough and is the phase of oscillating (but rapid) basin subsidence (refer to Table 1 for thickness changes). Jenkins (1990) interprets this basin subsidence as marking the last major phase of lithospheric stretching in the Adelaide Fold Belt during the Precambrian. The north-easterly trending faults which affect sedimentation of the Wonoka Formation adjacent to Wilpena Pound are good evidence for such crustal extension (Figure 7). In the Officer

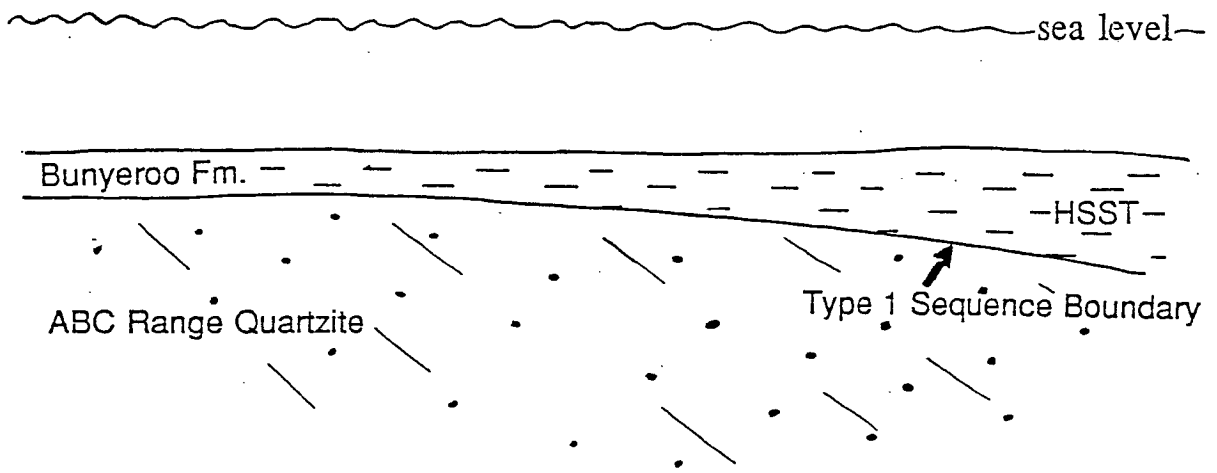
FIGURE 6

- a) Initially, before deposition of the Bunyeroo Formation, the weight of mantle addition along zones of weakness in the crust produced crustal sag.
- b) The Bunyeroo Formation was deposited with further subsidence of the crust in a high stand systems tract, and its base marks a Type 1 Sequence Boundary from the shallower ABC Range Quartzite deposits.
- c) A low stand systems tract prevailed during deposition of the Wonoka Formation wedge of sediments. Slumping and headward erosion in soft sediments of Unit 2/3 may have been possible mechanisms for canyon formation.

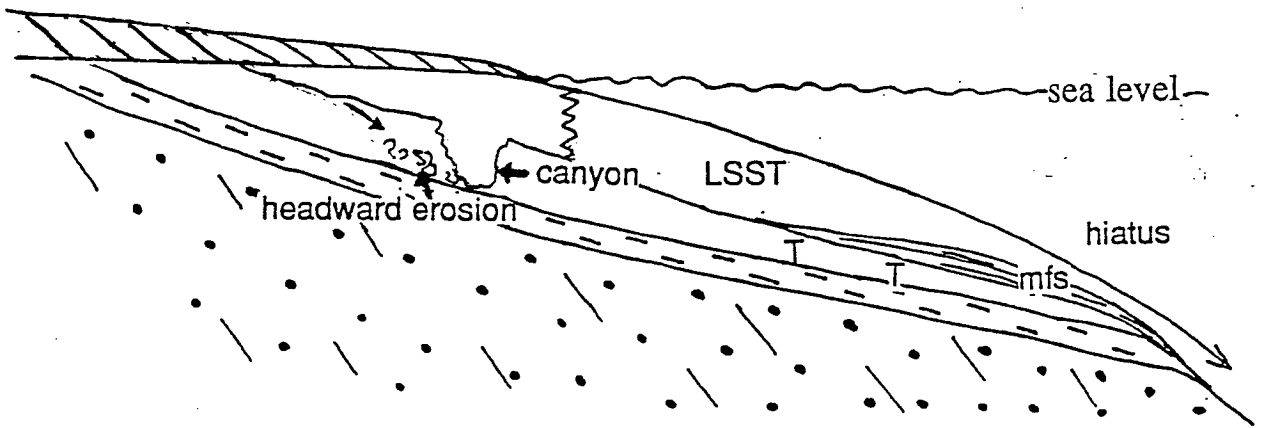
a



b



c



KEY

- HSST High Stand Systems Tract
- LSST Low Stand Systems Tract
- mfs maximum flooding surface
- T turbidites/tempestites

Basin, the Rodda Beds are affected by a network of east-northeast trending normal faults (Thomas 1990) which evidently formed during early Wonoka Formation time. Here the faults define narrow (average 1km wide) elongated tilt blocks with mean true dips of 80° north. In the Wilpena area, fault blocks show a true dip which is near vertical. Whether faulting is strike-slip or listrically induced, fault blocks appear tilted and rotated, therefore allowing the accumulation of thick sequences of Wonoka Formation.

