MORPHOTECTONIC EVOLUTION OF THE MUNDI MUNDI RANGE FRONT, BROKEN HILL REGION, WESTERN NSW

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ABSTRACT

Geomorphology, regolith geology and apatite fission track thermochronology (AFTT) have been used to constrain the later tectonic history of the Mundi Mundi range front in western NSW The Mundi Mundi range front approximates the trend of the Mundi Mundi Fault and divides the Mundi Mundi Plains to the west, from the Barrier Ranges to the east To the north the range front is crossed by the Kantappa Fault, which appears to have accommodated most of the more recent tectonic activity The Mundi Mundi Fault is an ancient structural feature originating in the Proterozoic, and has continued to be active up to recent times A pilot AFTT study clearly shows very different temperature-time paths for rocks on either side of the range front Samples from the west record initial cooling from palaeotemperatures >~100-110°C during the Early Palaeozoic (Cambrian-Ordovician, suggesting an association with the Delamarian Orogeny), whereas samples from within the Barrier Ranges immediately to the east show sigificant Mid-Late Palaeozoic cooling, suggesting an association with tectonism at this time (e g Alice Springs Orogeny or Lachlan Orogeny) Further cooling is also recorded during the Tertiary but the timing is less well constrained because it occurred from relatively shallow crustal levels Continued, younger tectonism is suggested by displacement of pediments and associated alluvial fan cover, deep stream incision, controls on the Cretaceous and Tertiary sedimentation and a series of strath terraces and related stream knickpoints in stream channels crossing the Mundi Mundi and Kantappa Faults These results are consistent with interpretations of greater denudation east of the range front, and its long term tectonic activity throughout the region's history of landscape evolution

Key words: Morphotectonics, Neotectonics, Apatite Fission Track Thermochronology, Regolith, Mundi Mundi Fault, Broken Hill, Mundi Mundi Plains, Faulting, Mineral Exploration

INTRODUCTION

The Mundi Mundi range front is one of the most prominent landscape features in the Broken Hill region This feature has been recognised by both geologists and geomorphologists, however its significance to the regional long-term landscape evolution and younger tectonic history is poorly constrained As morphotectonic evolution is a major control on regolith and landscape evolution its uderstanding allows physical and chemical dispersion patterns over time to be better constrained and applied to regional mineral exploration models This study provides an integrated approach to the study of long-term morphotectonic evolution, combining approaches such as apatite fission track thermochronology (AFTT), geomorphology and regolith studies for the area in the vicinity of the Mundi Mundi range front The AFTT approach is particularly powerful for reconstructing the thermotectonic history of the upper ~2-5 km of the continental crust, especially in crystalline terrains, where traditional stratigraphic and structural parameters are not available for palaeolandscape reconstructions

SETTING

The area considered here is located west of the city of Broken Hill, where the Mundi Mundi range front divides the Mundi Mundi Plains to the west, from the Barrier Ranges to the east (Figure 1)

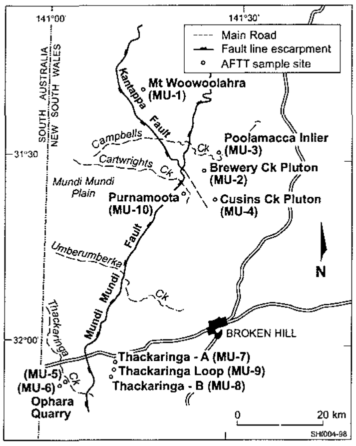

Figure 1: *Location map of the Mundi Mundi range front area*

The range front mostly approximates the trend of the Mundi Mundi Fault, however to the north it is split along both the Kantappa Fault and the continuation of the Mundi Mundi Fault The close association between the range front and these faults suggest a strong tectonic influence on its evolution Bedrock in most of the area contains a series of early Palaeoproterozoic metasedimentary and metaigneous rocks of the Willyama Supergroup (Stevens, 1980; Stevens *et al*, 1983; Stevens & Corbett, 1993), although to the north Neoproterozoic (Adelaidean) rocks occur across the range front area The area also includes granitic rocks (Mundi Mundi type intrusives) emplaced during the Mesoproterozoic Stevens (1986) and Gibson *et al* (1997) suggested that the origins of the Mundi Mundi Fault extend into the Proterozoic and it was active during Neoproterozoic continental extension associated with the break-up of Rodinia (Gibson *et al*, 1997) Interpretations from the recent Australian Geological Survey Organisation (AGSO) seismic line show that the Mundi Mundi Fault is a reverse fault dipping about 30 degrees to the east and southeast (Gibson, 1997; Gibson *et al*, 1998) Less is known about the Kantappa Fault Its southeastern section corresponds to the Kantappa Schist Zone, while further to the northwest Estill & Burns (1978) suggested that it has displaced Mesozoic and Cainozoic sedimentary units Hill *et al* (1994; 1997) and Gibson (1997) show that it is a significant morphotectonic structure

