

8 LANDSCAPE PROCESSES

8.1 INTRODUCTION

Critical to interpreting the geomorphology of the landscape and determining its evolution is an understanding of the modern and ancient chemical and physical processes involved. These geomorphic processes are often distinct to a dryland setting and are vastly different to models of geomorphological evolution developed to describe landscape formation in temperate perennial systems. The interaction between landscape morphology and the underlying geological units is often complex. A response to the multiple effects of a series of different chemical and physical processes has resulted in the expression of the landscape as it is seen today in the study area.

8.2 MARINE SEDIMENTATION, IRON DISULPHIDE FORMATION, AND ACID SULPHATE SOILS

8.2.1 The Global Biogeochemical Carbon & Sulphur Cycle

Sulphur plays an important role in regulating the world's oxygen through its interaction with carbon in the oceans and atmosphere (Utrilla *et al.*, 1992). Both the carbon and sulphur cycles represent global biogeochemical cycles that, through the exchange of reduced C and S between rocks and the atmosphere plus oceans, constitute the major controls on the worldwide level of oxygen (Berner, 1999). Changes in global oxygen levels, in turn, reflect and affect biological evolution throughout time. In particular, global vegetation (including oceanic vegetation) can be interpreted from oxygen mass balance. Past levels of oxygen reflects the historic global coverage of vegetation that influenced sedimentation, erosion and landscape development.

A closer examination of the carbon and sulphur cycles reveals that very little of the carbon can be stored in the ocean and inequalities between weathering and burial result in the reciprocal formation of CaCO_3 . This is similar for pyrite, calcium sulphate and sulphur (Berner, 1999).

The processes involved are summarised as (after Berner, 1999):

- i. Reduction and removal of dissolved inorganic carbon from seawater via the synthesis of organic matter followed by burial of dead organic remains in bottom sediments;
- ii. Oxidation during chemical weathering on the continents of ancient organic matter and pyrite in sedimentary rocks;
- iii. Removal of sulphates from seawater via bacterial reduction to hydrogen sulfide followed by the reaction of H_2S to form sedimentary pyrite;
- iv. The reaction of hot basalt with sulphate in seawater at mid-oceanic ridges; and,
- v. Degassing of reduced carbon and sulphur to the atmosphere and oceans as a result of thermal decomposition.

H_2S is produced via reduction of dissolved sulphate by bacteria using sedimentary organic matter as a reducing agent and energy source (Arkesteyn, 1980; Bottrell *et al.*, 2000). The initial product from this reaction is not pyrite but a series of metastable iron monosulphides that readily transform into pyrite during early diagenesis (Berner, 1970) (Figure 8.1).

NOTE: This figure is included on page 8-2 of the print copy of the thesis held in the University of Adelaide Library.

Figure 8.1: Diagrammatic representation of the overall process of sedimentary pyrite formation (From Berner, 1984).

In normal marine sediments (those deposited in oxygen-containing bottom waters), pyrite formation is limited by the amount and reactivity of organic material buried in the sediment. In euxinic sediments (those deposited in anoxic, H₂S-containing bottom waters) a plentiful supply of both hydrogen sulphide and organic matter results in the formation of high concentrations of pyrite, limited only by the reactivity of the iron minerals brought to the deposition site (Bernier, 1984).

In the Lake Eyre region the Cretaceous Bulldog Shale is described as a marine shale that is carbonaceous and pyritic (Alley, 1998; Krieg, 2000; Rogers & Freeman, 1996; Simon-Coinçon *et al.*, 1996). The common occurrence of pyrite in the Bulldog Shale makes it likely that it was deposited under anoxic conditions with large concentrations of iron monosulphides. Following deposition and burial these iron monosulphides would have been altered to pyrite, and with changing environmental conditions the pyrite was exposed to oxidizing conditions. These chemical conditions have had repercussions in the landscape throughout the Cainozoic. The Bulldog Shale is the most likely source of sulphur in the environment, and the response of sulphur to changing climatic and physical conditions has created a range of different landforms over time.

8.2.2 Acid Sulphate Soils and Silcrete

Soils containing sedimentary sulphides that have not been oxidized, as may occur under elevated groundwater levels, remain stable. If the groundwater conditions change and the sedimentary sulphides are exposed to an oxidizing environment, the iron sulphides present will react, leading to the development of acid sulphate soils (Dent, 1993).

Minor occurrences of silcrete exist within the study area (Williams & Krieg, 1975) that can be interpreted as a soil stratigraphic unit developed in older sediment and associated with a mid-Tertiary land surface (see Chapter 7.2.4). These outcrops provide the source material that supplies the material of the gibber plains. Within the Umbum Creek catchment duricrust-capped mesas rise up from the gibber plains. The gibbers form a dense lag of silcrete fragments derived from erosion of the mesas (see Chapter 7.2.10) (Callen *et al.*, 1986).

The silcrete source material formed as a response to the underlying geology. The Bulldog Shale was deposited in a marine environment during the Cretaceous. Fluvial sandstones were deposited over this unit in the Eocene. Following this, some 14Ma passed before the deposition of the Etadunna Formation. During this time three concurrent processes took place: weathering, tectonism and climate change. Groundwater fluctuations played a major role in the development of the silcretes (Krieg, 2000).

Widespread bleaching and iron staining of the Cretaceous sediments are the result of the oxidation of the sedimentary sulphides producing sulphuric acid and the mobilisation of iron. These geochemical conditions co-existed with saline groundwater solutions in low groundwater table, restricted flow, arid conditions. This allowed the formation of an acid environment without the loss of more soluble elements like potassium, sulphate and silica. As groundwater levels rose, a consistent hydraulic regime was established that transported the amorphous silica from the bleached profile laterally into fluvial sand units. Tectonism was responsible for uplift of these units and their exposure above the water table led to the induration of silica-charged sands (Benbow *et al.*, 1995; Krieg, 2000; Simon-Coinçon *et al.*, 1996). Tectonism postulated for the Late Pliocene-Early Pleistocene (Rogers & Freeman, 1993) led to uplift of the silcretes and subsequent erosion has caused their topographic inversion. Around the silcrete outcrops the surrounding gibber clasts are larger and more angular, indicating their local origin. As the gibber clasts are transported further they become rounded as a result of collisions and

abrasion by fine material being swept past during rain wash and by wind scour. Given the present widespread distribution of silcrete pebbles across the gibber plains in the study area, it is probable that silcrete deposits were spread more widely than the current distribution (Krieg, 2000).

8.3 AEOLIAN PROCESSES

Wind erosion occurs where abrasive particles are blown against surfaces of easily disintegrated, granular material. In the contemporary environment, strong winds are common in the region surrounding Lake Eyre. Gale force winds of 40–50 knots (Beaufort Scale) are common and Strong Gales 50–70 knots (Beaufort Scale) were experienced by the author during fieldwork between 2003 and 2005. Winds of these strengths are capable of transporting uprooted trees (visible on Lake Eyre as upended tree crowns resting on the surface of the lake) and have the ability to move considerable amounts of particles through a range of processes including abrasion, entrainment, saltation and reptation. Winds of these velocities are quite capable of moving grains normally considered too large to be affected by aeolian processes. Coarse grains in the order of 1–2 mm are readily entrained and grains up to approximately 10 mm are capable of being mobilised through saltation. It is important to keep this in mind when examining aeolian sediment as small pebbles can be seen in some dune exposures. Dust storms are common in the region and explain the omnipresence of fine-grained red-brown sand and silt and the strong aeolian overprint on most features.

The most prominent landscape features formed by wind erosion are irregular ridges, or yardangs, present within the aeolian sediment bordering the lake (Figure 8.2). These possess a prominent prow, keel and streamlined features, and are formed in homogenous aeolian dune sediment parallel to the dominant wind direction. Piping erosion has formed on their flanks indicating rainfall is also modifying the yardangs.

The western side of Lake Eyre consists largely of plains blanketed by alluvial and aeolian sediments. Deflation forms blowouts in sand sheets and at the bases of the dunes, forming playas that collect runoff. Deflation also contributes to the formation of gibber plains composed of an armoured layer of pebbles, one to two stones in thickness, set on or in deposits of sand, silt or clay. The level nature of the alluvial sediments on which the gibber plains formed is the result of long-term exposure to subaerial erosion by running water, not wind. Nevertheless, the effects of wind abrasion have altered many of the pebbles that form the gibber plains. A combination of direct sandblasting by sand-sized particles and abrasion from dust captured by vortices forms the characteristically faceted shape of ventifacts (wind-shaped pebbles), possessing a raised prow and keel with streamlined features. Wind erosion plays a role in the maintenance of gibber plains but is restricted to deflation of dust and fine particles, and the shaping of some stones into ventifacts (Breed *et al.*, 1997).



Figure 8.2: Yardang near the western shore of Lake Eyre approximately 3 m in height (~0693996E 6852960N).

8.4 GIBBER PLAINS

The formation of gibber plains (known as desert pavements, stony mantles, hamada, reg, serir and gobi elsewhere in the world) via deflation has gained widespread acceptance as a general explanation for pavement formation, based on early reports of Californian deserts late in the 19th Century (Cooke, 1970). On the western side of Lake Eyre the landscape has been exposed to subaerial erosion on and off since the Cretaceous. Terrestrial fluvial environments have dominated the area during the Cainozoic resulting in alluvial sediment deposition. Fluctuation in climate during this period has resulted in alternating erosional or depositional dominated periods (Alley & Pledge, 2000). The onset of aridity in the Quaternary has converted the blanket of alluvial sediments into gibber plains. The low relief, level surfaces that the gibbers lie upon were formed by landscape lowering processes. The armoured lags then formed as a response to a complex range of particle concentration processes.

8.4.1 Wind Erosion

Wind erosion is the widely accepted mechanism for the formation of gibber plains (Cooke, 1970). The presence of ventifacts on gibber plains in the western Lake Eyre region suggests that it is still a contributing factor. Wind erosion, however, is not the only mechanism and may not be the dominant force behind gibber plain formation in this study area. There is no doubt that loose, fine material can be removed by the wind, but features such as vegetation may prevent this from occurring by reducing the wind velocity at the surface below threshold velocities (Figure 8.3) (Cooke, 1970). Loose material may not always be present at the surface. Soil sealing can occur when fine material is deposited by flowing water and forms a crust (Figure 8.4) (Baird, 1997). This forms a thin, strong, relatively impermeable carapace that protects the underlying fines from removal (Cooke, 1970).

8.4.2 Physico-Chemical Weathering

Chemical and physical weathering processes propel the breakdown of rock and minerals. Chemical weathering alters the parent material through oxidation/reduction, causing the formation of secondary products. Physical weathering, either via frost or salt expansion, causes the splitting of rocks in the presence of water and/or salt as a result of volumetric changes associated with diurnal or seasonal temperature changes (Cooke, 1970). The resulting angular fragments are then distributed to the surrounding landscape via alluvial and colluvial processes (Figure 8.5).

8.4.3 Colluvial Wash and Banded Vegetation

Colluvial wash processes, such as shallow unchannelised flow, are active in the formation of gibber plains. Colluvial wash accounts for features such as the accumulation of fine material upslope of coarse particles, the downslope attenuation of rock fragments from their source, the displacement of varnished fragments and the development of terracettes parallel to the contours of sloping pavement surfaces (Cooke, 1970). These terracettes form from both wash or creep. Where wash is the dominant force, banded (or tiger stripe) vegetation forms (Figures 8.6 & 8.7). This is a synergy between geomorphic and ecological processes. The effect of raindrops falling on bare ground, where unimpeded by vegetation, causes entrainment of sediment. The rainfall forms shallow unchannelised flow that travels across the bare unvegetated run-off zones and is intercepted by the vegetated run-on zones, where it is halted and infiltrates the soil. The vegetation thus gets the benefit of receiving more rainfall than actually falls within the band. These bands and interbands are remarkably parallel to slope contours (Wakelin-King, 2003).

NOTE: This figure is included on page 8-7 in the print copy of the thesis held in the University of Adelaide Library.

Figure 8.3: A: Classical model of deflation where erosion from wind and water cause progressive landscape lowering and the concentration of particles. B: Vegetation can prevent deflation by reducing wind speed below threshold velocities (Cooke, 1970).

NOTE: This figure is included on page 8-7 in the print copy of the thesis held in the University of Adelaide Library.

Figure 8.4: Rainfall infiltration can cause cementing of surface fines and form a carapace preventing wind deflation (Cooke, 1970).

NOTE: This figure is included on page 8-8 in the print copy of the thesis held in the University of Adelaide Library.

Figure 8.5: Physico-chemical weathering causing outcrops of in situ rocks to break down. Chemical weathering alters the parent material via oxidation/reduction and physical weathering via frost or salt expansion causes splitting as a result of volumetric change. The resultant angular fragments are distributed across the landscape by alluvial and colluvial processes (Cooke, 1970).

NOTE: This figure is included on page 8-8 in the print copy of the thesis held in the University of Adelaide Library.

Figure 8.6: Banded vegetation formation. Shallow unchannelised flow travels across the bare unvegetated run-off zones and is intercepted by the vegetated run-on zones (Cooke, 1970).

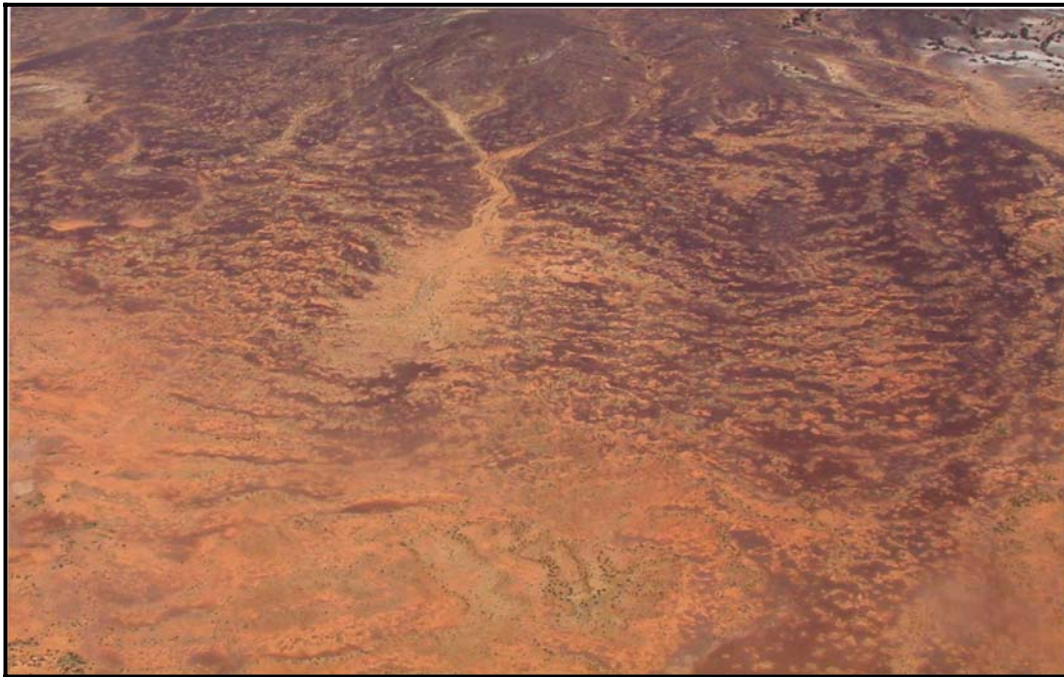


Figure 8.7: View of banded vegetation developed on Cadna-Owie Formation as seen from the air, showing the horizontal development of run-off and run-on zones (~612800E 6845000N). Scale approximately 2 km across.

Once formed, the capacity of the vegetated arc to slow sheet-flow is improved and sediments and organic matter are continually deposited within the bands, thereby maintaining them. At the upslope edge of banded vegetation, water flow slows, sediment and organic matter are deposited and water infiltration is increased. This leads to upslope germination of plants on the upslope edge of the band. Similarly, the downslope edge becomes starved of resources and the plants die off leading to upslope migration of the whole band (Tongway & Ludwig, 2001).

8.4.4 Upward Migration of Particles

The concentration of coarse particles at the surface may be due to cycles of saturation and desiccation (Figure 8.8). Fluctuations in wetting and drying cause the expansion and contraction of clay-rich soils. This results in the development of the features known as gilgai (micro-relief). Gilgai form as a response to lateral stresses due to the shrink-swell behaviour of the soil. In addition, it may cause movement of coarser material to the surface. It was suggested by Cooke (1970) that this occurs due to fine particles falling in place behind larger particles as the stones are lifted slightly. The ultimate result is an upward displacement of the stone.