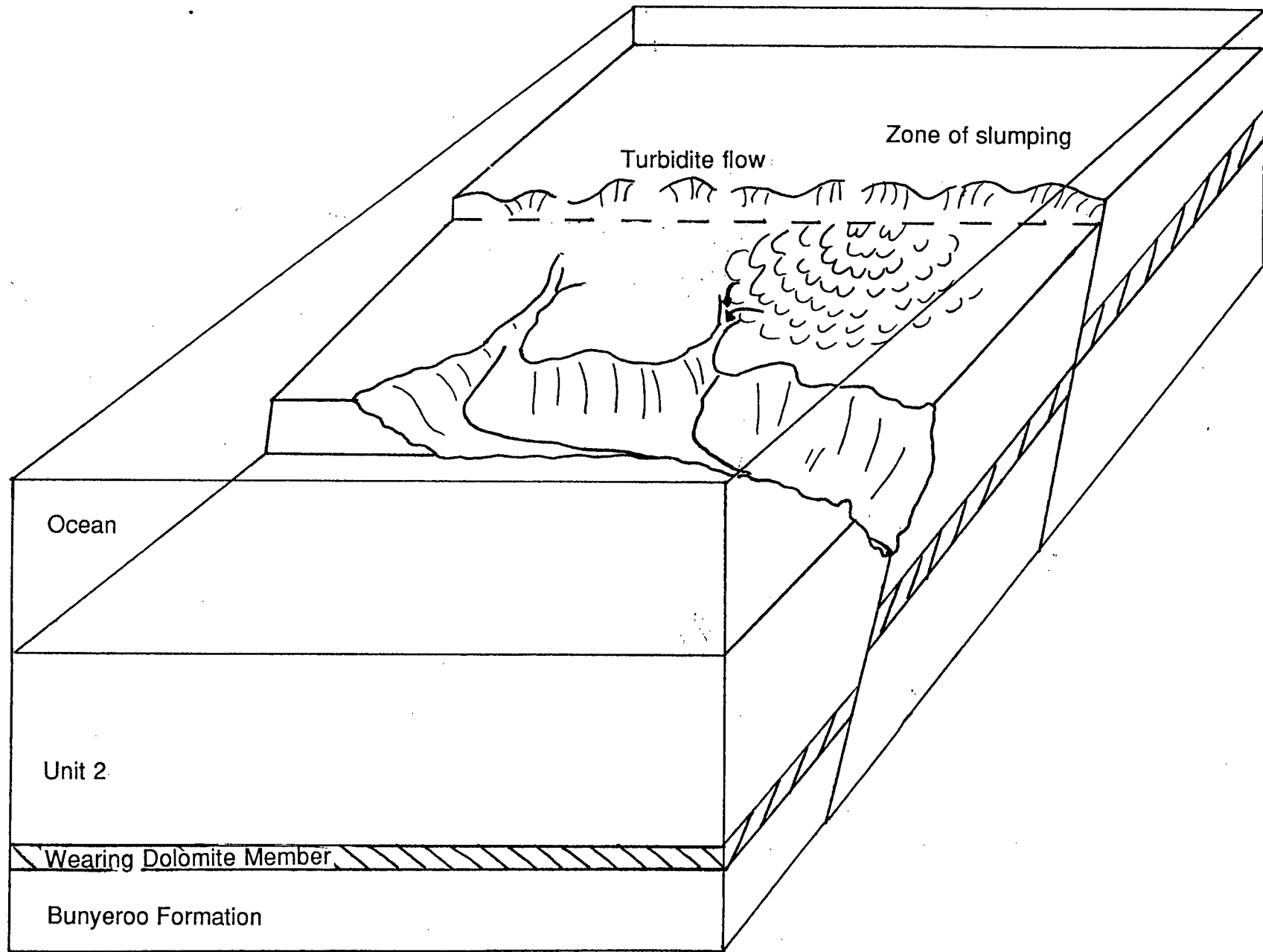
Canyon initiation processes are believed to have been active during Unit 3 of the Wonoka Formation (Haines 1987). It is a possibility that canyon structures are localised or formed through attenuation of underlying strata (Jenkins 1990), above zones of weakness in the underlying crust. However, canyons are so widespread within the Wonoka Formation that it is a major possibility that they were all formed in a regional province of extensional stress. Thickness variations in individual units of the Wonoka Formation appear to cease after deposition of Unit 7. Units 8 and 9 represent the regressive phase of the low stand systems tract. The uniform thickness of Unit 10 supports the idea that it reflects a subsequent transgressive event and hence is onlapping with a sequence boundary at its base.

Other evidence supporting the idea that faulting (tectonic movement) is syn-depositional with Units 3 to 7 is the presence of slumped bands near the margins of the Wilpena Trough. Slump structures are most common within Units 3 to 5, and occur on a variety of scales. Slumping presumably occurred in semi-consolidated sediments as a direct result of tectonic movement of underlying fault blocks. Many small scale faults, displacing Unit 1, (Fig. 8) reflect the overall extensional style of the controlling Woolshed and Wilpena Faults. This faulting style is also expressed in the Elatina Formation which underlies the Nuccaleena Formation (Plate 1a). Red tuffaceous deposits observed within Unit 7 could in fact signal a late phase of rifting. However, they certainly provide evidence that movement was still active at this stage. Some of the small scale faults are compressional and may be related to a later compressional phase.

If a comparison between Wonoka Formation canyons and the structure present on the eastern side of Wilpena Pound is to be made, it is necessary to assume that the

FIGURE 7

Block model showing how extensional faulting associated with a depositional palaeoslope may focus slumping and result in turbidite flows which erode canyons in the deeper palaeoslope.