PREVIOUS MORPHOTECTONIC ACCOUNTS

Although tectonism is well established as a major control on both regolith and landscape evolution, the recognition of its significance in Australia has featured major conflicts and changes of opinion Initially there was a strong consensus amongst landscape researchers that large parts of Australia experienced a major episode of tectonism and landscape rejuvenation during the Plio-Pleistocene, known as the "Kosciusko Uplift" (e g Andrews, 1911; Browne, 1969) With the development of better chronological controls an alternative paradigm of long-term tectonic and landscape stability achieved widespread support (e g Young, 1970; Ollier, 1978; Bishop, 1985; Gale, 1992) This paradigm largely found support in: (i) Australia's intra-plate setting; (ii) the established antiquity of many landscape facets and materials; (iii) the relatively low relief of much of the continent, paticularly relative to well known active orogenic zones, such as the Himalayas; and, (iv) its appeal as a response to the failings of the earlier paradigm of young tectonism Despite continued reports of neotectonism, the model of long-term tectonic stability dominates recent studies of Australian regolith and long term landscape evolution It is now appropriate to begin to re-evaluate this paradigm, incorporating observations of recent tectonic activity within models for the long term evolution of Australia's regolith and landscapes This study attempts to integrate and constrain tectonic activity throughout the history of landscape development along the Mundi Mundi range front

The Mundi Mundi range front is a prominent landscape feature recognised in many of the previous geological studies in the Broken Hill region Landscape features along the range front were originally interpreted in the context of recent tectonic activity along the Mundi Mundi Fault The prominent range front is widely recognised as a fault-line escarpment, which has eroded back to its present location slightly east of the Mundi Mundi Fault (Mawson, 1912, Andrews, 1922; Stevens, 1986; Hill *et al*, 1994; 1997) "Valley in valley" features, or strath terraces, have been recognised along streams crossing the range front, particularly in the Campbells Creek area to the north, and are thought to represent recent episodes of tectonically driven incision (Mawson, 1912; Andrews, 1922) Mawson (1912) and Stevens (1986) also suggested that concordant summits in the uplands of the Barrier Ranges represent remnants of an ancient palaeosurface that has been disrupted and incised due to recent tectonic activity along the Mundi Mundi Fault

Geomorphological studies of alluvial fans along the Mundi Mundi range front by Wasson (1978), suggested that other than an ancient contribution to range front development, there was no evidence of tectonic controls and modifications to the youngest units of these fans

The main escarpment accounts for most of the topographic relief of the range front (up to 120 m near Mt Ellie) and is located up to 250 m east of the Mundi Mundi faultline in places like major range front embayments near Rathole and Cartwrights Creeks. It is mostly composed of fresh to slightly weathered bedrock lithologies, with a thin colluvial and aeolian cover. The escarpment is of low sinuosity (S_{MF}=1.069) between Umberumberka and Cartwrights Creeks, although sinuosity is slightly higher to the north between Cartwrights and Morphetts Creeks (S_{MF}=1.249) and to the south between Umberumberka and Thackaringa Creeks (S_{MF}=1.135). Escarpment slope angles range from approximately 60° in the steeper sections between Umberumberka and Cartwrights Creeks, and <30° in some sections south of Umberumberka Creek where it forms a gently sloping front along a range of hills (Figure 4).