8.4.5 Accretionary Mantles

A surface of loose rocks that is exposed to sediment-bearing winds accumulates sediment beneath the lag by the gradual, episodic infiltration of aeolian sand, silt and dust. The progressive accumulation and pedogenesis of the infiltrated sediment result in the upward growth of a soil layer beneath the surface layer of stones. This fine material is called an accretionary mantle (Breed *et al.*, 1997) and the pebble lag settles evenly upon it. The accretion mechanism can operate at the same time as, and be assisted by, other processes such as colluvial wash. The even accumulation of the soil layer, and the resulting level surfaces of the gibber plains uplifted upon them, is explained by the uniform application of fine sediment by winds operating over broad areas. This mechanism also depends on wind for the formation of gibber plains (Breed *et al.*, 1997).

8.5 GIBBER PLAIN SAMPLING

To investigate which processes were active in the region, a series of pits were dug at nine sites in the northwest part of the Neales Fan (Figure 8.10). Each pit was less than 1.5 m deep and a sedimentary log was made of the pit walls.

8.5.1 JH002 & JH002a

Description

Figure 8.12 shows the two samples are within 3 metres of each other through two different landforms, a gibber plain and an adjacent alluvial sandplain. Pit JH002a was excavated to examine if the gibber plain extended beneath the sandplain. This was encountered at approximately 1 m. Pit JH002 was excavated within the gibber plain composed of rounded to subrounded polymictic clasts that were considered to be derived from fluvial sediments. No clasts were located within the underlying sediment. Incipient soil development was evident as an accumulation horizon of gypsum crystals.

Interpretation

The occurrence of gibber plain beneath the sandplain at Pit JH002a demonstrates that the sandplain was deposited as a later event following the formation of the gibber plain. It is interpreted that the most likely form of gibber plain development at this location was via lateral inputs as a result of alluvial processes.

NOTE: This figure is included on page 8-11 in the print copy of the thesis held in the University of Adelaide Library.

Figure 8.8: Shrink-swell soil behaviour. Rainfall infiltrates the soil, wetting clay particles and causing them to expand. This opens up small fissures around clasts and, when drying of the soil causes expansion, fines fall into these fissures gradually pushing the clasts upwards (Cooke, 1970).

NOTE: This figure is included on page 8-11 in the print copy of the thesis held in the University of Adelaide Library.

Figure 8.9: Accretionary mantle formation. Wind deposits fine particles that work their way beneath surface stones. These aeolian deposits grow and form a pediment, lifting the gibber plain (Cooke 1970).

8.5.2 JH005, JH006 & JH007

JH005 Description

Located on a highland area (approximately +25 m asl.) in this low topographic relief region, Pit JH005 was excavated in a silcrete-dominated gibber plain that has small isolated mobile sand dunes formed above it. Beneath the surface, the ground consists of red-brown sandy clay containing pebbles and rare cobbles of silcrete throughout.

JH005 Interpretation

This plain was interpreted to have formed as a result of deflation due to the similar size and composition of pebbles within the soil when compared with pebbles at the surface (Figure 8.12).

JH006 Description

The landform and pit reference diagram for JH005, JH006 and JH007 (Figure 8.12) shows that the section was conducted across a notable change in elevation of approximately 10 m where the expression of the gibber plain remained generally consistent. Pit JH006 was excavated on the flank of the hill. Soil development features were prominent, including manganese nodules and gypsum accretion.

JH006 Interpretation

The gibber plain at JH006 is interpreted to have formed through lateral input from colluvial sheetwash processes transporting gibber clasts downslope from the surface at JH005 to JH006.

JH007 Description

Pit JH007 was excavated at the base of the hill downslope of JH005 and JH006. An ephemeral alluvial channel is present at the base of the valley. Red-brown, fine-grained, ripple cross-laminated sands were evident in the upper part of this pit containing uncommon silcrete pebble clasts throughout. Gypsum and manganese accretion layers were present. Subsequent deflation has resulted in the concentration of gibber clasts at the surface.

JH007 Interpretation

The ripple cross-laminated sands indicate that the sediments of this pit were deposited by a stream. However, given the colluvial dominated processes operating at Pit JH006, it is probable that there is a significant component of clasts contributed from lateral downslope colluvial transport.

8.5.3 JH008 & JH009

JH008 Description

Pit JH008 (Figure 8.13) was chosen as the surface lag at this location was polymictic and appeared to be derived from fluvial sediment. Excavation revealed polymictic clasts and ripple cross-laminations within the sedimentary profile that suggest a fluvial origin for this sediment. Gypsum cementation and manganese nodule accretion were also present at the base of the pit.

JH008 Interpretation

This surface is interpreted to have formed as the result of deflation of fluvial sediments.

JH009 Description

Pit JH009 (Figure 8.13) was also selected because the land surface was covered with pebbles that appeared to be derived from fluvial sediments. Excavation of the pit revealed a fining-up sequence in red-brown sand overlying green-grey clay. Small pebbles were within both the sand and clay layers and were gypsum-cemented at the base of the pit.

JH009 Interpretation

The lower part of the sequence is interpreted as a lacustrine clay deposited in a pan that is overlain by fluvial sediments. The surface lag has formed as a result of deflation of this sediment and indicates the former existence of a palaeochannel.



Figure 8.10: Pit location diagram showing the relationship between pit sites and surrounding landforms.

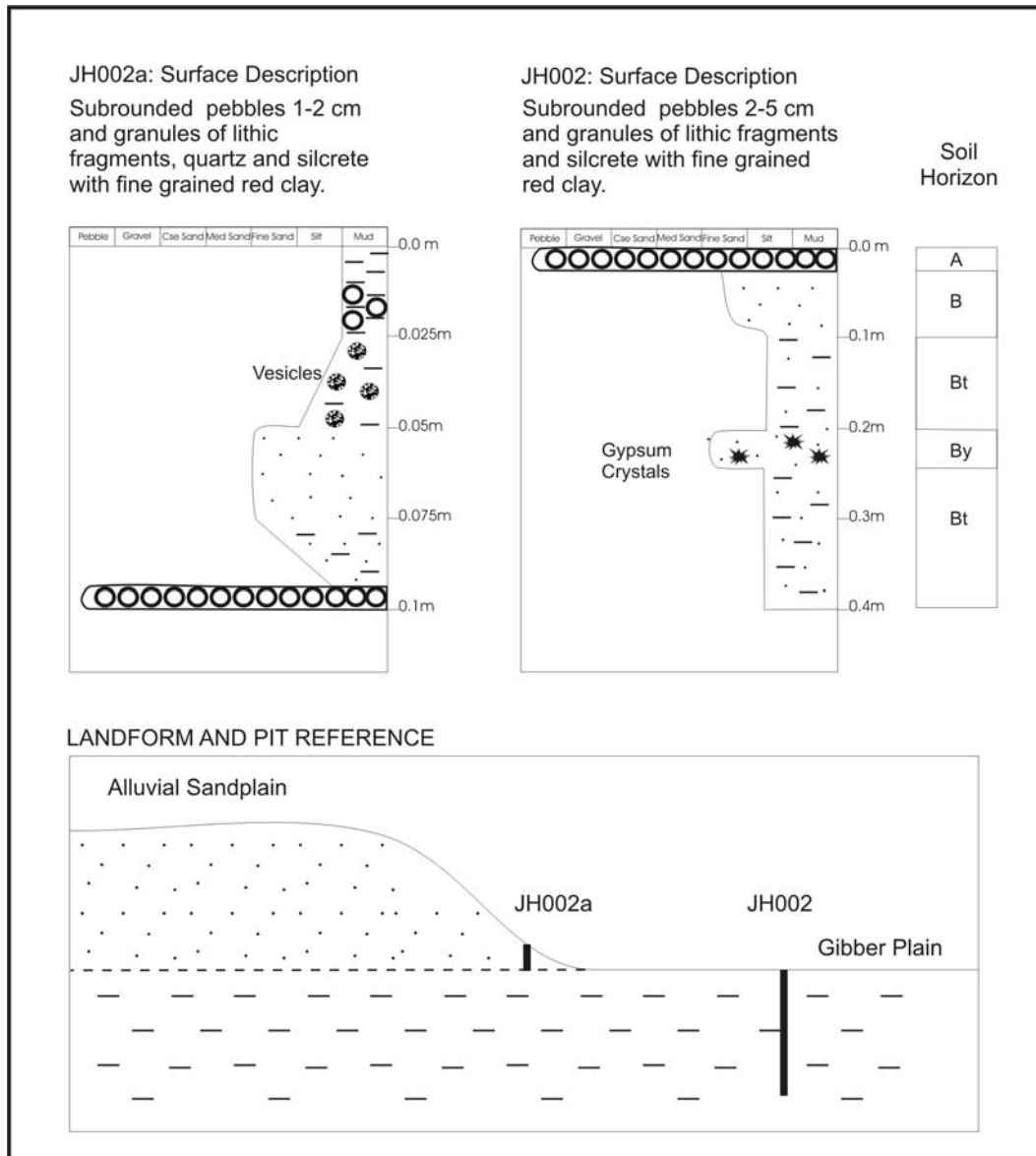


Figure 8.11: Sedimentary profile of Pits JH002a & JH002. JH002a (left) was sampled through alluvial sand and is demonstrated to overlie the colluvial plain. JH002 (right) is composed of slightly weathered alluvial sediment with a gypsum-cemented layer. Landform and pit reference diagram (bottom) showing the location of pits in relation to landforms (see Figure 8.10 for pit locations).

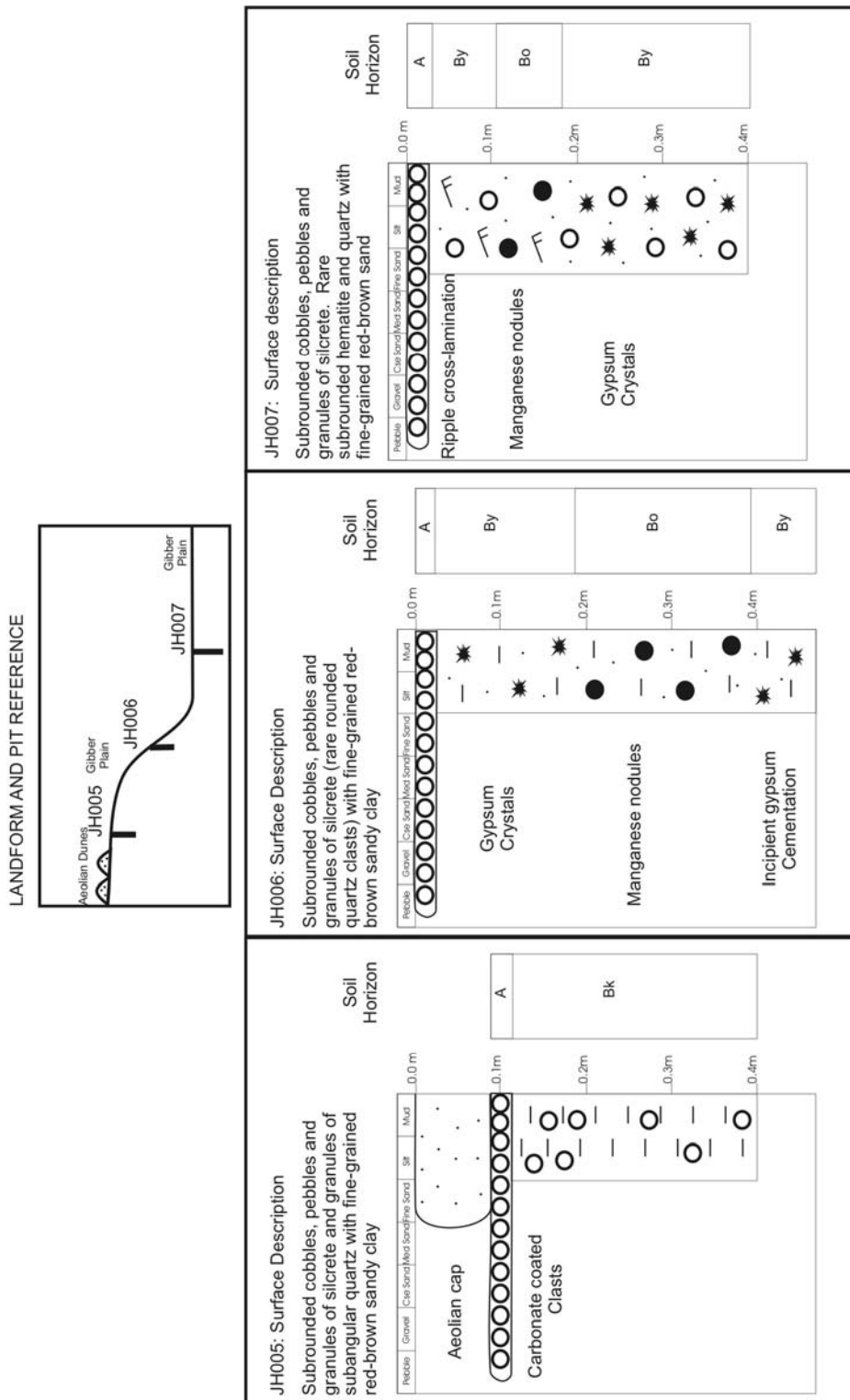


Figure 8.12: Section location and logs for pits JH005, JH006 and JH007 showing the variability in substrate beneath a continuous style of gibber plain surface. JH005 has carbonate-coated clasts, JH006 has gypsum cementation and manganese nodule development and JH007 shows gypsum cementation, manganese nodule development and ripple cross-laminations (see Figure 8.10 for pit locations).

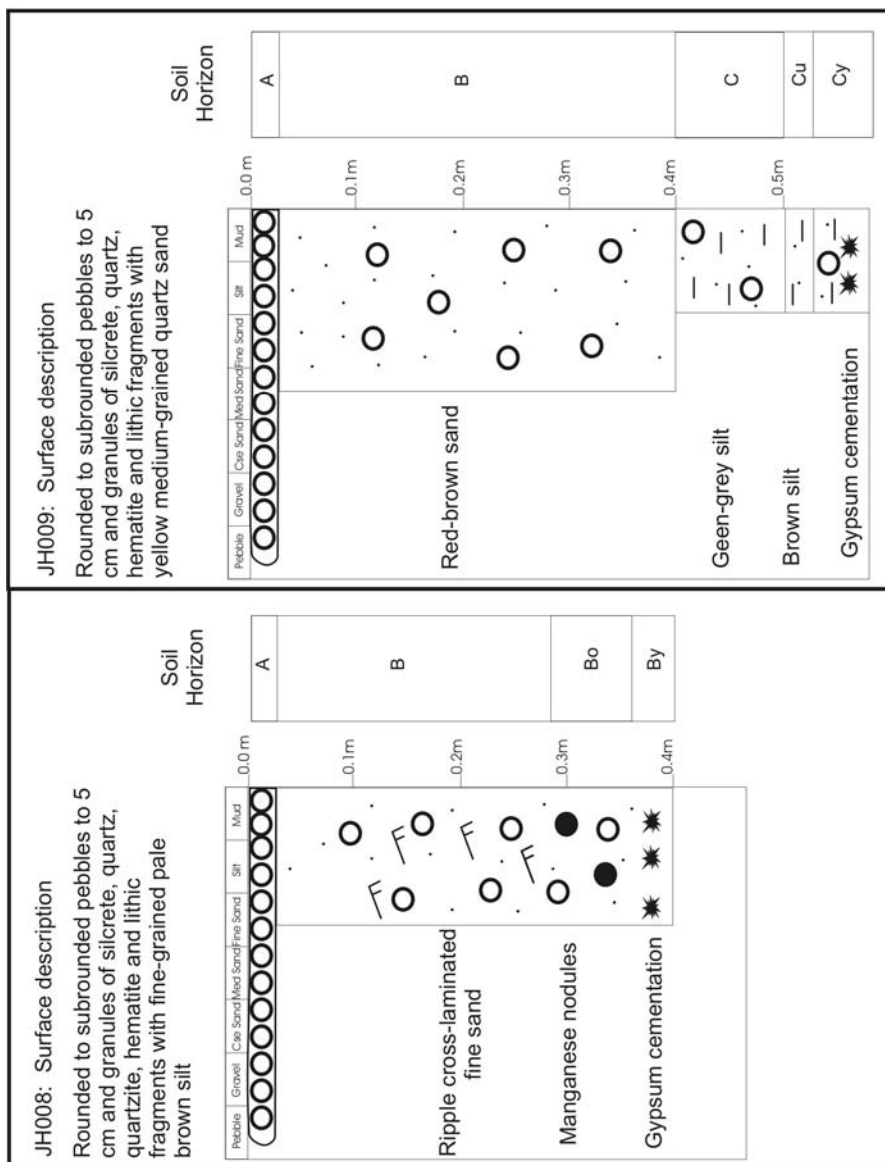


Figure 8.13: Pit logs for JH008 and JH009 showing the variability in substrate beneath a similar gibber plain surface. JH008 shows a ripple cross-laminated sand with gypsum cementation and manganese nodule development while JH009 shows a pebbly sand overlying a green-grey clay (see Figure 8.10 for pit locations).