Turbidite flow

Zone of slumping

Ocean

Unit 2

Wearing Dolomite Member

Bunyeroo Formation

Wilpena Trough is a canyon which failed to develop fully. When Coats (1964) first identified the 'canyons' as large scale slump structures, he sketched the features with fault bounded margins. All canyons may have initially begun to form along the lineaments created when blocks were down faulted and rotated, and adjacent higher crustal blocks uplifted as a result of thermal dis-equilibrium. Because slightly deeper basinal environments for the Wonoka Formation existed in the northern and southern Flinders Ranges (Haines 1990), currents redirected by the oscillatory basin subsidence may have been responsible for scouring out much evidence of initial faulting in the true canyons, and also responsible for deposition of Unit 2 on the floor of the basin. Unit 2 tempestites do not show the classic features of Bouma turbidites because of their relatively shallow setting. There is at present no reasonable explanation linking deep water currents with associated phenomena such as hummocky cross stratification. However, hummocky cross stratification, such as observed within Unit 2 tempestites, has been known to occur up to depths of 3300 metres (Allen 1985). Deep water hummocky cross stratification allows for a submarine palaeoenvironment at the time of initiation of the Wilpena Trough and other canyons. The Wilpena Trough possibly failed to fully develop all the characteristics of a true canyon due to a slightly shallower environment in the central Flinders Ranges. Although density currents were present in shallower regions, they may have failed to reach the same velocities as in deeper water settings. This may also explain the general lack of identifiable canyons in the central Flinders Ranges regions (Figure 7).

STRIKE-SLIP FAULTING AND BASIN FORMATION

Strike-slip deformation is directly responsible for basin formation along some transcurrent faults, whilst other basins are developed in different tectonic regimes in which strike-slip played only a minor role in the basin development (Christie-Blick and Biddle 1985). Sedimentary basins form along strike-slip faults as a result of localised crustal extension and also in zones of continental convergence, and localised crustal

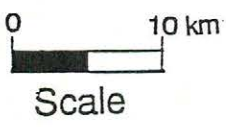
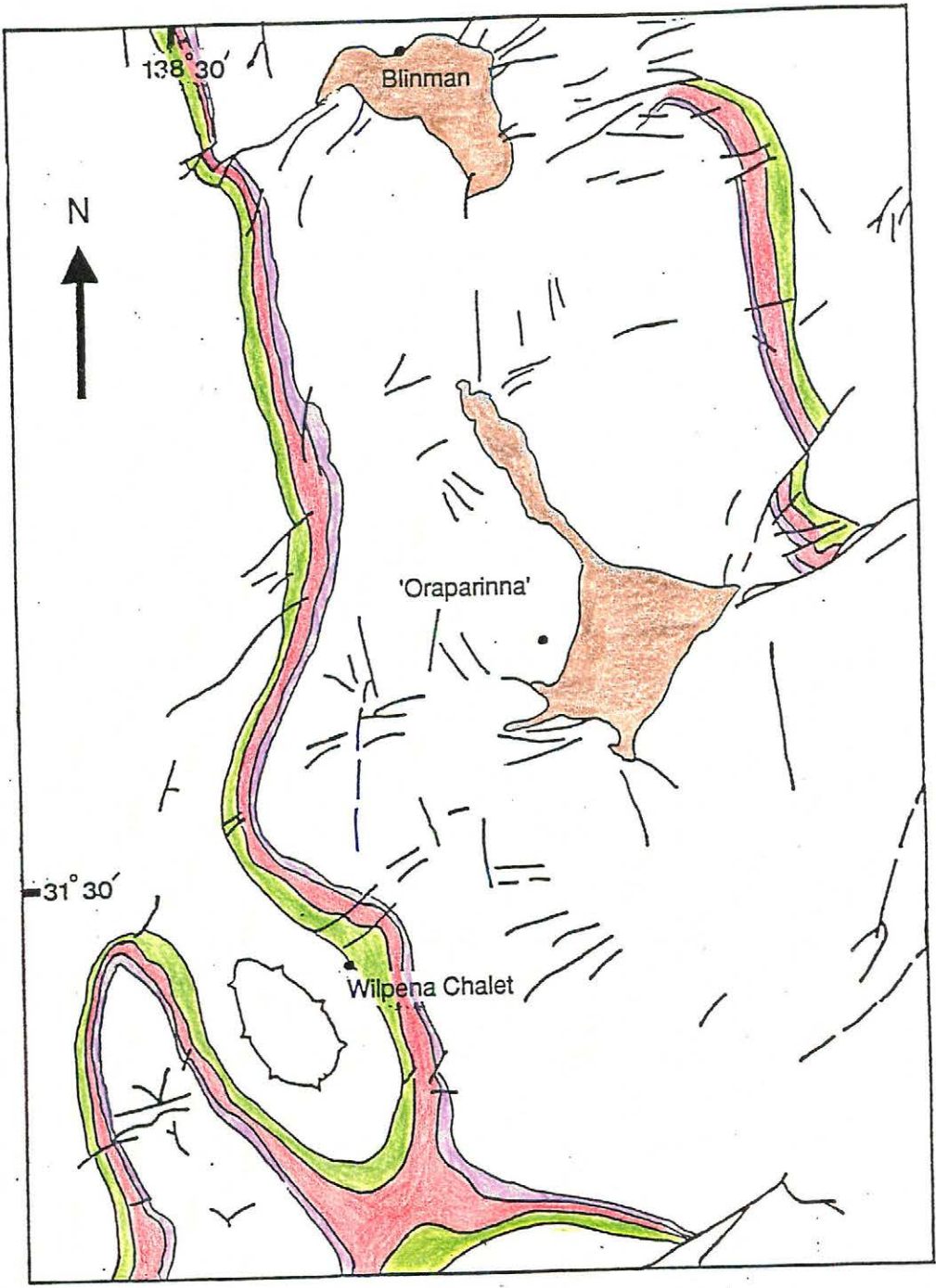
shortening. Such localised crustal extension has already been discussed as being the major factor in initiating the north-easterly trending faults bounding the Wilpena Trough.