Figure 4: *Photograph of the main Mundi Mundi escarpment looking south from near Umberumberka Creek.*

Gibson (1997) reports over 200 m of low seismic velocity material interpreted as sedimentary cover under the Mundi Mundi Plains, thickening towards the foot of the escarpment. Of the 200 m of sedimentary cover over 40 m and up to 100 m consists of red-brown coloured material lithologically similar to material in surficial alluvial fan exposures (Gibson, 1997). Gibson (1997) suggests these red-brown sediments are post-Miocene, consistent with the age of similar lithologies in the Lake Eyre Basin (Callen, 1977). The accomodation of this extensive thickness of young alluvial fan sediments close to the faultline suggests that this fault has had a significant component of activity in its later geological history (possibly post Miocene, assuming the red-brown sediments to be post-Miocene). Drilling by Teton in the 1970's (Estill & Burns, 1978) found similar sedimentary thicknesses and stratigraphy west of the Mundi Mundi Fault along much of the range front. Alluvial fans and the thickness of red-brown sediments are most extensive and best developed along the low sinuosity section of the range front between Umberumberka and Cartwrights Creeks, possibly representing a greater amount of more recent tectonism along this section of the fault.

The minor escarpment is less continuous than the main escarpment. It is less than 5 m high and situated closer to the Mundi Mundi faultline (Figure 5). Deep incision into the escarpment step and associated tread reveals that bedrock structure is continuous between the main and minor escarpments, suggesting that the step and tread are erosional pediment features. The pediment represents a period of local tectonic quiesence and erosional grading to a relatively stable baselevel during escarpment retreat. The pediment is now graded to a level up to 5 m (although mostly about 2.5 m) above the adjacent surface of the Mundi Mundi Plain. This pediment is widest where the main escarpment features broad embayments, such as north of Eldee Station where it is approximately 250 m wide, and near Umberumberka Creek where it is approximately 100 m wide. To the west the pediment terminates towards where the line of the Mundi Mundi Fault is extrapolated beneath sedimentary cover. The pediment is mantled by coarse proximal alluvial fan facies, lithologically equivalent to fan units now exposed in deeply incised gullies into the fans of the Mundi Mundi Plain and could either represent tectonic displacement of these fan facies or earlier fan units that have been uplifted and incised. The recognition of this raised pediment and associated sediment mantle along the foot of the main Mundi Mundi Escarpment are important indicators of relatively recent tectonic activity along the Mundi Mundi Fault.

Figure 5: *Photograph of minor escarpment and sedimentary cover 100m north of Umberumberka Creek.*

Features Along the Kantappa Fault Trend

The Kantappa Fault intersects the Mundi Mundi Fault near where Cartwrights Creek emerges from the Barrier Ranges onto the Mundi Mundi Plains. To the east of this point the Kantappa Schist Zone extends along the same trend as the Kantappa Fault, (Figure 1). To the west it follows a NW-SE trend before changing to more of a N-S orientation near Gum Park homestead, and extends towards Lynray Station to the north. The length of this structure is over 60 km. The Kantappa Fault defines the western margin of a faulted block, bordered to the east by the Mundi Mundi Fault, here referred to as the Kantappa Fault block. To the west of the escarpment is the low-lying Mundi Mundi Plains featuring a cover of alluvial and aeolian sediments.

The fault is associated with a prominent linear escarpment (S_{MF}=1.10) up to 30 m high between Willangee and Gum Park homesteads. As this escarpment changes to a N-S orientation north of Gum Park it becomes more irregular and embayed and therefore has a much higher S_{MF} value (1.68), although in places it is up to 40 m high. The escarpment is composed of highly weathered materials, usually mantled with a gravel lag composed of rounded detritus mostly composed of quartz, quartzite and silcrete.