8.5.4 JH010, JH011 & JH012

JH010 Description

Pits JH010, JH011 and JH012 (Figure 8.14) were excavated across a broad plain that displayed a possible structural discontinuity evident on satellite imagery. Pit JH010 was excavated and revealed a fine-grained, red-brown sandy matrix with pebbles and cobbles preserved in an indurated palaeosol at the base of the pit.

JH010 Interpretation

The upper fine-grained sand is interpreted as aeolian in origin and is considered as an accretionary mantle that has elevated a gibber plain formed on the surface of the palaeosol at some time in the past.

JH011 & JH012 Description

Pits JH011 and JH012 possess similar sedimentary profiles. They exhibit a thin layer of sand with rare pebbles close to the surface overlying a bioturbated layer. Beneath this layer are gypsum-cemented sands containing clasts.

JH011 & JH012 Interpretation

This surface is interpreted as a consequence of the upward migration of particles from the shrink-swell behaviour of the soil down to the wetting front and cemented layers. However, no micro-relief gilgai were observed in this location to support this hypothesis. It is also possible that an accretionary mantle formed over the cemented sediment that has since been indurated and bioturbated.

8.5.5 Overprinting of Processes Influencing Gibber Plain Formation

The processes that form gibber plains are highly variable in space and time and may be active at the same time but in different places, or, the same place but at different times. Even though different processes form two gibber plains, the ultimate results can appear the same. A gibber plain can be derived from the clasts in the substrate via deflation and shrink-swell soils.

Predominantly physico-chemical weathering and colluvial sheetwash, often associated with banded vegetation formation, cause lateral movement of clasts, smearing the provenance signal preserved in the clast compositions across the landscape as a mix of gibber types. This may not be recognised where sediments possessing similar clast provenances (e.g. silcretes) are formed by different processes (e.g. shrink-swell soils versus colluvial sheetwash).

Subsequent lateral transport and mixing cannot be distinguished by clast composition and the two units have similar surface expressions. Thus a gibber plain that appears continuous may be composed of several discrete elements formed at different times by different processes.

Gibber plain formation is a result of a complex interplay between surface processes, landscape evolution and sediment supply.

8.5.6 Sieve Analysis: Pit JH005

Deflation was suspected of being a contributing factor in the formation of the gibber plain overlying Pit JH005. A soil sample was taken from 10 cm below the surface of the trench. This soil sample was sieved to determine the relative abundance of clasts within the soil.

Sieve mesh sizes and relative grain size descriptions are given in Table 8.1 along with the results as both mass and percentage. Figure 8.15 displays the results as a pie chart. Of the aliquots, the portion between 500 μm (coarse sand) and 2.36 mm (granule-pebble) was predominately composed of aggregate grains and would require further sample processing to reflect an accurate assessment of grain size. This was not considered necessary in this case, as the sieve size of greatest significance was that over 2.36 mm (granule-pebble).

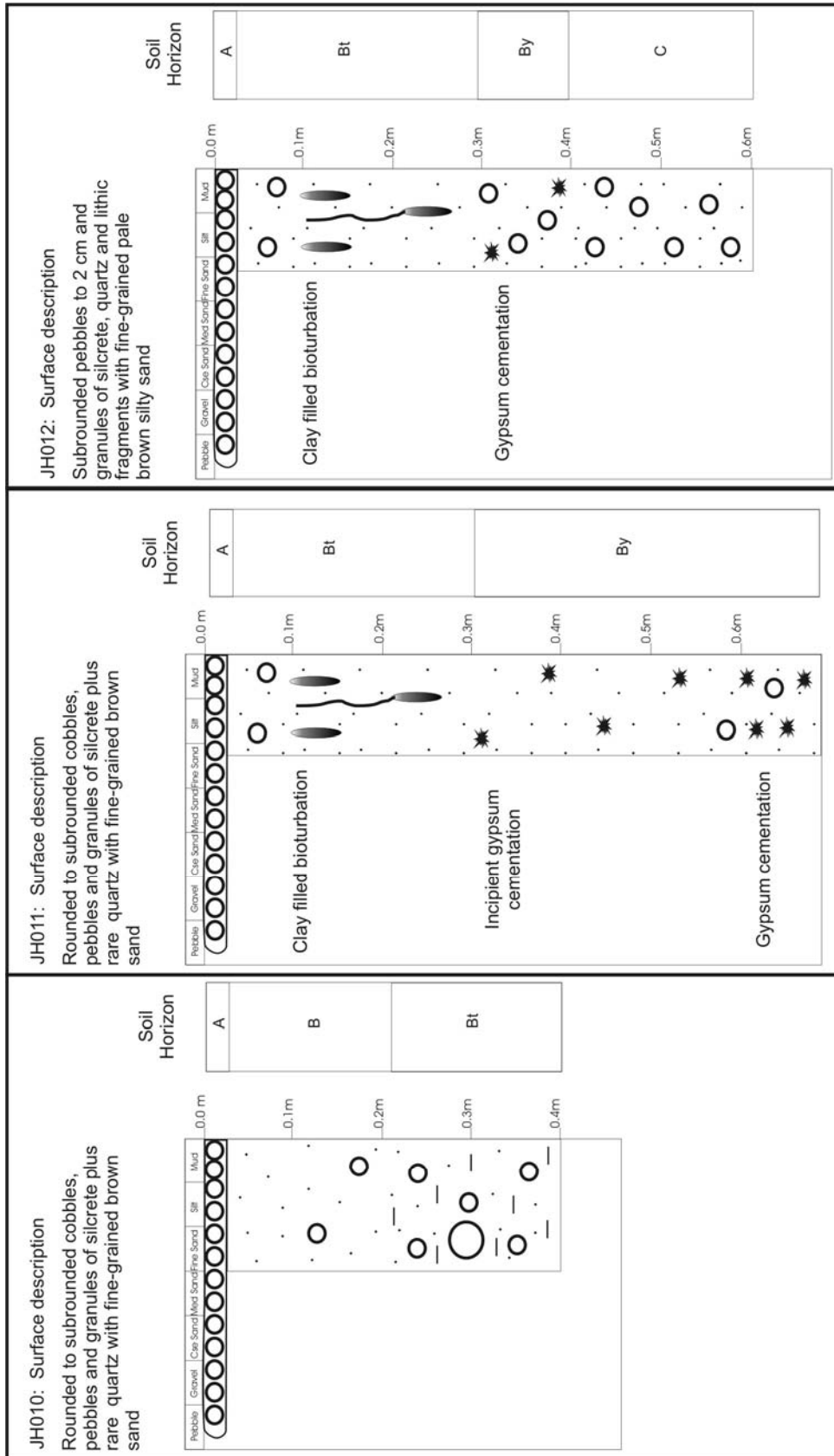


Figure 8.14: Pit logs for JH010, JH011 and JH012 showing the variability in the substrate between logs JH010 and JH011 that are beneath a similar gibber surface and the similarity between logs JH011 and JH012 that are beneath different gibber surfaces (see Figure 8.10 for pit locations).

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Volumetric calculations to determine the equivalent amount of deflation required to create a gibber plain.

The volume of the sample was initially measured and from this result the area of one side of a cube of equal volume was determined. The volume equivalent of the granule-pebble sample was used to calculate how much area a 2 cm thick layer of pebbles derived from this volume would cover. The amount of deflation required to generate a 2 cm thick layer could then be determined by dividing the original volume by the calculated volume.

Starting with a volume of 1500 mL of total sample, the length of one side of a cube of equivalent volume is given by the cube root (Figure 8.16).

$$\text{Length} = 1500^{1/3} = 11.5 \text{ cm}$$

Each square side of this cube has a surface area equivalent to the square of the length of each side.

$$\text{Area} = 11.5^2 = 131 \text{ cm}^2$$

From the measured sample volume, the 1500 mL cubic volume of the sample contains a volume of 453 mL of the pebble fraction. Assuming that a gibber plain is formed from the deflation of fines from a homogenous sample possessing different grain size fractions (eg silt, sand, granule and pebble fractions), it is estimated that the pebbles that form the gibber plain will make a layer approximately 2 cm thick. The equivalent volume of this 2 cm thick layer within the 1500 mL cube is given by the surface area of one face of the cube multiplied by the 2 cm thickness.

$$\text{Layer Volume} = \text{Area} \times \text{Thickness} = 131 \times 2 = 262 \text{ cm}^3$$

This layer represents 58% of the pebble fraction from the entire sample.

$$\text{Percent Volume} = (\text{Volume of Layer} / \text{Volume of Pebble Fraction}) \times 100 = 262 / 453 \times 100 = 58\%$$

It is assumed that the pebbles are distributed evenly throughout the 1500 mL sample cube. Therefore, in order to concentrate 58% of the pebble fraction into a 2 cm layer, 58% of the sample cube volume must also be removed via deflation.

$$\text{Volume} \times 58\% = 1500 \times 58\% = 870 \text{ cm}^3$$

This removed volume will still possess the same surface area on the top surface of the cube. Therefore, the depth of material removed will be given by the volume removed divided by the surface area of the cube.

$$\text{Thickness Removed} = \text{Volume Removed} / \text{Surface Area} = 870 / 131 = 6.6 \text{ cm}$$

Therefore, it is calculated that at site JH005 it is only necessary to remove 6.6 cm of material to produce a 2 cm thick gibber surface. A depth of this magnitude could be stripped in a very short period of time by the effects of wind and water. This suggests that deflation may contribute to the formation of most gibber plains in the region although this must be balanced against contributions from other mechanisms that may be active. Clasts that form gibber plains are predominantly subrounded to subangular. The clasts present in JH005 and the other pits were generally of similar sphericity, suggesting that most of the wearing down of the clasts has occurred during the transport event that deposited the clasts at the site, rather than from abrasion due to the passage of fine material during rain wash and wind scour (Krieg, 2000). These observations point to a relatively rapid rate of formation of gibber surfaces.

Table 8.1: Sieve results for soil sampled from pit JH005.

Sieve Mesh Size	Aggregate Name	Mass (g)	%
2.36 mm	Granule-pebble	687.55	30.24897
500 µ	Coarse Sand	338.63	14.89813
250 µ	Medium Sand	516.89	22.74073
125 µ	Fine Sand	486.44	21.40107
63 µ	Very Fine Sand	122.73	5.399543
63 µ	Silt	120.73	5.311553
	Total	2272.97	100

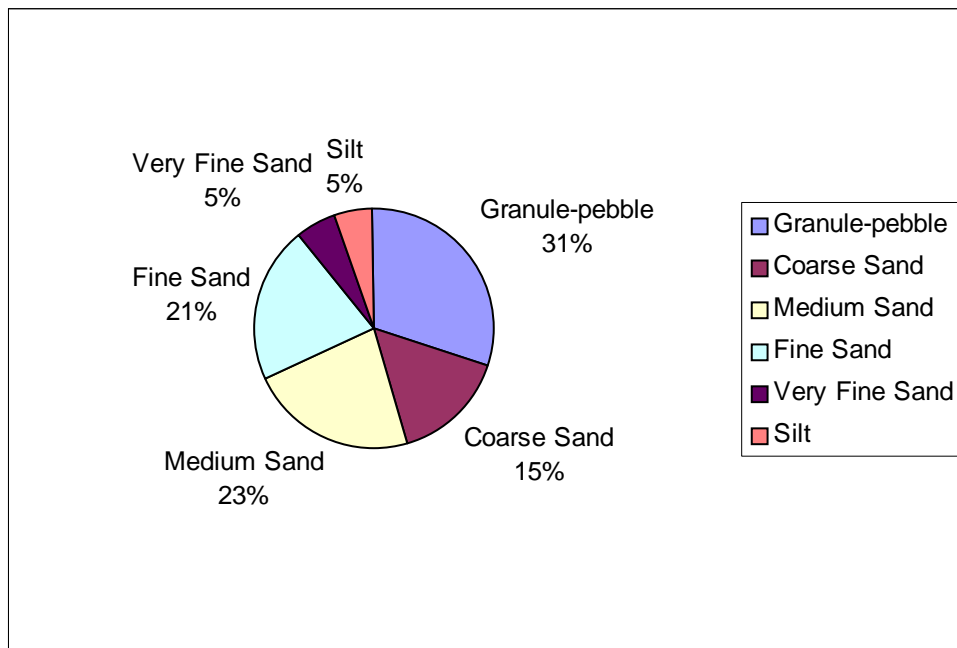


Figure 8.15: Pie chart plot of sieve results for the soil sample from pit JH005 showing nearly a third of the sample composed of granule to pebble-sized clasts.

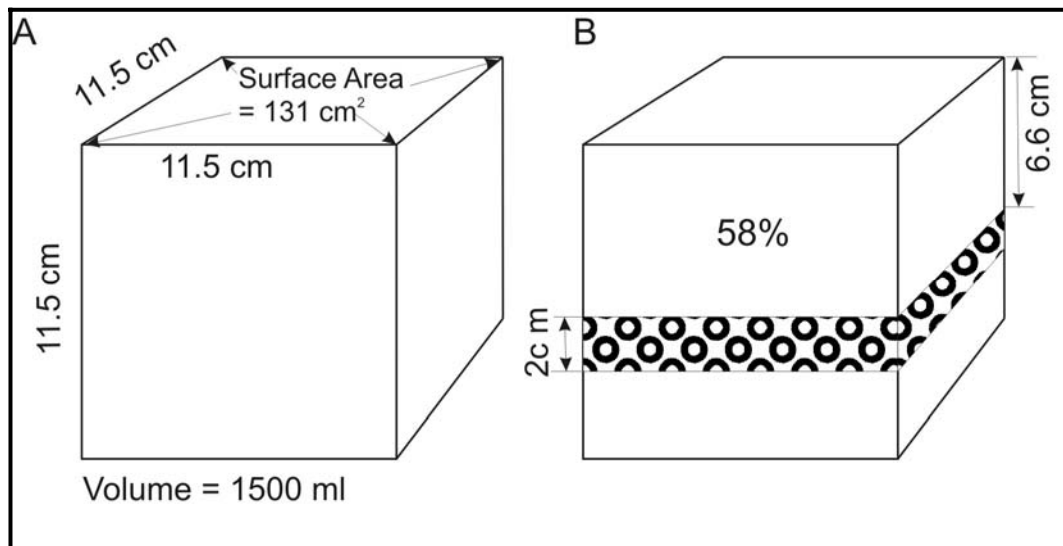


Figure 8.16: Diagram of (A) a 1500 mL cube showing the length of each side and (B) the depth of material removed to create a 2 cm thick layer of gibber plain.

8.6 GYPSUM AND GYPCRETE.

Gypsum is the common name for hydrated calcium sulphate ($\text{CaSO}_4 \cdot 2(\text{H}_2\text{O})$). Within the region it is expressed in a variety of forms:

- Twinned selenite crystallised as veins in marine sediment (Figure 8.17A);
- Tablelands of gypsum-rich patterned ground (Figure 8.17B);
- Gypsum-cemented sands (Figure 8.17C);
- Agglomerations of acicular gypsum crystals, or 'Desert Roses' (Figure 8.17D);
- Rhizomorphs (Figure 8.17E); and,
- Crystallisation of gypsum as part of the soil profile (Figure 8.17F).

It forms a distinct part of the soil and groundwater chemistry and the induration associated with gypsum cementation controls erosion throughout the lowlands in the study region.

The distribution of gypsum crusts and gypsum soils throughout the world is associated with arid environments receiving less than 200 mm/a rainfall and is indicative of a specific climatic environment where there is a monthly excess of evaporation over precipitation throughout the year (Watson, 1979). However, the preservation potential of gypsum crusts is limited as they are susceptible to dissolution if climatic conditions change to a wetter environment (Watson, 1979).

Gypsum patterned ground is visible throughout the field study area. It is particularly prominent at the margins of plateaux (Figures 8.17B, 8.18A & 8.18B) and forms grey, fine-grained, indurated, gypsum-rich sediment that commonly forms five sided polygons 0.2–0.8 m wide that are concave. These possess a raised lip creating the edges of cracks (Figure 8.17G). These cracks are infilled with vertically laminated gypsum sediment. Horizontal lamination is also present within the gypsum polygon. In some areas they display draping of land surfaces and across units, for example, mantling Palaeoproterozoic inliers at Lagoon Hill (Figure 8.18C) and silcrete outcrops near Four Hills (Figure 8.18D). Karstic dissolution features are also evident within some polygons (Figure 8.15H) and gypsum often reprecipitates downslope from exposures of gypsum patterned ground (Figures 8.18E & 8.18F). This tendency towards dissolution suggests that the gypsum polygonal surfaces may not be laterally extensive beneath the plateaux and may represent either a discontinuous surface or a fringe effect near the edge of the plateaux.

Within Pleistocene sediments of the Umbum Creek catchment there are many occurrences of gypsum-cemented sands such as gypsum-cemented fluvial gravels containing rhizomorphs. The presence of these rhizomorphs indicates a terrestrial depositional environment with a likely high water table (Figures 8.17C & 8.17E).