Another approach is to consider the subsidence and thermal history of the Wilpena Trough in the context of pull-apart basin theory, and relating it to strike-slip mechanisms. In the model of McKenzie (1978), subsidence results from instantaneous, uniform extension of the lithosphere, and from subsequent cooling by vertical conduction of heat. It may be argued that the phase of warping prior to Unit 3 of the Wonoka Formation, or even a phase of continental rifting produced the necessary control for strike-slip basin formation.

A prominent feature of many strike-slip faults is the occurrence of 'en echelon' faults and folds within and adjacent to the Principal Displacement Zone (Christie-Blick and Biddle 1985). The recognised slump features within Units 3 to 7 may in fact be 'en echelon' folds, as the vergence is directed away from the faulted margins of the Wilpena Trough suggesting material has moved down-slope. However, in divergent strike-slip faults, folds are not as well developed as in convergent situations, and commonly consist of flexures arranged parallel to the Principal Displacement Zone (Christie-Blick and Biddle 1985). The extension in the lithosphere prior to the Wonoka Formation caused subsidence during early Wonoka deposition which in turn produced block rotation and divergence along an initial relatively straight fault segment (or zone of weakness in the crust). Block rotation was not a local phenomenon occurring only in the Wilpena area. The widespread occurrence of canyons in the Flinders Ranges and the continuation of the north-easterly Trough lineament into the Oraparinna area suggests the same tectonic controls were operating across broad regions (Figure 8).

FIGURE 8

Map showing north-easterly sense of faulting in the central Flinders Ranges (after Preiss 1987).



- Wonoka Formation 
- Bunyerroo Formation 
- ABC Range Quartzite 
- Diapir 

CHAPTER FIVE

CONCLUSIONS

The configuration of the Wilpena Trough is structurally similar to that of several 'true' canyons that occur elsewhere in the Flinders Ranges and may therefore be used as evidence to deduce mechanisms that triggered canyon formation.

The formation and movement of extensional faults (such as the Wilpena and Woolshed Faults) above zones of weakness, caused some rotation and slumping of adjacent sediment blocks into the subsiding Wilpena Trough. Abrasive submarine currents eroded the underlying strata within other canyons, but may have failed to do so in the Wilpena Trough as currents did not reach maximum velocities. Current velocities were increased in the deep water palaeoenvironments of the northern and southern Flinders Ranges. The Wilpena Trough is located in a marginally shallower environment.

The depositional environment of the Bunyeroo Formation was that of a starved basin at the time of a high stand systems tract. The environment changed to a shallow shelf for deposition of the Wearing Dolomite Member with significant intraclastic input from episodic (traction) currents. The overlying sediments of Units 2 to 9 of the Wonoka Formation characterise the prevailing low stand systems tract, with initiation of tectonic activity that produced the Wilpena Trough commencing near the Unit 2/3 transition. Fault controlled sedimentation ceased during late stages of deposition of Unit 7. A sequence boundary may exist at the base of Unit 10 due to the fact that sediments above this surface show a shallow water transgressive aspect.

The proposal by von der Borch et al. (1989) that a Messinian style evaporitic drawdown produced sea level falls in the order of 1500 metres, enabling subsequent subaerial formation of canyons in the Wonoka Formation, is not supported by any record of salt deposits. However, during a low stand systems tract, sea level falls may be in the order of a hundred metres or so, allowing headward erosion and fault related slumping in soft sediments to form canyons in submarine palaeoenvironments.

The mixed carbonate/dolomite sequence of the Wonoka Formation in the central Flinders Ranges is characterised by low amounts of organic carbon (0.0 - 0.057 wt% TOC). However, the identification of spheroid acritarchs and filamentous microfossils at the Unit 8/9 level provides evidence for biotic activity at least in the upper units of the Wonoka Formation. Therefore, TOC values tend to suggest some degree of thermal re-equilibration and post depositional destruction of organic matter.

The sharp negative excursion in the stable carbon and oxygen isotopic profile for the Wonoka Formation in Bunyeroo Gorge records a true secular change in isotopic ratios. Stratigraphic and seismic evidence (Thomas 1990) for the correlation of intervals of the Rodda Beds (Officer Basin) with the Bunyeroo, Wonoka and Billy Springs Formations of the Adelaide Fold Belt enables stable isotope data from the two regions to be combined. The carbon isotope curve, which is less affected by thermal alteration than the oxygen curve, shows a trend from the sharp negative excursion into a broad low positive excursion with the addition of Pells' values (1989). The negative carbon isotopic signature reflects a time of oxidation of organic carbon and compares favourably to a global negative excursion. This illustrates the potential for using isotopic data to compare late Proterozoic basins on an inter-regional scale.

PLATE 1

1a. Extensional faulting of the Elatina Formation by north-easterly trending faults 5.3 km north-east of Wilpena Chalet.

1b. Concretions of Nuccaleena Formation in surrounding shales of the lower Brachina Formation. Concretions are found in association with the major north-easterly trending fault in the northern region of the map area.

1c. Outcrop of the Acraman impact ejecta layer occurring 95 metres above the base of the Bunyeroo Formation, north-east of the Wilpena Fault.

1d. The 15 cm thick gritty sandstone unit of the Acraman impact ejecta layer, which shows thin sets of crossbedding and hosts fragments of Gawler Range Volcanics. Occurs at same locality as 1c.

1e. The Bunyeroo Formation/Wearing Dolomite transitional boundary on the southern faulted margin of Wilpena Trough. The fold axis cuts through the centre of the creek.