The exact nature of the weathered material along most of this escarpment is uncertain. Estill & Burns (1978) interpret the weathered material on the northeastern side of the Kantappa faultline escarpment as comprising a sequence of weathered Mesozoic and Cainozoic sedimentary units. Most importantly they suggest major displacement of weathered Precambrian basement and progressively less displacement of the overlying Mesozoic and Tertiary units and the uppermost Quaternary sediments, indicating a long history of ongoing tectonism. This however, is based on stratigraphic interpretations and extrapolations from two drill holes either side of the Kantappa Fault, without direct observations across the structure. Gibson (1997) interprets the material exposed along the escarpment and within many parts of this faulted block as being weathered Precambrian bedrock and Cretaceous sediments. The gypsiferous, shaley mudstones are dark blue-grey when fresh and similar to lithologies from the Albian-Aptian Marree Subgroup. Some of these grey silty and clayey lithologies may also be taken to resemble Tertiary Namba Formation, or fine overbank deposits of the Eyre Formation, or even shalely parts of the Adelaidean sequence. Although many of these stratigraphic interpretations may be valid for parts of this area, the lack of firm chronological constraints at this stage makes them rather bold. Samples collected for palynology by David Gibson (AGSO, pers. comm., 1997) have so far failed to yield any microfossils, even though they are dark grey, organic-rich, shaley lithologies similar to those that have yielded microfossils near Fowlers Gap (Gibson, 1997). Earlier publications from this study have been less commital as to the stratigraphy of parent materials in this area (Hill *et al.*, 1994; 1997). Adelaidean and Willyama Supergroup lithologies and Mundi Mundi intrusives also occur immediately east of the Kantappa Fault, and some of this weathered material may be derived from these units. Distinguishing some of these units based on lithology alone, particularly when it has been highly weathered and fragmented by percussion drilling, is extremely difficult. Although the Kantappa Fault appears to have offset the Precambrian and overlying Cretaceous and Cainozoic units, the exact nature of tectonic activity throughout the Cainozoic is therefore somewhat speculative due to problems with determining the stratigraphy of tectonically offset units.

Many of the creeks that have incised through the Kantappa Fault Block feature series of paired strath terraces. The best example of this can be seen along Campbells Creek near Willangee homestead, where at least four sets of paired strath terraces have been incised into the highly weathered materials (Figure 6a). Several of these terraces may also be seen to extend upstream along Campbells Creek, across the Mundi Mundi escarpment and into the valleys within the Barrier Ranges. Some terraces appear to be very closely related to stream knickpoints observed along Campbells Creek and its tributaries (Figure 6b). This suggests that recent tectonism has been facilitated along the Kantappa Fault in preference to the northern continuation of the Mundi Mundi Fault in this area. Sedimentary cover is extremely thin along the surfaces of these terraces, restricted mostly to a coarse pebble lag. Although these terraces have been mapped at 1:100,000 scale, further detailed mapping (1:25,000) including surveying levels, and chronological information would contribute greatly to a better understanding to the tectonic and landscape evolution of this area.

Within the Barrier Ranges, east of the Mundi Mundi Fault, the morphotectonic significance of a possible continuation of the Kantappa Fault along the Kantappa Schist Zone is less clear. Strong lithological controls on topography and extensive stream incision are a feature of this area, making the recognition of morphotectonic controls more difficult.

Figure 6(a): *Morphotectonic controlled landforms upstream of the Kantappa Fault. a) Photograph of strath terraces along Campbells Creek near Willangee Station;*

Figure 6(b): *Stream knickpoint along Brewery Creek, 1.5km upstream of its junction with Campbells Creek.*

AFTT Results

The results of the AFTT analysis are shown in Table 1. The nine samples processed all yielded good to excellent apatite grains, and for most >12 grains were counted and at least 30 confined tracks measured. All samples yielded ages significantly younger than the Proterozoic intrusive or metamorphic ages of the host rocks. Furthermore, most of the mean track lengths are relatively long (>13(m) and the standard deviations are typically relatively short (<1.5 (m) suggesting that cooling from palaeotemperatures >~100-110°C occurred rapidly and that samples have remained at cooler temperatures over long periods of time.

Figure 7 shows modelled temperature-time paths for most samples. Samples MU-5 and MU-6 from west of the Mundi Mundi fault show a markedly different cooling history compared to all other samples studied. This difference is principally related to the timing of onset of cooling below palaeotemperatures >~100-110°C. The two samples record initial cooling >~100-110°C during the Early Palaeozoic (Cambrian-Ordovician) whereas the other samples show this cooling to have occurred during the Late Palaeozoic (Carboniferous). In both cases the Palaeozoic cooling was relatively rapid with cooling to temperatures ~70°C followed by a period of relative stability. A further period of accelerated cooling is recorded during the Tertiary but the timing is less well constrained because it occurred from relatively shallow crustal levels where annealing of apatite fission tracks is very slow or insignificant (ie. from temperatures less than those of the partial annealing zone. Assuming a mean annual surface temperature of ~20°C this would indicate ~30-40°C of Tertiary cooling. An AFTT investigation of two boreholes from the Broken Hill North Mine provides a more accurate constraint on the timing and magnitude of this cooling, and for that area indicates ~25-35°C cooling, probably between 60 and 20 Ma, with a palaeogeothermal gradient of ~20°C/km, similar to that of the present day (Kohn *et al.*, 1998).