The growth and development of gypsum in the soil profile can be seen in most soils on the Neales Fan where a strong B-horizon is developed just beneath the surface. This takes the form of mottling and micro-crystalline gypsum powder that can form a well-indurated layer in the soil (Figure 8.17F). Additionally, displacive gypsum crystal deposition occurs in some Late Pleistocene sediments, forming acicular agglomerations, or 'desert roses' (Figure 8.17D).

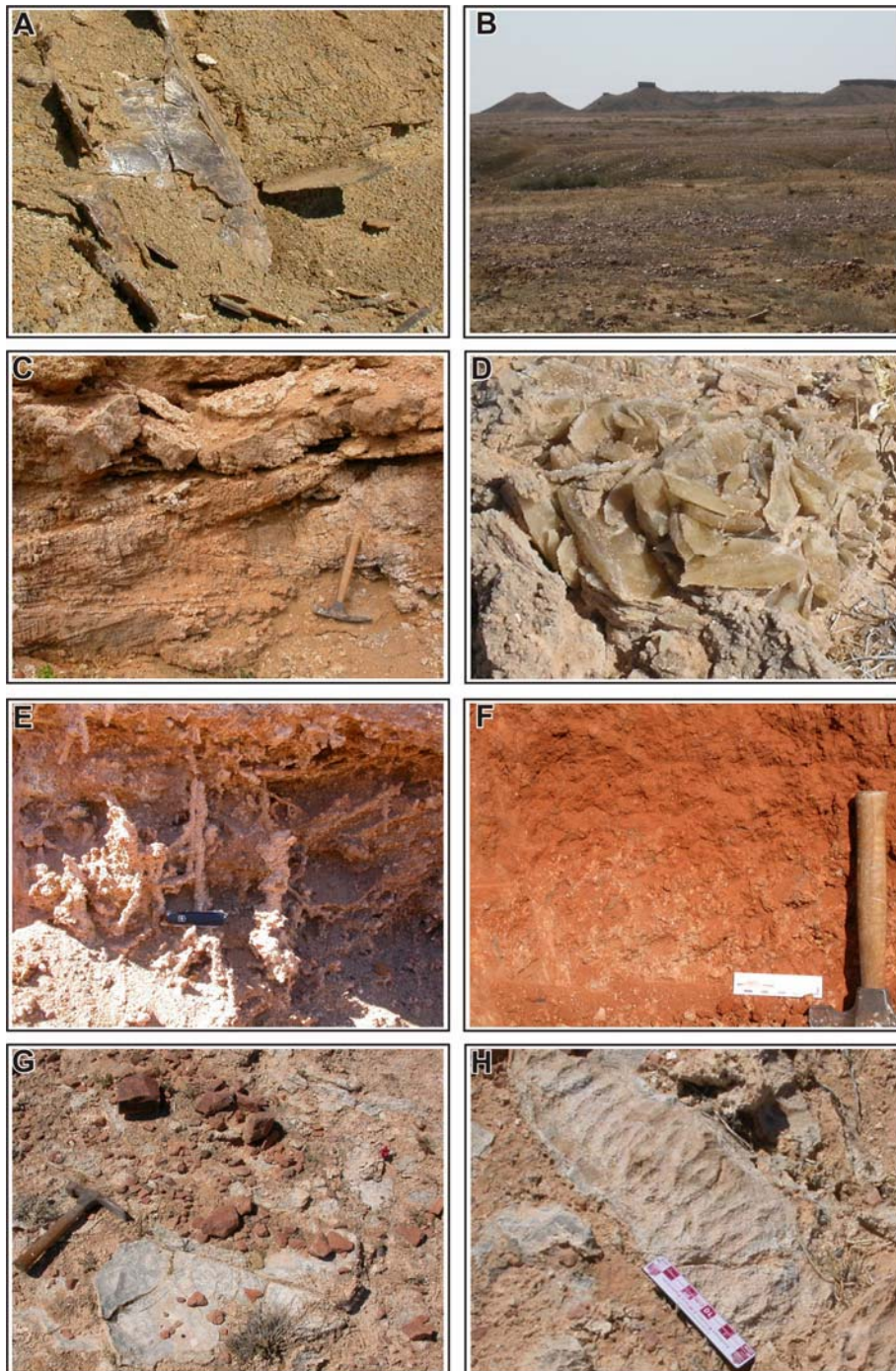


Figure 8.17: Styles of gypsum sedimentation within the Umbum Creek Catchment.
 A) Sheets of selenite deposited as veins within gypsum-rich shales (0647491E 6855831N).
 B) Mesas formed by headward erosion of gypsum-cemented upland surface (~063557E 6881581N);
 C) Gypsum-cemented sands (0641071E 6855015N);
 D) Gypsum deposited as 'desert rose' crystals (0641071E 6855015N);
 E) Gypsum-cemented rhizomorphs (~0678429E 6884775N);
 F) Incipient gypsum precipitation in the soil profile (0659525E 6872501N);
 G) Gypsum patterned ground (0635696E 6872482N); and,
 H) Karstic dissolution of gypsum patterned ground (~0680062E 6872808N).

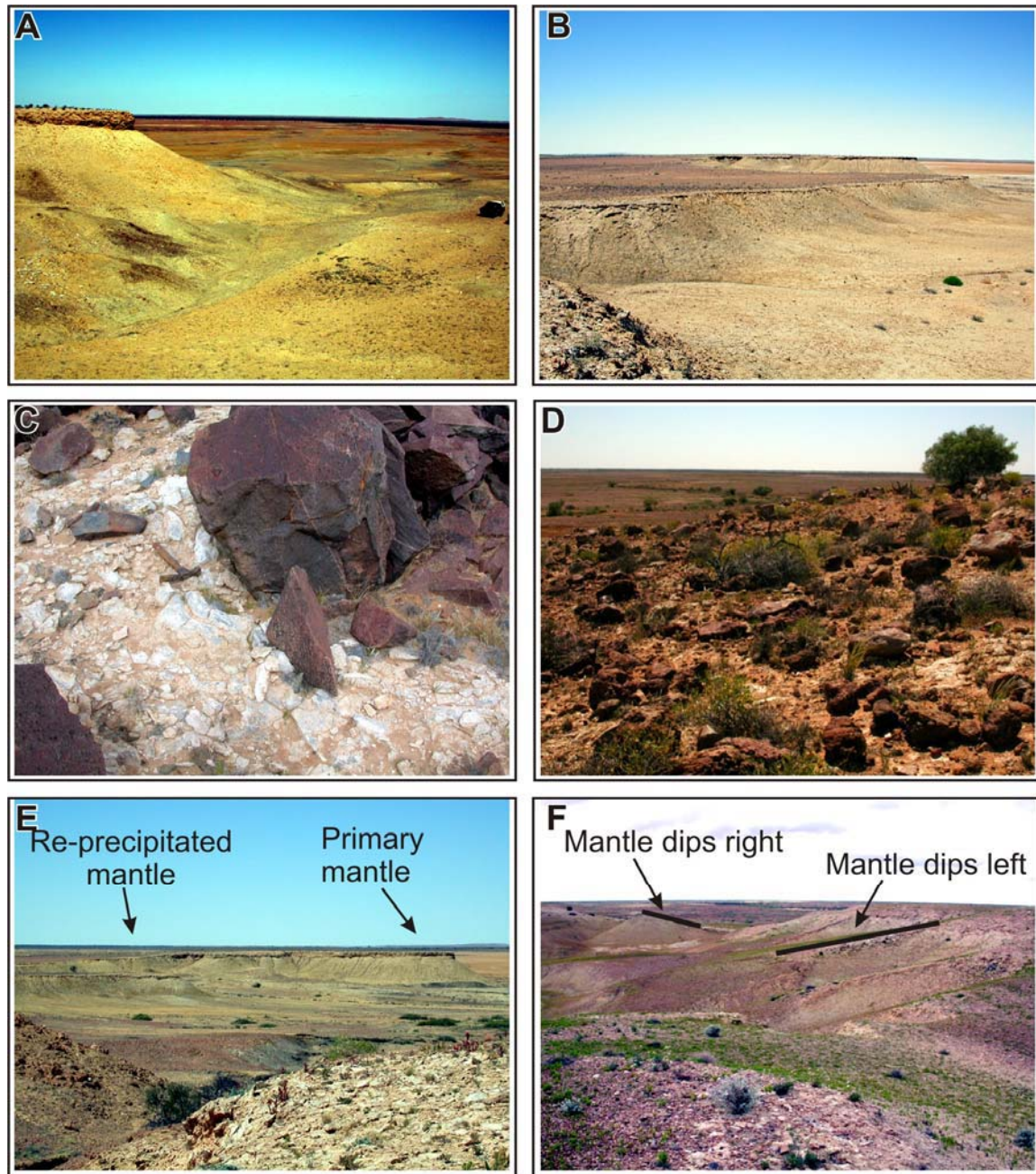


Figure 8.18: Morphological features of gypsum patterned ground.

- A) Margin of a gypsite tableland displaying headward erosion (~637466E 6882051N);**
- B) Broad gypsum patterned ground tableland with preserved surface elevated above modern baselevel (~636227E 6872579N);**
- C) Gypsum patterned ground forming a mantle on Palaeoproterozoic quartzite inselberg (0634839E 6870580N);**
- D) Gypsum patterned ground forming a mantle on outcrop of Miocene silcrete (0664347E 6846169N);**
- E) Gypsum patterned ground surface showing meso-scale reprecipitation of gypsum downslope (0635696E 6872482N); and,**
- F) Gypsum patterned ground displaying mantling of the land surface. The mantle dips in both directions over undeformed sediment (0620755E 6855839N).**

Watson (1979, 1983, 1985) summarised studies of gypsum occurrence worldwide and developed a classification system that encompasses previous work but removes many of the inconsistencies.

These classifications are (after Chen *et al.*, 1991; Watson, 1979; 1983; 1985):

- Shallow water evaporites, characterised by size-graded bedding;
- Subsurface crusts of either microcrystalline groundwater evaporites or mesocrystalline illuvial accretions; and,
- Surface crusts subdivided into columnar, powdery and cobble forms, predominantly composed of alabastrine gypsum.

Methods of formation include:

- Lacustrine

Shallow water and supra-tidal sedimentation in closed lake basins via evaporation of brines to form gypsum. This model accounts for varved-style gypsum deposits (Watson, 1985).

- Per Ascensum

The subsurface precipitation of gypsum from the top of a fluctuating water body saturated in calcium sulphate. This corresponds to the displacive growth of 'desert rose' crystals. A subset of the *per ascensum* model occurs in the soil moisture zone of sediments overlying gypsum-rich sediments or bedrock. Capillary action draws calcium sulphate to the surface where it is accumulated as a displacive crystal growth (Watson, 1985).

- Lateral Inputs

Aeolian deflation from sabkhas, chotts or playas during dry periods mantles the surrounding landscape in gypsum powder (Watson, 1985).

- Per Descensum

As a consequence of the mantling process of wind-blown gypsum, rainfall causes dissolution of the gypsum and remobilises it to a subsurface horizon. Through deflation this subsurface horizon is exhumed and becomes a surface crust (Watson, 1985).

8.6.1 Modes of Formation of Gypsum in the Umbum Creek Catchment.

Within the Lake Eyre region all of these mechanisms of gypsum formation have been observed. The lake appears to be currently dominated by halite deposition but was a magnesium-rich lake dominated by gypsum deposition during the Miocene (Alley & Pledge, 2000). Climate change during the Pliocene-Pleistocene resulted in a fluctuating water table with periods of aridity that would have allowed the stripping of lake sediments during dry intervals (lateral inputs) followed by *per descensum* concentration of the gypsum forming mantles across the palaeo-land surface. During wetter periods, rising water tables would allow the formation of gypsum-cemented sands and the displacive growth of gypsum crystals via the *per ascensum* mechanism.

Modern floodplains in the region do not display strongly developed gypsum layers. Floodplains form as the result of overbank flow and inundation of the surrounding channel margins with water. This would have a tendency to dissolve any gypsum formed in the floodplain. It is probable that the gypsum surfaces that form plateaux are related to a Pleistocene land surface (Wopfner & Twidale, 1967). Further mantling of the land by gypsum fines may not have occurred after depletion of lacustrine gypsum deposits via deflation at some point in time.

The gypsum plateaux may also represent mantling sourced locally from gypsum crystallised within the Bulldog Shale as per mechanisms proposed by Aref (2003), where leaching of gypsiferous shales combined with evaporation result in the mantling of land surfaces with gypcretes. Later erosion dissects and inverts the gypcrete layers (Figure 8.19). Dissolution of gypsum within the soil profile leads to the preferential concentration of clasts in the sediments into surface pebble lags (Aref, 2003).

8.7 ARID ZONE PROCESSES

8.7.1 Dryland Catchments and Ephemeral Streams

The majority of standard fluvial facies models have been developed for perennial rivers. The conditions in drylands, such as Central Australia, are quite different to those under which the general models are conceived. Rainfall in dryland areas is often highly variable in space and time. For example, the Lake Eyre Basin is subject to incursions from the Australian Monsoon. Historical documentation shows that during the major Lake Eyre filling events of 1984 and 1989, transient depressions provided the source of precipitation for the basin's western catchments (Croke *et al.*, 1999). In situations like this, short-term daily rainfall totals can exceed long-term averages and, where storm cells in the order of 10 km in diameter are the source of precipitation, rainfall may be patchy and locally highly concentrated (Tooth, 2000b). A single thunderstorm, therefore, may create flow in only one tributary, or a moving storm may initiate non-synchronous flow in a sequence of tributaries. Commonly, flow extends for only a portion of the river system. Sedimentary deposits derived from arid regions, therefore, display a similar variation spatially with coeval deposits existing at the same stratigraphic level but displaying widely different sedimentary style. Disequilibrium landforms are common and strongly influence the development of arid zone rivers. They may be prone to a catastrophic style of sedimentation (Wakelin-King, 2003).

Studies indicate that Central Australian floodplains possess landforms that imply fluvial activity at three scales (Patton *et al.*, 1993; Pickup, 1991). Large-scale fluvial landforms are represented by large sand sheets, sand threads and mega-ripple-covered channels that are related to a few enormous floods. Meso-scale fluvial landforms are represented by the currently active inner floodplain and consist of channel-levee complexes, floodouts, unchannelled floodplain and floodbasins. Overprinted on this are small-scale landforms represented by erosion cells. Erosion cells are composed of a source zone, a transfer zone and a sink. The source zone is an area of erosion and actively sheds water and sediment. The transfer zone occurs downslope and is an area occupied by discontinuous patches of sediment in transit or in temporary storage. The sink lies downslope of the transfer zone and is an area of sediment accumulation. Erosion cells occur at a number of different scales so that small cells may be located within larger cells. It is also possible for the source area of one cell to migrate upslope into the sink area of another cell, creating an alternating sequence of erosion and deposition. Streams also respond in a similar manner with erosion cells being repeated down the axis of a river, and may exist at several scales (Wakelin-King, 2003).