1f. Brecciated Wearing Dolomite Member in surrounding shales adjacent to the fold axis and at the same locality as in 1e.



a



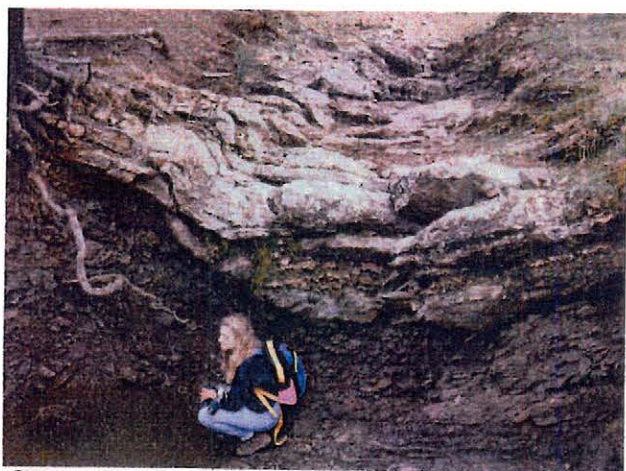
b



c



d



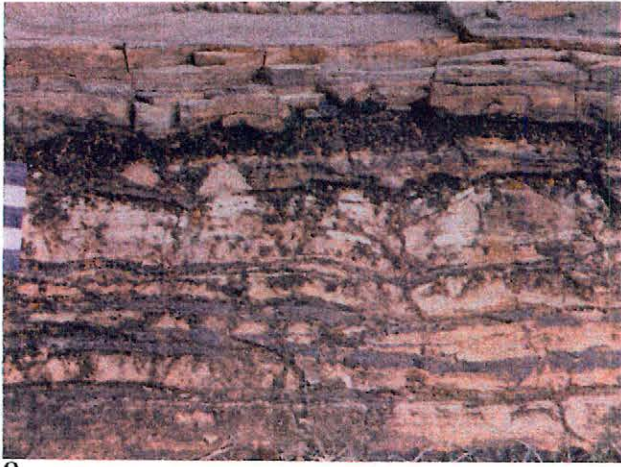
e



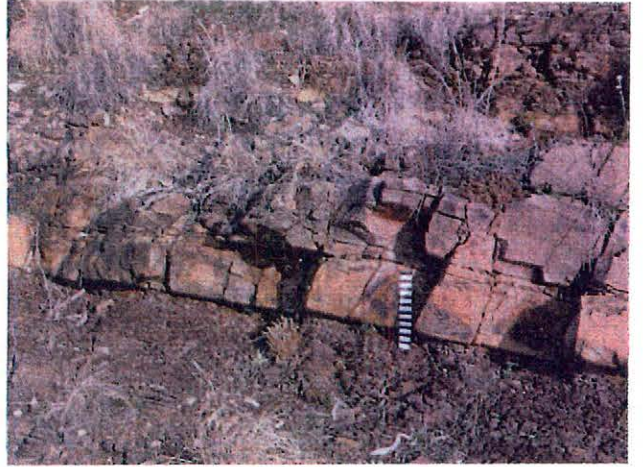
f

PLATE 2

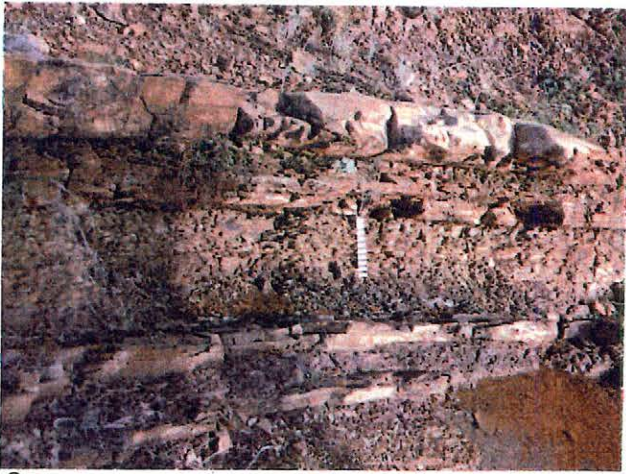
- 2a Thin dolomitic units of the Wearing Dolomite Member showing sharp bases and gradational tops.
- 2b. Thick amalgamate sandstone tempestites of lower Unit 2 in the central Trough region.
- 2c. Thin tempestites near the base of Unit 2 in the central Trough region grading into a bed which marks the appearance of the first thick sandstone (Bouma T_{A, C, E} divisions)
- 2d. Tempestite of mid Unit 2 in the central Trough region showing the sharp wavy top of the Bouma T_C division.
- 2e. Flute casts from the base of a tempestite near the top of Unit 2 in the central Trough region. Flutes in outcrop give an average palaeocurrent direction of 060°.
- 2f. Chocolate-red shales and pink-red limestones at the Unit 2/3 transition in the central Trough region.



a



b



c



d



e



f

PLATE 3

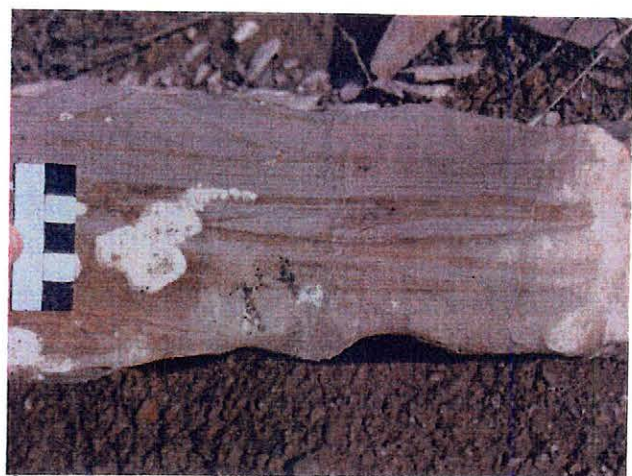
3a. Climbing ripple sets and cross-bedding near the base of Unit 4 on the southern side of Woolshed Fault.