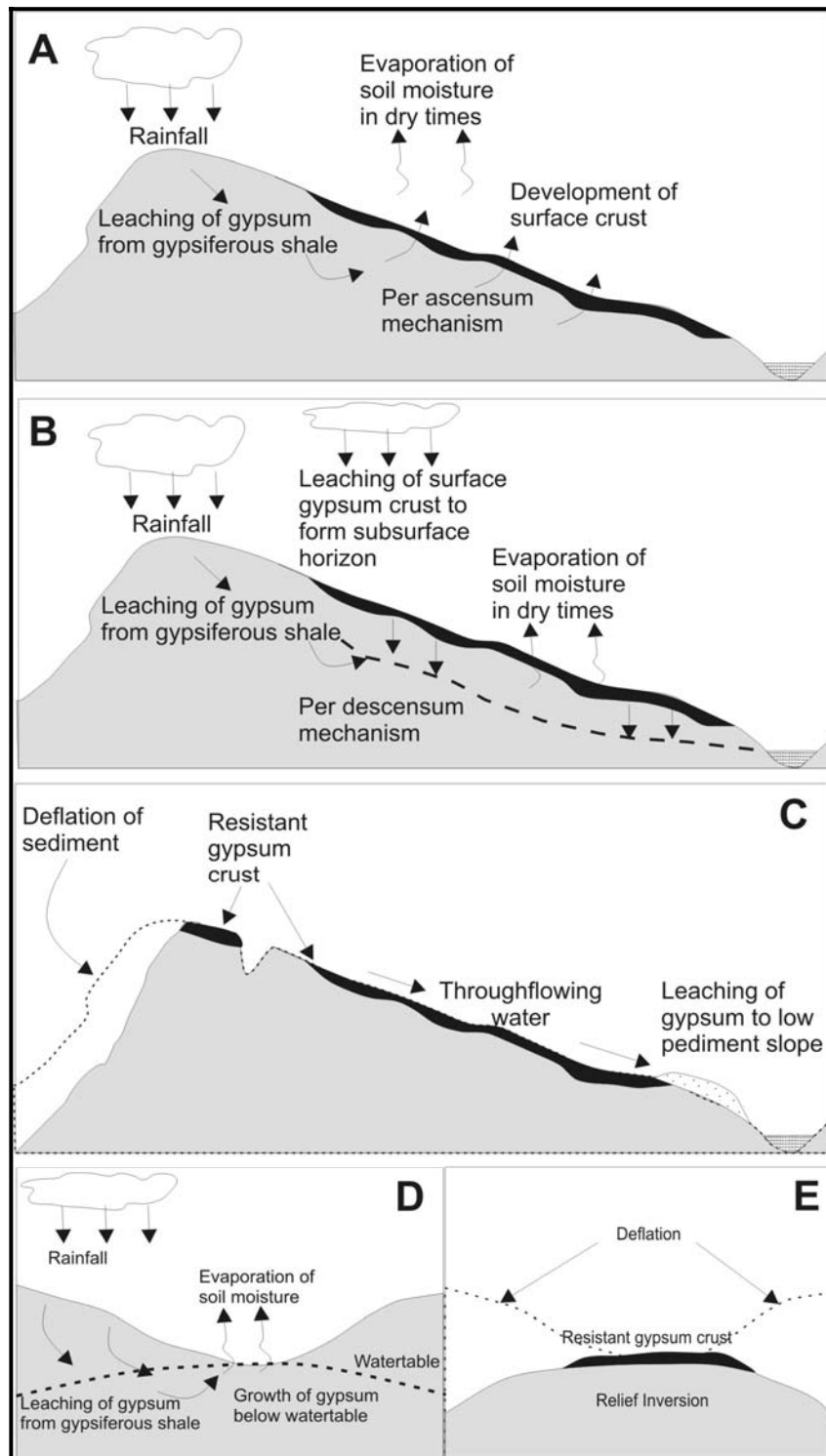


Figure 8.19: Processes of gypsum formation (from Aref 2003). (A) Rainfall causes leaching of gypsiferous shale that reprecipitates as a result of evaporation and the per ascensum mechanism. (B) Further rainfall leaches the gypsum crust reprecipitating gypsum as a subsurface profile via the per descensum mechanism. (C) Deflation erodes unconsolidated sediment producing gypsum capped mesas. Runoff dissolves the gypsum crust that then reprecipitates downslope. Other mechanisms involve rainfall leaching of gypsum into the watertable and (D) growth of gypsum below the watertable forming a gypsum hardpan. (E) Deflation and erosion then result in topographic inversion of the gypsum hardpan.

Flow in arid zone streams starts wherever local rainfall causes sufficient run-off. This intermittent flow results in incomplete sediment transport and the development of erosion cells (Figures 8.20 & 8.21). Scour is initiated in one part of the landscape, but sediments do not enter a continuous system as seen in a perennial river, they enter a limited transport system. As flow proceeds, transmission losses decrease water volume, increasing sediment concentration and water viscosity, thus decreasing water velocity. The sediment is eventually deposited as flow ceases (Bourke & Pickup, 1999). Erosion and aggradation not only happen in the same river, but also during the same flow event, and therefore, episodes of channel incision and terrace formation cannot be correlated from place to place, nor used to draw conclusions about palaeoclimate (Wakelin-King, 2003).

8.7.2 Headward Erosion and Gully Formation

The Umbum Creek catchment is a 'Badland' characterised by a barren landscape and rugged terrain. These develop where soft, predominantly horizontally bedded, relatively impermeable rocks are exposed to rapid fluvial erosion. Badlands display steep-sided residuals rising above gently sloping alluvial or pediment surfaces. Micro-relief is complex with pipes, rills, and vertical faces alternating with rounded forms. They are subject to high rates of erosion and large rapid runoff that often results in high sediment yields. Thus, a majority of sedimentary deposits may be derived from a minor portion of the watershed (Campbell, 1997). Badland gully systems may be divided into three categories (after Campbell, 1997):

1. Gullies in alluvial valley fills;
2. Gullies cut in valley sides; and,
3. Gullies forming as headcut extensions of a drainage system on undissected upland surfaces.

These three categories can also be observed in the Umbum Creek Catchment where generally northeasterly draining streams dissect the landscape, forming undulating low hills and alluvial valleys. Within these valleys most streams form as gullies, displaying slump and collapse by basal sapping. Flowing into these trunk streams are gullies that are cut into valley sides. These tend to form at the base of steep slopes developed at the edges of plateaux formed on top of the Bulldog Shale. They are fed by piping and mass wasting of weathered and friable shale deposits, resulting in steep sides to the broad alluvial valleys. Further erosion into the plateaux is effected by headcutting extensions of the drainage system into the upland surface. These can cause deep embayments in the plateau edge. The plateaux, however, are not level but consist of undulating surfaces, or interfluvies, separated by shallow alluvial channels draining these broad colluvial sheetwash-dominated plains. Many features of well-developed badlands are not present, such as meso-scale pipe development, large gullies and tributary valley formation. The lack of mature gully features may indicate a relatively young age for the geomorphological development of the land; however, it has been demonstrated that gravel lags are capable of stabilising a land surface and consequently retarding erosion (Alexander *et al.*, 1994) so that a surface may require several centuries in order to reach complete equilibrium stabilisation. Interruptions may occur due to long-term effects such as tectonics or climatically induced base-level changes or through short-term effects like major storms. Short-term effects can create conditions of considerable disequilibrium, as within the Bulldog Shale there are large quantities of weathered material available and erosion is limited only by the frequency and magnitude of fluvial events of sufficient energy to transport large volumes of material (Campbell, 1997). The land surface in the Lake Eyre region is a complex mix of stabilised surfaces, disequilibrium landforms and highly erosive active gully systems, reflecting a variety of complex surface and subsurface adjustments to different thresholds.

NOTE: This figure is included on page 8-29 in the print copy of the thesis held in the University of Adelaide Library.

Figure 8.20: Schematic diagram of erosion cell formation showing the development of production-transfer-sink zones and the interlinking of erosion cells in a mosaic (from Bourke & Pickup, 1999).

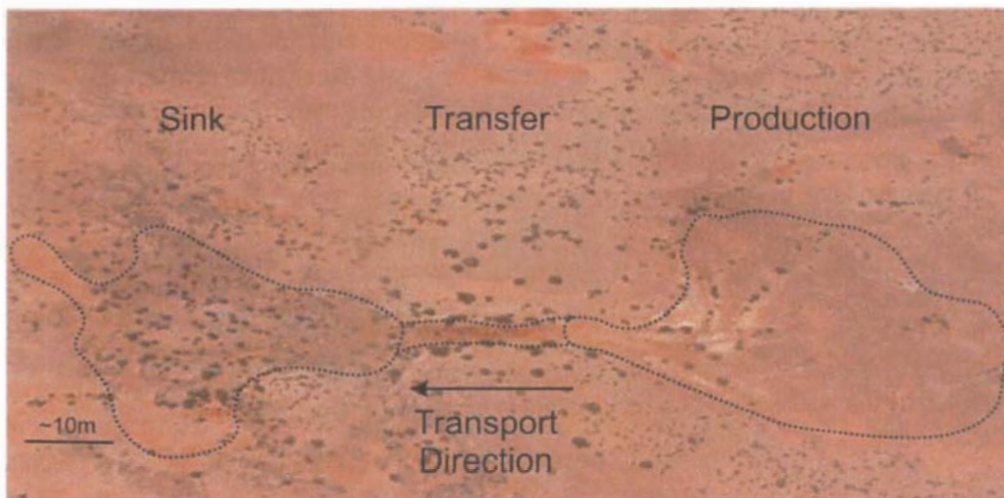


Figure 8.21: Erosion cell on the Neales Fan showing the demarcation between the production zone, the transfer zone and the sink with the direction of sediment transfer indicated.

8.8 LANDSCAPE PROCESSES SUMMARY

Silcrete Development

Silcrete in the study area formed as a consequence of sedimentary pyrite precipitated within the Bulldog Shale. The oxidation of these sedimentary sulphides produced sulphuric acid in a low watertable, restricted flow, arid regime. Subsequent climate change to a wetter environment caused rising groundwater levels and mobilised amorphous silica laterally into permeable sand units. These sands became indurated and developed relief inversion.

Gypsum Development

There are many different expressions of gypsum in the Lake Eyre landscape and these are formed via four basic methods of gypsum deposition: lacustrine deposition, *per ascensum*, lateral inputs and *per descensum*. All four processes have been active in the Lake Eyre region.

Gibber Plain Development

There are many different methods of gibber plain formation in the Lake Eyre region. These different processes may operate on the same gibber plain or mix across different gibber plains, forming a patchwork of different systems in the landscape. They may form very rapidly, requiring less than 10 cm of deflation to produce a gibber plain and then form a stable land surface for thousands of years.

Arid Zone Processes

Rainfall in the Lake Eyre Basin is highly variable in space and time. This variation results in similar variation in coeval sedimentary deposits at the same stratigraphic level displaying different sedimentary style. Irregular scour-transport-fill erosion cells form a patchwork across the landscape and within river channels at various scales. Therefore, channel incision cannot be correlated from place to place nor used to predict palaeoclimate. Further complexity is added by the scale of formation as Central Australian rivers form at three scales related to the size of flow events. The landscape is a complex mix of stabilised land surfaces and disequilibrium landforms. It is highly eroded.

8.9 DISCUSSION

The complex processes involved within each of the subject areas outlined above indicate that the landscape evolution of this region is extraordinarily complex. Each of the separate processes interacts across the landscape in a complex series of events to produce the landscape seen today. For instance, it is probable that gypsum hardpans formed via lateral inputs and *per descensum* accretion, forming plateaux and escarpments as a result of gully formation via mass wasting in the underlying Bulldog Shale. On top of these plateaux, gibber plains formed by the lateral transport and in situ deflation of soils bearing silcrete clasts that were created by the acidification of groundwaters in much more laterally extensive deposits than visible today.

The Umbum Creek Catchment represents a highly eroded landscape that was probably eroded very rapidly. Gravel lags, however, may prevent erosion from occurring over short time frames but the gravel lags probably also form very rapidly. It is probable that both erosional landforms and gibber plains formed very rapidly during the Pleistocene and have since been preserved by caprocks, indurated surfaces and stone mantles.

9 LANDSCAPE EVOLUTION MODEL

9.1 LANDSCAPE EVOLUTION

9.1.1 Pre-Cainozoic

The Pre-Cambrian geology of the region has been extensively studied and is documented by Drexel & Preiss (1995). Pre-Cambrian rocks influence the field study area as they are exposed in the Davenport Ranges and provide much of the source material that contributes to surficial lags and sands. However, they have a greater influence in terms of underlying structure. The underlying structure of the region has clearly had a strong impact on the later development of sedimentary basins and faults. In the Pre-Cambrian, Australia experienced an eastward and northeastward pattern of cratonic accretion as the Western Craton was buttressed by the Yilgarn and Pilbara blocks resulting in a pattern of west to northwest and north to northeast trending lineaments forming in the basement during the early Proterozoic (Gale, 1992). Within the area irregular basement topography is implied by the protrusion of several Precambrian inliers (Teluk, 1974).

A comparison between these lineaments and seismic activity within the study region (Chapter 3) demonstrates that there is an association between the location of earthquake epicentres and lineaments (Figure 3.1). This implies that the lineaments are active faults that may be experiencing low intensity ongoing tectonic activity. This is further supported by the comparison of rainfall, bore pressure and earthquake frequency data that shows a low-level correlation between these datasets. This information supports a model of ongoing seismic tremors, driven by changes in hydrostatic pressure caused by rainfall fluctuations in the recharge zone of the Great Artesian Basin. The identification of modern seismic activity, and possible mechanisms causing it, indicates that it is probable that evidence for neotectonic disturbances are preserved within sediments and landforms of the study area.

The geomorphic evolution of the landscape begins with the planation of Adelaidean and Palaeozoic rocks to form the Mt. Margaret Surface sometime between the Early Permian and Late Jurassic (Rogers & Freeman, 1993). This event was associated with a period of weathering that caused intense alteration within the sediments.

During the Late Jurassic, large meandering to braided rivers, flowing in a landscape of low to moderate relief, deposited the Algebuckina Sandstone (Alley & Pledge, 2000). It contains a basal unit with highly weathered kaolinised shale pebble clasts derived from the earlier phase of weathering (Krieg, 2000). Differences in the sedimentology of the Algebuckina Sandstone suggest that it was subject to climate change during its deposition, beginning with a climate of occasional large flood events in either an arid to semi-arid climate or fluvial run-off derived from seasonal melting of snow. The climate developed into a more uniform regime with wetter conditions and higher precipitation (Rogers & Freeman, 1993).

The Cadna-Owie Formation was deposited in the Early Cretaceous disconformably overlying the Algebuckina Sandstone. It represents a marine transgression and was deposited in a range of environments formed along the encroaching coastline, including near offshore, shoreface and foreshore, marine shoal or lagoonal shoreline, intertidal, high-energy beach and back-barrier lagoon or coastal marsh (Rogers & Freeman, 1993).

The contemporaneous Mt. Anna Sandstone Member inter-digitates with the Cadna-Owie Formation. It was deposited in a high-energy system with large rivers and contains clasts of Gawler Ranges Volcanics, indicating that the river system drained northwards from the Gawler Craton, in the region near Lake Gairdiner (Rogers & Freeman, 1993).

The Bulldog Shale conformably overlies the Cadna-Owie Formation and Mt. Anna Sandstone. It was deposited in a low to moderate energy, shallow marine environment during a period of maximum marine transgression (Rogers & Freeman, 1993). Dropstones are common in the lower units and were delivered by ice-rafting. The prolific development of pyrite within these sediments indicates that they formed in a euxinic environment (Krieg, 2000). It is this pyrite that plays an important role in the future development and expression of the landscape (see Chapter 8).

During this period the Palaeoproterozoic inlier at Lagoon Hill was a basement high as evidenced by shoreline features recorded on its sides. Wave-worn surfaces and beach deposits indicate that this shoreline was a high-energy environment. Further transgression continued to deposit up to 10 m of sediment above this beachline (Rogers & Freeman, 1993). Other basement inliers at Spring Hill and Mt. Charles, along with Lagoon Hill, were primary basement structures that influenced deposition during the Mesozoic (Teluk, 1974). The Coorikiana Sandstone represents a regressive unit deposited in a predominantly intermediate wave energy shoreface environment. It overlies the Bulldog Shale conformably (Rogers & Freeman, 1993).

Conformably overlying the Coorikiana Sandstone is the Oodnadatta Formation. It represents a transgressive regime with a shallow marine shelf environment and frequent episodes of high-energy storm and wave-generated current activity (Rogers & Freeman, 1993). The conformable Winton Formation can be seen as a further shallowing of the depositional environment to a non-marine, fluvial/lacustrine environment (Krieg, 2000).

9.1.2 The Cainozoic

Following the end of the Mesozoic a hiatus formed of approximately 30 Ma and ushered in a period of weathering and silcrete formation until the Eocene (Alley & Pledge, 2000). This represents the first of approximately three phases of silcrete development. The silcrete derived from the exposure of the pyritic Bulldog Shale as sea levels fell. This resulted in the oxidation of the sedimentary sulphides producing sulphuric acid and the mobilisation of iron. This occurred under a low groundwater table and restricted-flow, arid condition. Following this, palynological evidence supports a warm, wet period during the Palaeogene, conditions that promoted rising groundwater tables (Alley & Pledge, 2000). This increase would produce acid sulphate soil conditions. The new hydraulic regime led to the transport of amorphous silica, developed in the bleached profile, laterally into other units resulting in the formation of silcrete (Simon-Coinçon *et al.*, 1996).

During the Late Palaeocene, tectonic subsidence caused the Lake Eyre depocentre to form. This resulted in the proto-Davenport Ranges creating a drainage divide in a subdued-relief terrestrial environment. Weathering and erosion produced a stable landsurface and the breakdown of silcrete deposits (Alley, 1998).

Between the Late Palaeocene and Middle Eocene the Eyre Formation was deposited as a fluvial sandsheet in large low-sinuosity meandering to braided streams and restricted swamps and lagoons (Krieg, 2000). Drilling has demonstrated that Eyre Formation is present in the

subsurface of the Neales Fan (Croke *et al.*, 1998). It appears to form a continuous sand sheet beneath the fan, but is absent elsewhere within the study area except as isolated outcrops of the time equivalent Mirakina Conglomerate (Rogers & Freeman, 1993).

The Mirakina Palaeochannel (MPC) was a drainage system that flowed in a southeasterly direction parallel to the modern Stuart Range Divide (Figure 7.38). It is composed of fluvial channel deposits referred to as the Mirakina Conglomerate (Alley, 1998). Equivalents of this unit extend along a trend that is coincident with the ultimate trend of the MPC at its termination (Figure 7.38). It is possible that the Mirakina Conglomerate equivalents represent a continuation of the MPC, but they more probably represent similar but separate channel and floodplain sediments of a broad alluvial plain or delta. These sediments are contemporaneous with Eyre Formation sediments but are currently located at significantly higher elevations than recorded outcrops of Eyre Formation. This difference in elevation is due to subsequent uplift and topographic inversion of these palaeochannel sediments

Following deposition of the Eyre Formation and the Mirakina Palaeochannel equivalents was a period of weathering, silicification and tectonism. Tectonic activation of the basement structural features led to subdued uplift and downwarp. Those areas that were elevated above the water table began to harden as the 'silica-charged' sediments were exposed (Krieg, 2000). Thus, the Cordillo Surface and Cordillo Silcrete were formed in extensive areas near Oodnadatta, north of the field area, and within the Mirakina Conglomerate equivalents and parts of the Eyre Formation. The Cordillo Silcrete was deformed prior to the deposition of the Etadunna Formation (Alley & Pledge, 2000). The Lake Eyre Fault was activated and resulted in normal block tilting along a northwest-southeast trend forming the Neales River and Browns Creek valleys.

As the Australian continent moved northwards the climate began to change (Williams, 1984). The Etadunna Formation, composed of white dolomite overlain by green-grey magnesium-rich claystone, was deposited in an evaporative lacustrine environment (Alley, 1998). During the Late Oligocene to Middle Miocene neither the Davenport Ranges nor the Neales Fan existed. The landscape was subdued and contained extensive, shallow alkaline lakes.

Continental plate boundary interactions began to play a role in the development of the landscape as the rate of movement of the Indo-Australian and Pacific plates changed. This variation resulted in a change in the intra-plate stress field of the Australian plate and was accompanied by tectonism in southeastern Australia (Reynolds *et al.*, 2003). The fluctuations in the stress field have continued since the Late Miocene and account for reactivation of tectonic activity throughout southeastern Australia (Sandiford, 2003). Contemporary with the deposition of the Etadunna Formation was the deposition of the Stuart Creek Palaeochannel to the south of the study area. These fluvial sediments are interpreted as facies time-equivalents of the Etadunna Formation (Alley & Pledge, 2000). Within the study area similar, equivalent facies would have existed as the lacustrine shore was nearby. Following the deposition of the Etadunna Formation, a further hiatus occurred of approximately 12 Ma with associated weathering, erosion and the development of silcrete. The Stuart Creek Palaeochannel was silicified during this period (Alley & Pledge, 2000). Outcrops of silcrete at Four Hills have been interpreted as possessing two layers representing two silcretisation events (see Chapters 7 & 8): the first associated with the Cordillo Silcrete and the second with the Stuart Creek Silcrete. The second event is characterised by a capping unit of fine-grained, brecciated silcrete with 'reed mould' structures on the silcrete outcrops of Four Hills (Figures 7.24 & 7.25). The 'reed mould' structures are preserved pedogenic features that formed vertically in a low-gradient

fluvial floodplain environment. This indicates that the silcretes of the previous phase remained at or near the surface. The 'reed mould' structures are now present at angles of 20–30 degrees, indicating tilting by tectonic processes (Figures 7.9 & 7.23). This tectonic event occurred between the Pliocene and Middle Pleistocene. It was also responsible for the uplift of the Davenport Ranges and Mt. Margaret Surface along the Mt. Margaret and Levi faults. Sediments ranging in age from Jurassic to Miocene were dragged upward along the faults and the Etadunna Formation was deformed. Hawker Creek originally flowed across the ranges and subsequent incision has preserved antecedent meanders in the Proterozoic rocks (Figure 5.6). Peake Creek, a major tributary to the Neales River, also displays antecedence where it incises into the Denison Ranges to the north.

Silcretes in the study area became exposed and began to erode. The breakdown of these and the Cordillo Surface silcretes resulted in the formation of a silcrete-dominated surface.

9.1.3 Landscape Evolution of Umbum Creek Catchment

The landscape evolution of the Umbum Creek Catchment started in the Early Pleistocene. The land surface was disrupted as basement fractures were activated causing the foot of the ranges and the Neales Fan to be dissected along a northwest-southeast trending axis (Figure 9.1). A series of irregularly stepped blocks formed the basis of subsequent topography and stream pathways throughout the Pleistocene. In the southern section of the study area, fluvial conglomerates were deposited between Davenport and Sunny Creeks. These palaeochannel sediments may have been more extensive, possibly causing stream erosion on silcrete surfaces in the same area (Figure 7.26).

As a result of uplift along the Mt. Margaret Fault, broad alluvial fans formed at the base of the ranges (Figure 9.1). These extended from 10–15 km in length to the northeast. They include sediments derived from the Davenport Ranges. Remaining exposures of these alluvial fans are matrix-supported suggesting a predominance of fluid-gravity processes (debris flows). Following the primary deposition of these fans, reworking of the fan surface commenced, forming braided stream networks across the fan surfaces. These eroded and dissected the fan surfaces, forming broad alluvial terraces (Figure 7.5). The alluvial fans created along the range-front may have been much thicker than current exposures. They are now approximately 5 m thick at the base of the ranges and become thinner towards the distal zone where they are less than a metre thick. The Neales River/Umbum Creek system acted as the axial river to the alluvial fan systems.

Following the deposition of the alluvial fans, tentatively dated as Early Pleistocene, stabilisation of the land surface occurred. This included the formation of gypsum-cemented surfaces (Figure 9.2). As discussed in Chapter 8, the formation of gypsum surfaces is complex and an accurate date for their formation is not certain. Later redissolution of the gypsum and precipitation down-slope may lead to the formation of lower elevation gypsum surfaces (Figure 8.19). Gypsum surfaces also mantle the landscape and are not necessarily correlatable as lithological units. Gypsum surfaces deposited during this period preserved the landscape topography of the Early Pleistocene. They have generally formed at the hydrologically impermeable contact with the Bulldog Shale.

During the Middle Pleistocene a tectonic reactivation occurred, causing movement on the Mt. Margaret and Levi faults (Figure 9.3), demonstrated by the low sinuosity of their associated escarpments (Table 5.2) and rejuvenated alluvial fans along the escarpment front. The shape of hypsometric curves (Figure 5.19) has shown that the northern segment of the Umbum Creek

catchment is more eroded than the southern section. This implies that the southern part of the Mount Margaret Fault has either been less active or has a north-south tilt. The southerly trend on the topography of the Neales Fan infers a relative uplift along its northern edge that supports a similar north-south component (Figure 5.30). Streams were diverted by reactivated lineaments (Figure 5.2, 5.4 & 7.17) and in some cases the tectonic adjustment caused them to break their banks and deposit either overbank or alluvial sediment (Figure 7.15 & 7.16). Assymetric drainage along Davenport Creek indicates a preserved palaeochannel forming an elevated ridge along a probable basement fault (Figure 5.5). Four Hills is bounded by faults and dominated by divergent drainage, interpreted as a zone of uplift. (Figure 5.4). Mound springs developed along faultlines and basement highs (Figure 9.3). They deposited travertine deposits and black sulphidic muds. These developed on the lower surfaces, typically causing incision of upper gypsite terraces via headward erosion away from the growing mound at the springhead.

This was followed by a period of active deposition in the Neales River system until a phase of aridity at 20 ka (Croke *et al.*, 1996). This initiated landscape incision as the base level of the lake changed (Figure 9.4). The degree of erosion was intense and rapid causing topographic inversion of palaeochannel sediments (Figure 7.37), the incision of the Neales River, incision of alluvial fan sediments and concomitant entrenchment of the fan head channel (Figure 5.11). Up to 50 m of sediment is estimated to have been removed from the Four Hills area. Areas that had formed subsurface gypsum hardpans became topographically inverted (Figures 8.17 & 8.18). The sediment that was previously situated above the hardpans was stripped and degraded by landscape lowering processes, leaving a surface composed of angular quartzite clasts where the alluvial fans had been. The breakdown of silcrete from topographically inverted outcrops led to the formation of silcrete surficial lags in adjacent areas, as the silcrete clasts were transported via alluvial and colluvial processes. These lags are tentatively dated between 2–4 Ma (Fujioka *et al.*, 2005) (Figure 7.1). The southern alluvial fans became degraded, and eroded the carbonate-cemented palaeochannel (Figures 7.39, 7.40 & 7.41), distributing large rounded cobbles throughout the region. As the climate changed to more arid conditions and the alluvial systems incised, they formed new alluvial terraces in broad, box-shaped valleys. These streams then incised to approach an equilibrium state as shown by the approximately graded longitudinal stream profiles (Figure 5.8, 5.9, 5.10).

Colluvial sheetwash became a very active process, developing the gibber plains and redistributing sediment (Chapter 8). Exposed Jurassic sediments became reworked and distributed across the landscape as white, rounded, quartz pebble lags and sand sheets (Figures 7.6 & 7.7). Increasing aridity caused the development of longitudinal dunes on gibber plains as a result of deflation of sand from underlying sediments. Along Douglas Creek, a phase of uplift occurred, possibly associated with either buried Adelaidean sediments or a granitoid body. This caused Douglas Creek to incise, while stripping the sand dunes from the surface of the rising dome (Figure 7.42). Alluvial systems developed their current expression as tri-modal streams incising the terraces formed on the alluvial fans.

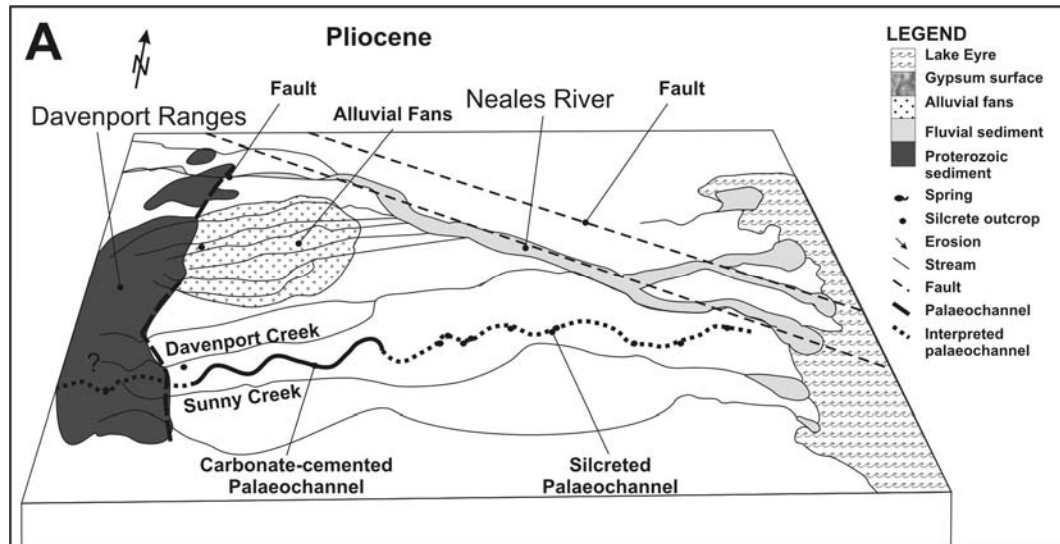


Figure 9.1: Diagram of the development of the Umbum Creek Catchment with an oblique view to the north, showing the formation of alluvial fans along the rangefront following the uplift of the Davenport Ranges along the Mt. Margaret and Levi faults. The Neales River flows along the Lake Eyre Fault and diverges across the Neales Fan. A possible palaeochannel is present along the southern section of the study area.

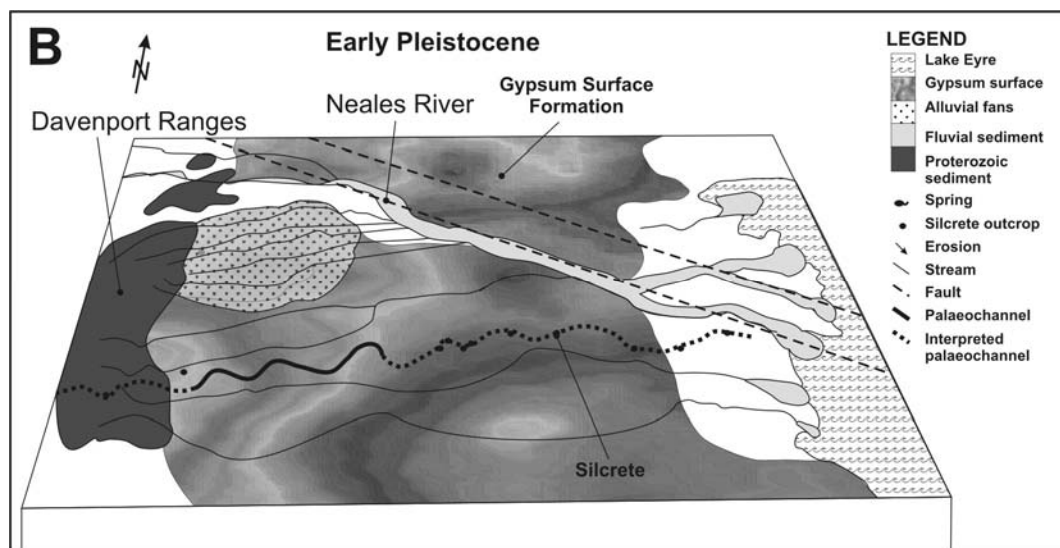


Figure 9.2: Diagram of the development of the Umbum Creek Catchment with an oblique view to the north, showing the development of a gypsiferous horizon related to the topography.

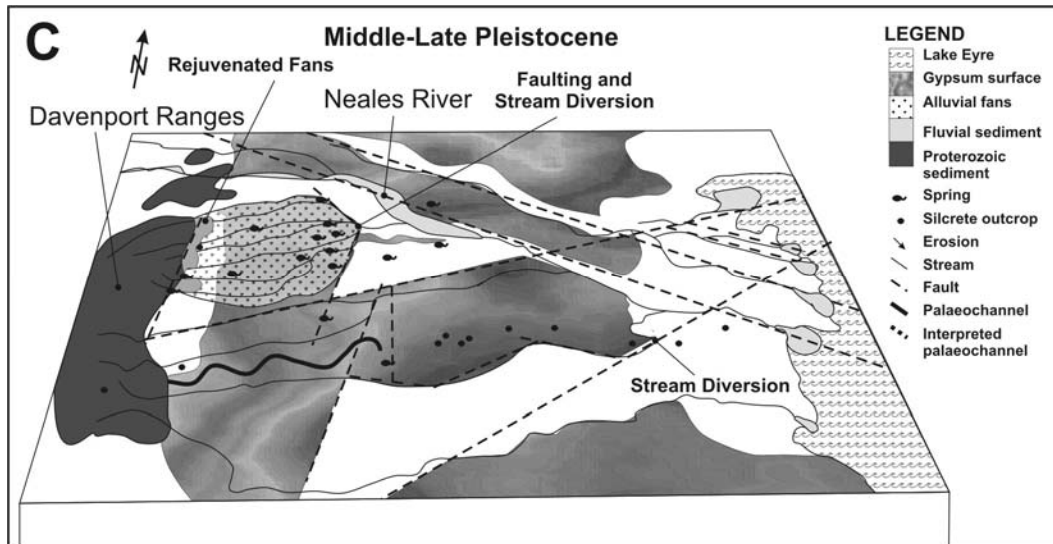


Figure 9.3: Diagram of the development of the Umbum Creek Catchment with an oblique view to the north, showing renewed tectonism causing reactivation of the rangefront faults and alluvial fans, disruption of the land surface, stream diversions and mound spring development along faults and basement highs.