3b. Small scale truncation of bedding in the red limestones of mid Unit 5 occurring in the centre of the Wilpena Trough.

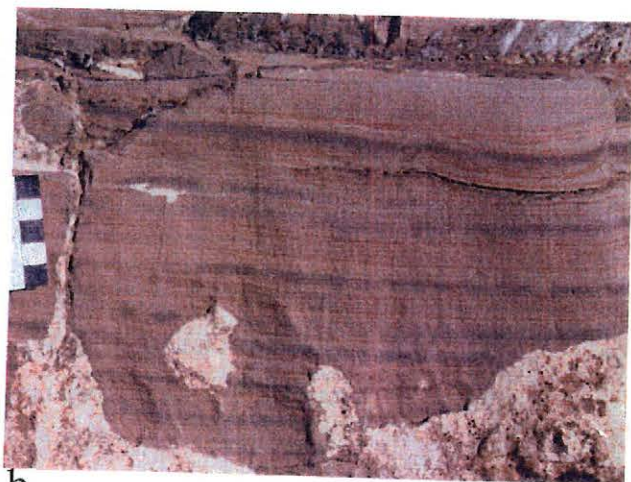
3c. A syn-depositional limestone slump bed of Unit 5 occurring near the northern faulted Trough margin (adjacent to Woolshed Fault)

3d. A tightly hinged slump fold in a sandy limestone of lower Unit 6 occurring near the northern faulted Trough margin (adjacent to Woolshed Fault).

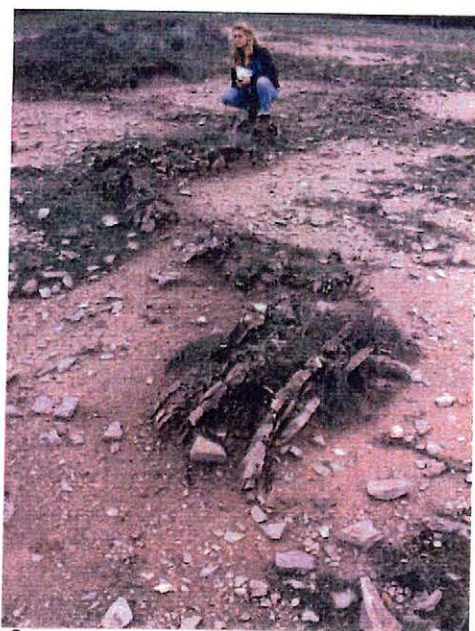
3e and 3f. The stromatolite assemblage of Unit 11, outcropping 1.1 km south west of the Wilpena Chalet.



a



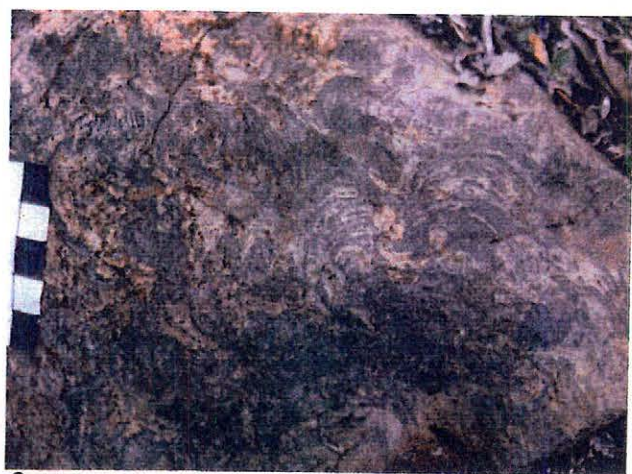
b



c



d



e



f

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A special acknowledgement to those people who provided much needed moral support and friendship (particularly Kath for her field assistance! and colouring; and fellow Honours students for stimulating conversation). The artistic ability of the Henderson family and the typing skills of Bjorn, Morgan and Phil deserve credit.

I kindly thank the Department of National Parks and Wildlife for allowing me to map in the Flinders Ranges National Park.

Finally, thanks go to my mother and Brian for transportation and to my grandmother for just caring.

APPENDIX 1

Bunyeroo Gorge Geochemical Data

GEOCHEMICAL DATA - BUNYEROO GORGE

d>mfs (m) - depth above maximum flooding surface (tape measured metres)

TOC - total organic carbon

Sample No.	d>mfs (m)	$\delta^{18}\text{O}$ ‰PDB	$\delta^{13}\text{C}$ ‰PDB	% Dolomite	TOC
931-01	100.0	-13.520	-8.09	0.00	0.034
931-02	130.0	-13.970	-7.92	0.00	0.035
931-03	160.0	-12.890	-7.52	0.00	0.039
931-04	190.0	-12.640	-7.66	9.30	0.027
931-05	200.0	-12.890	-7.59	7.56	0.046
931-06	220.0	-12.840	-7.42	0.00	0.022
931-07	250.0	-12.790	-7.56	12.90	0.021
931-08	280.0	-12.780	-7.48	0.00	0.040
931-09	310.0	-12.480	-7.64	17.20	0.057
931-10	340.0	-12.620	-7.41	7.30	0.021
931-11	370.0	-13.590	-7.79	15.00	0.016
931-12	400.0	-13.690	-8.62	24.20	0.013
931-13	430.0	-13.180	-7.62	4.80	0.019
931-14	460.0	-11.640	-6.51	0.00	0.022
931-15	490.0	-12.790	-7.36	12.60	0.034
931-16	520.0	-11.020	-6.77	0.00	0.016
931-17	550.0	-10.510	-6.87	4.10	0.041
931-18	580.0	-10.630	-5.74	4.00	0.030
931-19	610.0	-10.020	-5.25	8.30	0.024
931-20	640.0	-11.700	-3.27	14.60	0.012
931-21	670.0	-11.970	-1.49	23.70	0.020
931-23	730.0	-15.250	-3.03	11.60	0.041
931-24	760.0	-5.850	2.05	0.00	0.052
931-30	-100.0	-7.390	-2.43	86.50	0.016
931-31					0.005

*see table
(above)*

APPENDIX 2

Sample Locations: Bunyeroo Gorge

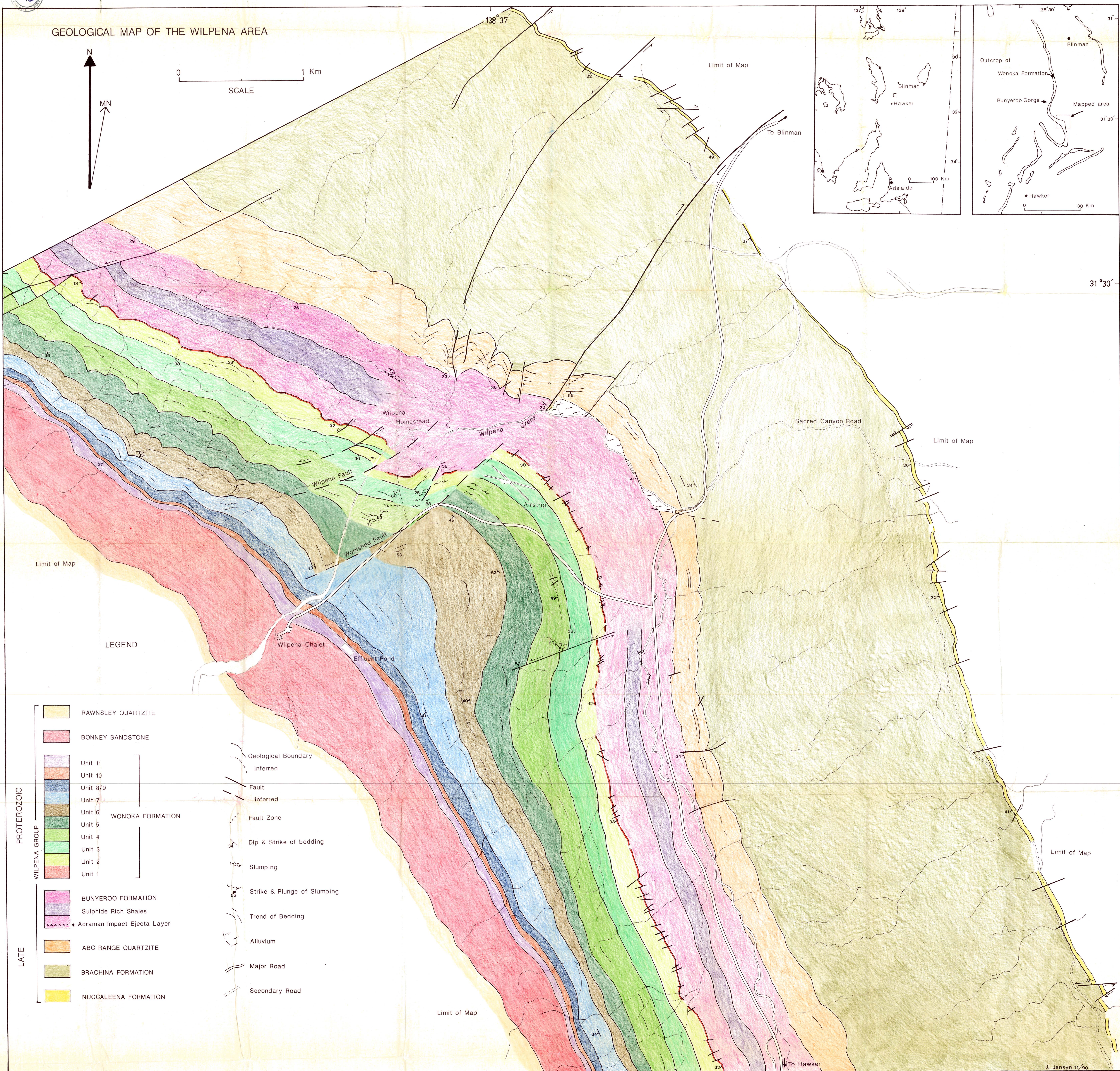
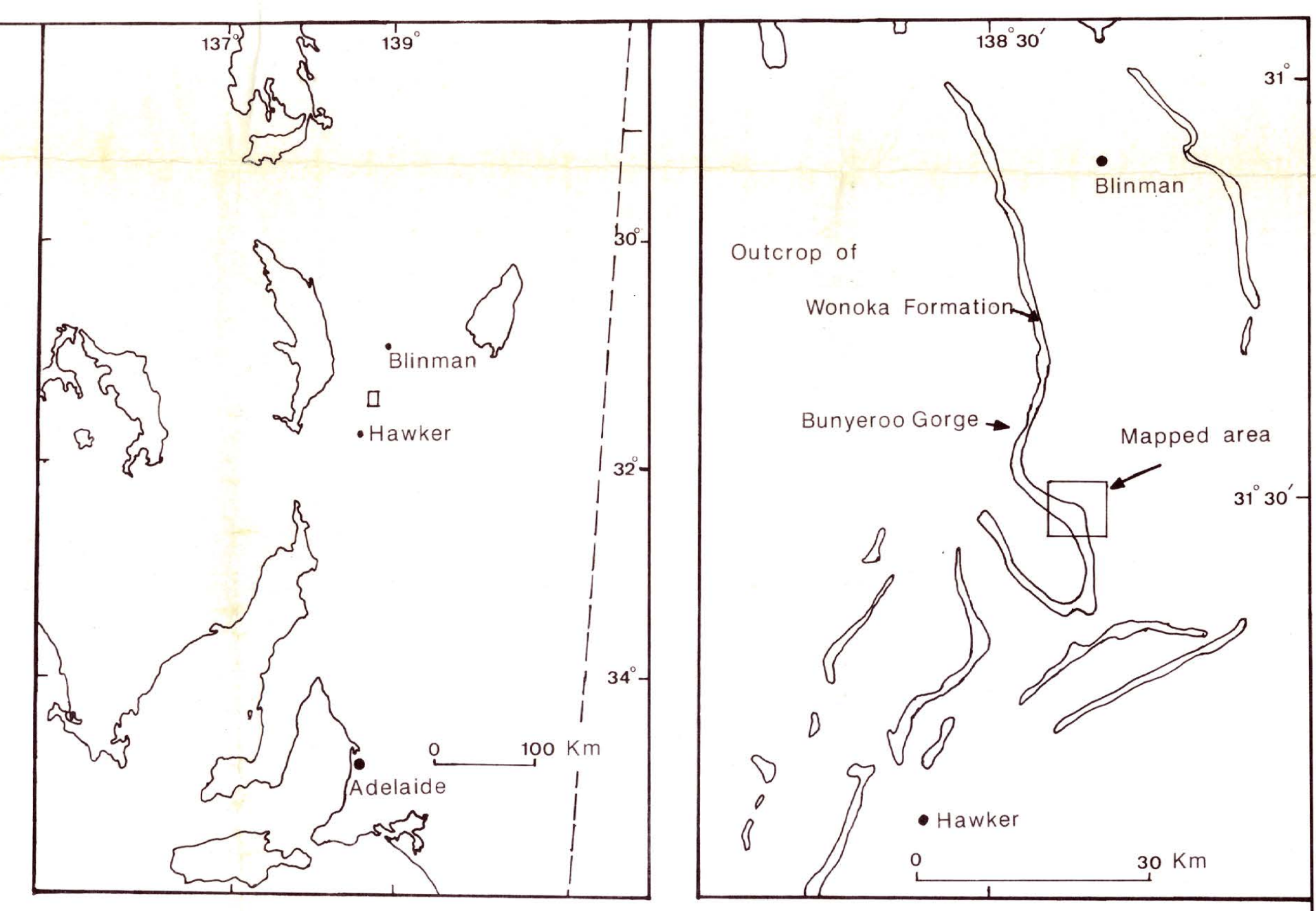
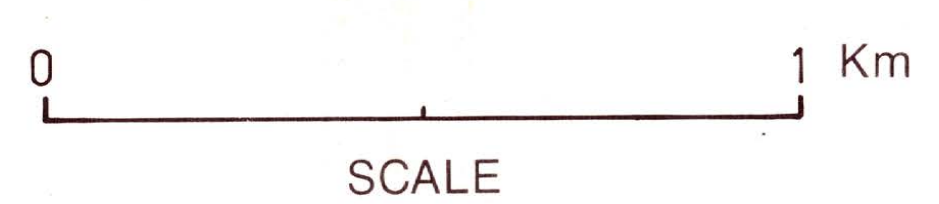
The following listed samples were collected from the
Wonoka Formation at Bunyeroo Gorge