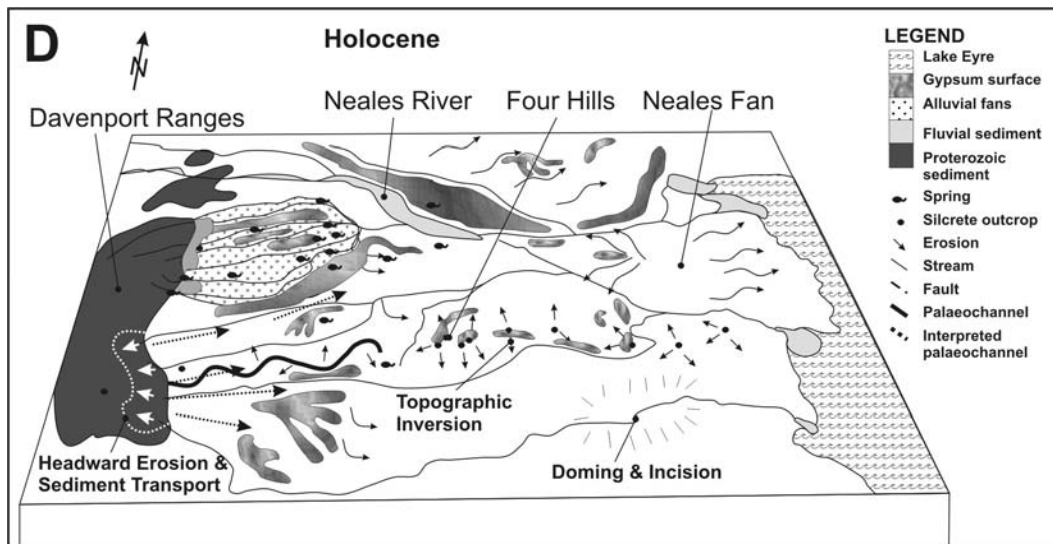


Figure 9.4: Diagram of the development of the Umbum Creek Catchment with an oblique view to the north, showing widespread erosion and dissection of the landscape. Silcrete outcrops become topographically inverted and colluvial processes become very active, creating gibber plains and reworked Jurassic surface lags and stream inputs. Uplift along Douglas Creek causes doming of the land surface and concurrent incision of Douglas Creek.

9.1.4 Landscape Evolution of the Neales Fan

The Pliocene tectonic event resulted in the constraint of the Neales River along the trend of the Lake Eyre Fault (Figure 9.5). This tectonic movement reorganised the topography of the Neales Fan so that it formed a network of intersecting fault planes that defined a series of tilted blocks trending northeast, tilting northwest and trending northwest, tilting northeast (Figures 5.29 & 5.30). The Neales Fan has been relatively downthrown when compared to the western side of the Lake Eyre Fault. The arrangement of the landscape controlled subsequent fluvial deposition. The ancestral Neales River did not take its current course but passed some ten kilometres further southeast and flowed out across the fan (Figure 9.5), as demonstrated on the ASTER thermal image for this area (Chapter 7.2.9 & Figure 7.19). Identified palaeochannel remnants are bounded and controlled by the faults (Chapter 7.2.15 & Figure 7.36). Browns Creek at this time may have been redirected along the current Neales River valley on the northern edge of the Neales Fan.

The development of a small zone of gypsum-cemented surface at the apex of the fan over the Oodnadatta Formation is evidence of a Pleistocene landsurface. The surficial lag surrounding this area is also dominated by silcrete and suggests a connection with the northern side of the river. A large section of the fan apex is dominated by Cretaceous substrate and has a thin veneer (less than one metre) of colluvial sediment deposited on its surface (Figures 5.29 & 5.30). This implies that the Neales Fan has not formed as a fan-delta but as a series of structurally controlled rearrangements of the main channel.

The palaeochannel across the Neales Fan is truncated at the apex (Figures 7.19 & 7.20). This Palaeochannel has been uplifted in its headwaters. The truncation of the palaeochannel on the Neales Fan is evidence of tectonic uplift near the fan apex, because if it was just climatic impact, increasing discharge for example, then the palaeochannel would have incised rather than being truncated. The uplift resulted in the upper reaches of the Neales River readjusting to flow down the Umbum Overflow, forming the larger currently inactive part of the Umbum Delta (Figure 9.6). Remaining sedimentation on the fan continued via this new channel. Thus, the oldest sediments are preserved on the middle third of the fan, with the youngest sediments preserved on the northern third associated with the Neales River.

Measurements of slope gradient indicate that the area where the Neales River crosses the Lake Eyre Fault is the area of the greatest slope along the channel (Figure 5.21), indicating probable fault movement and headward erosion. This change in slope is interpreted as a nick-point caused by a tributary gully to Browns Creek having eroded back and captured the main Neales River channel (Figure 9.7)

These events were then followed by the deposition of the Neales Formation (Croke *et al.*, 1998) (including the Warmakidyaboo beds, Ghost Yard Beds and Piarooka Beds). The lake highstand event associated with the Ghost Yard Beds appears to have been roughly coincident with the modern day outcrop limit of the Etadunna Formation. Modelled +10 m shorelines do not coincide with this outcrop and similarly for the +5 m AHD shoreline (Figure 5.23). A topographic bench is preserved on the Neales Fan at 0 m AHD and may represent the actual +5 m AHD shoreline, although this would require the Neales Fan to be downthrown some 5 m (Figure 6.15). The plain below the break in slope is associated with a mixed-lithology surficial lag that is interpreted as the effect of lacustrine erosion exhuming fluvial sediments (Figure 7.1).

Following a change to an arid environment, the Neales and Umbum drainage became incised due to a climatically induced fall in base level and scouring of the channel during high discharge events. Aridity caused the deflation of the palaeochannel on the Neales Fan, Umbum Delta and Douglas Delta forming large sand dunes along the coast, whilst forming sand dunes, claypans and sand plains inland (Figure 9.8). Inactive dunefields downwind of deltas indicate that deflation is a powerful landscape process in the region. Similar dunefields are at the ends of the palaeochannel where probable palaeo-deltas form a scalloped shoreline on the modern lake shore (Figure 7.36). Structurally controlled dunes and associated claypans may represent deflated palaeochannels formed as avulsion channels by overbank floods prior to the incision of the Neales River. The coastal dunes have subsequently been inundated by a palaeo-lake-level rise as evidenced by the -3.5 m palaeo-shore preserved and the supersurface that permeates the dunes.

Increasing aridity and monsoonal activity led to greater river runoff during flood events. Alluvial erosion began to take place in earnest and resulted in the development of erosional depressions and topographically inverted palaeochannel remnants (Figure 7.37). As erosion took hold, the influence of the underlying Etadunna Formation became apparent as it caused erosion to form preferentially along its outcrop extent, resulting in the Neales Overflow (Figures 6.11 & 6.15), and by acting as a drainage divide caused drainage to flow westwards back towards Umbum Creek (Figure 7.35). Fluvial sediments were deflated to form dunes and surficial lags formed and were transported laterally. Sand dunes began to erode and deposit granular lags on the edges of interdunal pans (Figure 7.31). The topography of the Neales Fan became more uneven as erosion accentuated the asymmetry across the surface of the fan, forming an elevated northern edge and a degraded southern edge (Figure 5.30).

The Neales River and Umbum Creek developed their trends by structural control, but their planform from underlying substrate lithology (Figure 6.15). They now operate as a tri-modal river system depositing sediments into Lake Eyre as the Neales and Umbum deltas/terminal splay complexes.

The preceding landscape evolution model is summarised in Tables 9.1 & 9.2. Evidence supporting the neotectonic interpretations included in this model are outlined in Table 9.3 along with the origin of the data. Further evidence supporting other factors included in the landscape evolution model are outlined in Table 9.4, with the origin of the data also indicated.

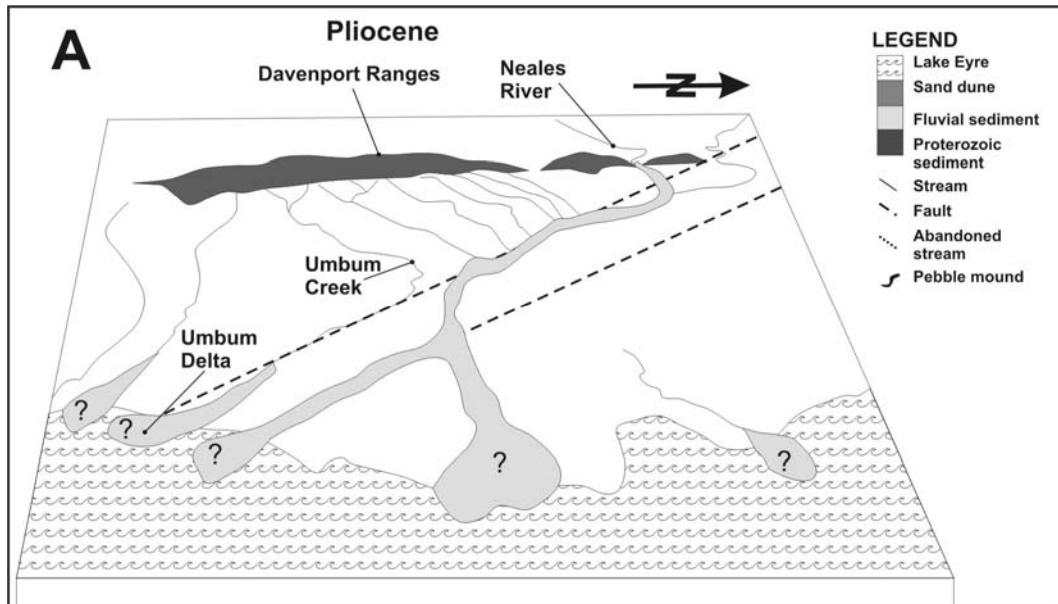


Figure 9.5: Diagram showing the development of the Neales Fan in the Pliocene with an oblique view to the west, showing the trend of the Neales River structurally controlled by the Lake Eyre Fault and Browns Creek Fault.

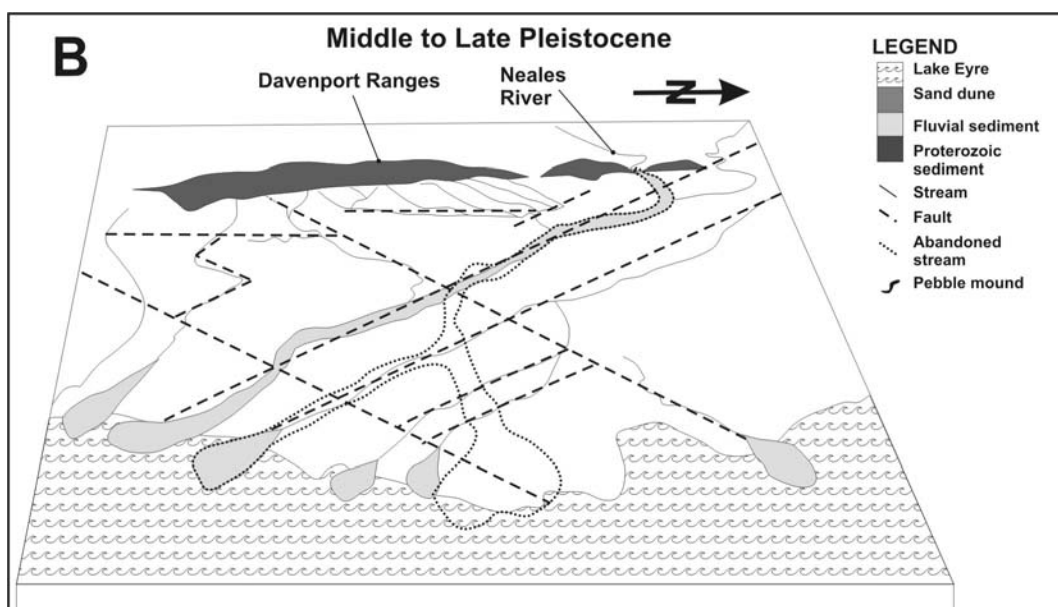


Figure 9.6: Diagram showing the development of the Neales Fan in the Middle to Late Pleistocene with an oblique view to the west, showing renewed tectonism causing rearrangement of the landscape topography and tectonic cut-off of the Neales River, redirecting flow down the Umbum Overflow. Small-scale streams develop along faults.

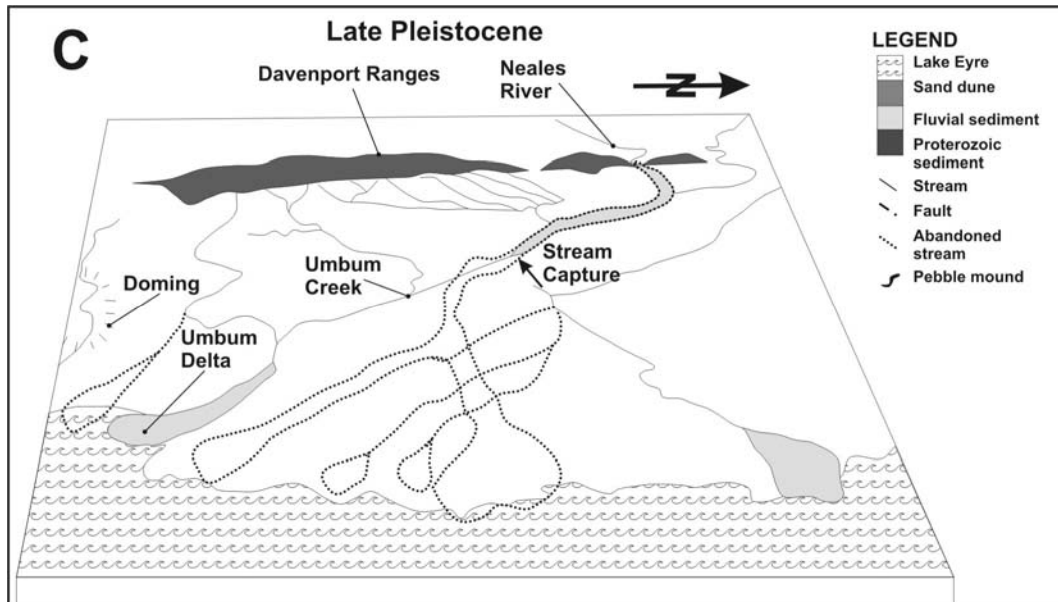


Figure 9.7: Diagram showing the development of the Neales Fan in the Late Pleistocene with an oblique view to the west showing abandoned channels forming the Neales Fan following stream capture of the Neales River via headward erosion from a smaller northern stream.

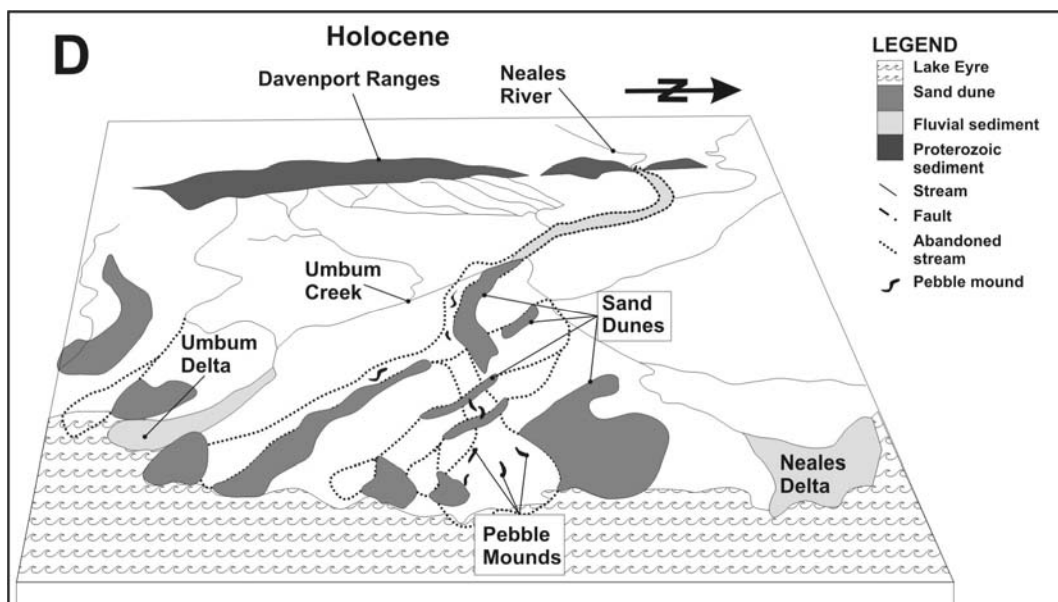


Figure 9.8: Diagram showing the development of the Neales Fan in the Holocene with an oblique view to the west showing the growth of arid landforms under the influence of deflation. Sand is blown out of the palaeochannel leaving arcuate cobble-covered mounds and forming sand dunes and sand sheets.

Landscape Evolution of the Umbum Creek Catchment
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Table 9.1: Landscape evolution summary chart for the Plio-Pleistocene. Times in bold represent dated sediments, see text for details.