<u>Sample Number</u>	<u>Comment</u>
931-01	Top of Unit 3
931-02	Unit 4
931-03	Unit 4
931-04	Unit 4
931-05	Unit 4
931-06	Unit 4
931-07	Unit 5
931-08	Unit 5
931-09	Unit 5
931-10	Unit5/Unit 6 transition
931-11	Unit 6
931-12	Unit 6
931-13	Unit 6
931-14	Unit 7
931-15	Unit 7
931-16	Unit 7
931-17	Unit 7
931-18	Unit 7
931-19	Unit 8
931-20	Unit 8/9
931-22	Unit 10
931-23	Unit 10/11 transition
931-24	Unit 11
931-30	Wearing Dolomite Member - Unit 1
931-31	Wearing Dolomite Member - Unit 1

095-13
035



GEOLOGICAL MAP OF THE WILPENA AREA



LEGEND

- | | | | |
|-------------|---------------|-----------------------------|------------------|
| PROTEROZOIC | WILPENA GROUP | RAWNSLEY QUARTZITE | |
| | | BONNEY SANDSTONE | |
| | | Unit 11 | WONOKA FORMATION |
| | | Unit 10 | |
| | | Unit 8/9 | |
| | | Unit 7 | |
| | | Unit 6 | |
| | | Unit 5 | |
| | | Unit 4 | |
| | | Unit 3 | |
| | | Unit 2 | |
| Unit 1 | | | |
| LATE | | BUNYEROO FORMATION | |
| | | Sulphide Rich Shales | |
| | | Acraman Impact Ejecta Layer | |
| | | ABC RANGE QUARTZITE | |
| | | BRACHINA FORMATION | |
| | | NUCCALEENA FORMATION | |
-
- | | |
|------------------------------|--|
| Geological boundary inferred | |
| Fault | |
| inferred | |
| Fault Zone | |
| Dip & Strike of bedding | |
| Slumping | |
| Strike & Plunge of Slumping | |
| Trend of Bedding | |
| Alluvium | |
| Major Road | |
| Secondary Road | |

SPEC-COLL
THESIS
093-B
J35

STRATIGRAPHIC SECTIONS THROUGH UNIT 2 OF THE WONOKA FORMATION



SOUTHERN LIMB CENTRAL SAG NORTHERN LIMB