Time	Age	Tectonic Activity	Landscape Processes	Sedimentation & Stratigraphy
Present	Holocene		Continued landscape incision. Deflation, dissolution and re-precipitation of gypsum mantles. Development of gilgai and banded vegetation on colluvial surfaces.	Arid zone sedimentation including deposition in streams, terminal splay complexes, aeolian deposits, playas, colluvial sediments and erosion cell mosaics.
2-4 ka	Holocene		Erosion and topographic inversion of silcrete outcrops forming gibber plains	Gibber plains
20 ka	Late Pleistocene		Arid dune formation, high-angle piedmont fans, incision and stream capture of the Neales River	Simpson Sands Alluvial Fans Neales Delta
50-31 ka	Late Pleistocene		Erosion and channel incision	
60-50 ka	Late Pleistocene		Unrestricted ephemeral flow with multiple channels and ponding	Piarooka Beds
70-60 ka	Late Pleistocene		Erosion	
100-96 ka	Late Pleistocene		Low-gradient delta	Packsaddle Beds
130-100 ka	Late Pleistocene		Perennial lake with high watertables and deposition of evaporative gypsum	Ghost Yard Beds
170-130 ka	Late Pleistocene		High-energy meandering perennial river	Warmakidyaboo Beds
>200 ka	Late Pleistocene		Stream Capture	
~0.6 Ma	Middle Pleistocene	Tectonic compression	Uplift of Davenport Ranges forms the Mt. Margaret escarpment. Movement on the Lake Eyre Fault and other faults causes stream diversions	
~1.2 Ma	Early Pleistocene		Deflation, reworking and <i>per descensum</i> accretion form gypsum mantles	Gypsite
			Low-angle piedmont fans	Alluvial Fans
~1.8 Ma	Pliocene	Mild tectonic compression and warping	Folding of Etadunna Formation. Uplift of the Mt. Margaret Plateau and entrenchment of meander valleys in the Davenport Ranges	

Landscape Evolution of the Umbum Creek Catchment
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Table 9.2: Landscape evolution summary chart from the Permian to the Pliocene.

Time	Age	Tectonic Activity	Landscape Processes	Sedimentation & Stratigraphy
5.3	Late Miocene		Silcrete development	
7.1	Miocene		Large, shallow, magnesium-rich lakes. Deposition of evaporative gypsum	Etadunna Formation
23.8	Oligocene	Mild tectonic compression and tilting	High watertables leading to silcrete and ferricrete development	Cordillo Surface
37	Middle Eocene		Low-sinuosity meandering to braided streams and restricted swamp and lagoons. High rainfall temperate rainforest along channels	Eyre Formation Mirackina Conglomerate and equivalents
55	Late Palaeocene	Extension and subsidence creates Lake Eyre depocentre	Weathering, erosion and silcrete development	
83.5	Late Cretaceous		Marginal marine braidplain and lakes	Winton Formation
99	Early Cretaceous		Shallow marine shelf	Oodnadatta Formation
			Regressive beach face	Coorikiana Sandstone
			Shallow marine, euxinic, cold climate Wavecut platform formed on basement highs	Bulldog Shale
			Meandering river to deltaic with a Gawler Craton provenance	Mt. Anna Sandstone
			Marginal marine/coastal	Cadna-Owie Formation
144	Late Jurassic		Terrestrial rivers under oxidising conditions	Algebuckina Sandstone
150	Jurassic			
206	Triassic		Erosion and weathering	Mt. Margaret Surface
248	Late Permian		Erosion and weathering	

Landscape Evolution of the Umbum Creek Catchment
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Table 9.3: Main parameters indicating neotectonic activity.

Variables	Sources			Interpretations Indicators of active tectonics
	Field Obs.	Remote Sensing	DEM	
Seismicity		x		Seismic activity coincides with basement faults
Geology				
Deformed Etadunna Fm.	x			Neotectonic deformation prior 177ka
Tilted fluvial silcretes	x			Tilting
Tilted Eocene-Pliocene sediments flanking Mt. Margaret Fault	x			Pleistocene faulting
Topography				
Mountain front sinuosity		x		Young, active fault scarp
Sharp breaks in slope	x	x	x	Faulting, structural surface
Active scarps (crestal face, free face debris wedge)	x	x	x	Fault scarp, degraded
Geometry of erosional surfaces		x	x	Initiated by faulting
Neales Fan geometry			x	Structural rearrangement of fluvial sediment
Drainage pattern morphometry				
Physiography of the drainage pattern		x		Structural control
Drainage diversions		x	x	Capture
Drainage Basin				
Drainage basin asymmetry		x		Tilting
Stream longitudinal profiles		x	x	Reflect disequilibrium conditions (tectonic disruption, warping, rock type)
Hypsometric curve and integral			x	Highly eroded catchment (uplift?)
Stream Power			x	Faulting, stream capture
Sediment Transport Capacity			x	Faulting, stream capture
Landforms				
Relict surfaces	x	x	x	Topographically truncated surficial lags, faulting
Alluvial fan terraces	x		x	Lateral disruption of terraces/surfaces
Mound springs		x		Structural control, faulting
Overbank deposits	x	x	x	Fault induced floodouts
Neales Fan Palaeochannel	x	x		Degraded 'wind gap'
Stripped sand dunes	x	x	x	Warping

Landscape Evolution of the Umbum Creek Catchment
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Table 9.4: Main factors affecting landscape evolution.

Variables	Sources Field Obs.	Remote Sensing	DEM	Interpretations
Silcrete Development				Palaeo-environmental indicators
Sedimentary pyrite	x			
Oxidation	x			
Rising groundwater	x			
Lateral movement and induration	x			
Gypsum Development				
Lacustrine deposition	x	x		Modern playa, Etadunna Fm.
<i>per descensum</i>	x			Gypsum escarpments and mantles
<i>pre ascensum</i>	x			Fluvial deposits
Lateral input	x	x		Gypsum escarpments and mantles
Gibber Plain Development				
Deflation	x	x		Catchment-wide
Physico-chemical weathering	x	x		Monadnocks/inselbergs
Colluvial wash	x	x		Colluvial plains
Upward migration	x	x		Degraded alluvial fans
Accretionary mantles	x	x		Saprolite pediments
Arid Zone Processes				
Variable rainfall	x			Variable deposition and incision
3 scales of flow events	x	x	x	3 scales of fluvial deposition
Scour-transport-fill	x	x		Heterogeneous landscape
Landforms				
Relict surfaces	x	x	x	Tectonically disrupted and incised
Mound springs	x	x	x	Faulting
Degraded alluvial fans	x	x	x	Deflation since formation
Incised fan heads	x			Change in baselevel, degradation of fans
Overbank deposits	x	x	x	Tectonic uplift
Claypans	x	x	x	Delineate faults and palaeochannels
Longitudinal dunes	x	x		Product of deflation
Neales Fan dunes	x			Deflated and exhumed fluvial sediment
NW trending dunes	x		x	Delineate faults
Coastal dunes	x	x	x	Deflation of deltas
Surficial Lags				
Alluvial fans	x	x		Degraded remnants of low-angle braid plain fans
Colluvial silcrete	x	x		Colluvial breakdown of silcrete outcrops
Alluvial	x	x		Degraded remnants of alluvial plain
Exhumed fluvial	x	x	x	Lake bottom exhumation of fluvial sediment
Palaeochannels				
Colluvial erosional rise	x	x	x	Remnant palaeochannel
Carbonate-cemented conglomerate	x			High-energy alluvial palaeo-environment, source of surficial lag
Silcreted fluvial sands	x			Fluvial palaeo-environment followed by high groundwater levels
Topographic inversion	x			High levels of erosion
Sand dunes, sand sheets and claypans	x	x		Degraded palaeochannel
Truncated palaeochannel	x	x	x	Neotectonic disruption
Cobble armoured mounds	x			Palaeo-channel point bars
Palaeo-deltas and shore	x	x		Palaeo-lake level indicators

Landscape Evolution of the Umbum Creek Catchment
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Table 9.4 continued

Variable	Sources Field Obs	Remote Sensing	DEM	Interpretation
Sediment distribution				
Reworked Jurassic sands	x	x		Changes in fluvial grainsize distribution
Clays	x	x		Erosional depressions and floodouts
Evaporites	x	x		Playas and mound springs
Smectite		x		Alluvial fans have mature sediment
Alunite/Pyrophyllite		x		Longitudinal dunes have immature sediment
Silica		x		Silcrete lags
Calcite		x		Alluvial channels transport calcite

10 DISCUSSION & CONCLUSIONS

A wide variety of new methods have been applied to the study area to determine the impact of neotectonic activity on the landscape. At this time many of these methods are new and in the early stages of development with significant improvements in technology and technique likely in the foreseeable future. In most instances this study represents the first time these methods have been applied within the study area and potentially the first time they have been applied in conjunction to develop a landscape evolution model.

10.1 DISCUSSION

The Lake Eyre region lies at the junction of continental-scale basement geological features that impart their structural fabric to overlying geological units (Figure 1.6). Continental-scale structural trends are visible as the dominant trends of faults within the Umbum Creek Catchment and are reflected in geophysical datasets (Figure 3.4). The structural trends are also reflected in the geomorphology and landforms of the catchment. The expression of this 'master' tectonic fabric in the landscape suggests the presence of neotectonic activity however, structural control may occur without tectonic rearrangement. Evidence of modern seismicity of the region indicates that basement structural features remain active. The basement structural features appear to be activated by changes in hydraulic pressure at depth due to fluctuations in the recharge zone of the Great Artesian Basin, and appear to conform to the principal of hydroseismicity. It has been demonstrated that during the Cainozoic, tectonism was active in the Late Miocene. This period is identified as a period of variation in plate boundary motion as the velocities of the Australian and Pacific plates changed about 6 Ma ago, resulting in the uplift of the Southern Alps of New Zealand (Norris *et al.*, 1990). The change in stress field at the edge of the continental plate influenced tectonism in Central Australia throughout the Pliocene and continues to the present day (Sandiford, 2003). This tectonic model for the greater study area implies that there are intra-continental responses to variations in plate boundary stresses.

Although no direct geological evidence for neotectonic activity has been found, geomorphic evidence for drainage readjustment by neotectonic activity is abundant and geophysical evidence demonstrates faulting in Pleistocene sediments. It is noted that in most circumstances geological evidence of neotectonic activity is usually exposed in road, railway and mine cuttings, that result from human intervention in the landscape. This area has not been subject to such infrastructure projects and it is possible that the geological evidence sought in the form of attributes such as displaced sediments may be buried. The only naturally occurring equivalent are riverbanks where the lateral movement of the river has created stable cliffs and banks such as at the Neales Cliff. At this site, geological evidence of Pleistocene deformation could not be convincingly detected. Both tectonic rearrangement and structural inheritance will cause the river to align *along* a fault due to the fault's inherent weakness. Any evidence of displacement is, therefore, either destroyed via the erosion of the stream or remains buried beneath the base of the channel. Under these circumstances, the topography and geometry of the landscape that is formed by structural readjustment, rather than erosion, is best expressed. A number of landform features exist to support this interpretation. Channel deviations are the most prominent of these, but on their own do not support this hypothesis. However, where coupled with regolith-landform features, such as remnant gravel lags, topographic changes and stream floodouts, the deviation of the channels can only have occurred via neotectonic rearrangement. Similarly, palaeo-landforms preserved on the Neales Fan display structural control via underlying tectonic fabric. Their relationship with neotectonic activity is more difficult to prove because of the effects of erosion that have degraded the

landforms. However, a strong coincidence between the landforms and faults indicates that the topography created by the faults was a controlling factor for the evolution of palaeo-channels across the surface of the Neales Fan. Subsequent neotectonic rearrangement, and not climatically driven avulsion, has led to the redirection of the palaeochannels that formed the Neales Fan into Umbum Creek. Headward erosion due to climate change ultimately led to stream capture of the ancestral Neales River by the northern distributary that presently feeds the Neales Delta.

The expression of faults on satellite imagery that are not observable on the ground would suggest that there has not been neotectonic activity. However, GPR data demonstrates otherwise, and shows that most neotectonic faults do not rupture the surface (see Chapter 6). This would render them difficult to detect in such a low-relief environment, yet demonstrates that they definitively exist and were active at least as late as the Pleistocene.

Other lineaments have been identified that are not associated with faults. In particular the margin of the Etadunna Formation creates a very identifiable north-south trending lineament across the landscape. The margin and lateral extent of Etadunna Formation substrate have been shown to control landscape evolution across the Neales Fan, creating significant meanders in the modern channels of the Neales River and Umbum Creek from a change in gradient, and partially controlling the bifurcation of the main palaeochannel down the centre of the Neales Fan. The Etadunna Formation margin also controls the surface expression and location of the Neales Overflow, which diverts along the edge of the Etadunna Formation outcrop during extreme flood events. This creates a very obvious lineament composed of the Neales Overflow and subcropping exposure of Etadunna Formation linked to changes in stream planform (the meanders) that might erroneously be interpreted as a fault. The identification of this lithological control significantly allows the interpretation of the Neales Fan as a relatively thin succession of degraded fluvial sediments with a highly erosional topography controlled by lithology.

10.2 CONCLUSIONS

The development of the Umbum Creek Catchment has been determined through the use of satellite imagery, DEMs and GPS data coupled with regolith-landform mapping. A landscape evolution model has been established and a regolith-landform map at 1:250 000 scale has been created.

10.2.1 Landscape Evolution

The dominant factor influencing the evolution of the landscape in the Umbum Creek Catchment was the deposition of sedimentary sulphides within the Bulldog Shale. The excess sulphur, which this sediment supplied to the landscape over time, created the necessary conditions for the formation of a range of landscape features to form that would not otherwise exist.

Weathering, oxidation and leaching of the sedimentary sulphides led to the development of silcrete, that in turn developed into gibber plains. The silcrete was originally formed in fluvial sediment and preserved a palaeo-distributary system. Subsequent weathering and tectonic activity led to the breakdown of this system and to the wide distribution of silcrete across the landscape.

Sulphur from the Bulldog Shale continued to contribute to the landscape process by forming intra-formational gypsum and precipitating as gypsum hardpans.

High erosion rates associated with uplift from tectonism and increased run-off from the onset of aridity in the Pleistocene led to topographic inversion of many features. Palaeo-Proterozoic inliers formed inselbergs, silcrete outcrops formed capstones, gypsum hardpans protected underlying sediment from erosion, creating plateaux of gypsum-patterned ground, and palaeo-channels on the Neales Fan were eroded to make heavily armoured mounds and associated sand dunes and sand sheets.

The modern environment displays a landscape rich in smectite clays with gibber plains rich in both iron oxide and silica. The gibber plains have multiple mechanisms of formation. These mechanisms are related to their position within the catchment but are also capable of overprinting each other.

The Davenport Ranges represents the major provenance for sediment within the streams of the catchment apart from the Neales River that sources sediment from further afield. Streams display a response to the underlying lithology by altering their planform.

Climate change has contributed to the landscape evolution as landforms developed under wet conditions during the Palaeogene and Neogene and were preserved by the development of aridity in the Pleistocene.

10.2.2 Neotectonic Activity

The underlying structural fabric of the basement has played a guiding role in the development of the surface morphology of the Umbum Creek Catchment. Neogene tectonic activity occurred at the end of the Miocene and has probably continued into the present at more subdued rates. The terminal Miocene phase is identified by significant deformation of the Etadunna and Eyre formations. It is expressed as warping, tilting and thrusting of these sediments and was probably related to movement in the Lake Eyre Fault Zone.

Pleistocene faulting has been identified from GPR data and is expressed as minor 'blind' faulting associated with pre-existing basement faults. These faults remain active and current seismic activity is driven by changes in hydrostatic pressure (hydroseismicity). The scale of Pleistocene faulting and modern seismic activity demonstrates that since the Pliocene tectonic activity has been subdued.

The arrangement of basement faults is reflected in the distribution of surface landforms, and in the topography of the land surface. Movement associated with these basement structures is indicated by tilting of Eocene to Pleistocene sediments, surface landforms that conform to basement faults and structurally controlled streams where diversions are associated with a change in topography, remnant fluvial lags and stream floodouts.

10.2.3 Recommendations

This study has concentrated on the neotectonic expression of landforms which is only one of the many possible aspects of landscape evolution that could have been examined. There remain many facets of this area yet to be examined in detail. During the course of this study reference has been made to landscape-forming processes. These were reported in a qualitative manner rather than quantitatively. In particular, the role of gypsum in the landscape warrants further examination. At several locations varve style gypsum outcrops along creeks. It should be possible to sample these gypsum 'varves' for sulphur and oxygen isotopes, and

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perhaps match these curves with other isotope climate curves to gain a better understanding of climate change during the Pleistocene.

Gibber plain formation remains enigmatic and, while the general principles are understood, this study suggests that they may form far more rapidly than expected and, as a consequence, may be potentially much younger than previously thought. Further trench sampling, profiling and isotopic dating would begin to answer this question.

The point at which the Neales River diverges from Umbum Overflow has been interpreted in this study as evidence of river piracy, the result of tectonic rearrangement of the landscape. Sampling these two streams for Optically Stimulated Luminescence dating of quartz grains may provide dates for this major movement along the Lake Eyre Fault.

This study has examined the Umbum Creek Catchment and the Neales Fan at a broad scale and has attempted to answer questions regarding the evolution of the Neales Fan. However, a more indepth study that focuses on the Neales Fan would answer questions raised by landforms observed on the Neales Fan, such as the arcuate cobble-armoured palaeochannel mounds, the direction of modern drainage, the unusual sand dune formations and the possible locations of palaeo-shorelines. This could be examined in far more detail than investigated here. Coupled with a drilling program this could produce an indepth model of the Neales Fan in three dimensions over time.

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