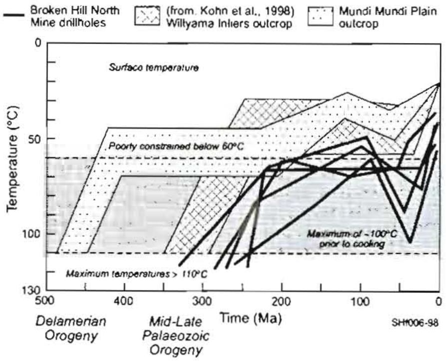

Figure 7: *Modelled temperature - time paths for some AFTT samples.*

The AFTT age for each grain is plotted relative to chlorine composition in Figure 8. Although the data points seem a little "scattered", a more detailed examination indicates that grains from the two samples MU-5 and MU-6, located on the Mundi Mundi Plain west of the Mundi Mundi Fault (on the Mundi Mundi Plain), generally contain the highest chlorine values and oldest AFTT ages. This can be more clearly seen in Figure 8b where the AFTT central age for each sample is plotted against the mean weight% Cl value. The higher chlorine values in the two samples implies that they cooled from higher temperatures than those for the fluorine apatites and have been less sensitive recorders of cooling during most of the Phanerozoic. The initial timing of cooling of these samples shown in Figure 7 would not be affected by the variations in apatite chemistry, rather it is a question of the magnitude.

Table 1: *Apatite fission track data from western Broken Hill region.*

SAMPLE NO.	UNIT/ LITHOLOGY	GRID REFERENCE	ELEVATION (M)	NO. OF GRAINS	STANDARD TRACK DENSITY ($x10^6$ CM-^{2})	FOSSIL TRACK DENSITY ($x10^6$CM-^{2})	INDUCED TRACK DENSITY ($x10^6$CM-^{2})	URANIUM CONTENT (PPM)	CHI SQUARE PROBABILITY %	AGE DISPERSION %	FISSION TRACK AGE (± 1σ) (MA)*	MEAN TRACK LENGTH (μM)	STD. DEV. (μM)
Barrier Ranges, east of Mundi Mundi Fault - north of Kantappa Fault, Broken Hill Inlier													
MU-2	Brewery Ck pluton/granite	538421/6513261	260	13	1.353 (4527)	3.418 (991)	2.873 (833)	27	25.1	7.20	304 ± 16	13.21 ± 0.26 (49)	1.81
MU-3	Poolamacca Inlier/granite	539000/6513000	300	12	1.360 (4527)	4.337 (805)	4.089 (759)	38	74.0	0.18	271 ± 14	13.34 ± 0.22 (20)	1.00
MU-4	Cusins Ck pluton/granite	540898/6516080	300	12	1.367 (4527)	3.032 (844)	2.787 (776)	26	21.6	7.16	279 ± 16	13.01 ± 0.12 (64)	0.96
Barrier Ranges, east of Mundi Mundi Fault - south of Kantappa Fault, Broken Hill Inlier													
MU-7	Thackaringa - A/amphibolite	516400/6451200	300	4	1.388 (4527)	3.606 (300)	3.281 (273)	30	72.5	0.00	286 ± 24	13.62 ± 0.48 (12)	1.67
MU-8	Thackaringa - B/amphibolite	515855/6448490	300	14	1.395 (4527)	4.184 (1154)	3.767 (1039)	34	84.6	0.18	291 ± 13	13.14 ± 0.15 (67)	1.22
MU-10a	Purnamoota Station - A/granite	534702/6501965	320	14	1.409 (4527)	2.236 (591)	2.349 (621)	21	46.8	6.67	253 ± 16	13.39 ± 0.15 (41)	0.96
West of Mundi Mundi Fault in Kantappa Fault Block													
MU-1	Mt. Woowoolahra/granite	521010/6545500	160	17	1.346 (4527)	2.116 (661)	2.040 (637)	19	97.3	0.00	262 ± 15	13.45 ± 0.19 (21)	0.87
West of Mundi Mundi Fault, Mundi Mundi Plain													
MU-5	N. of Ophara Quarry/amphibolite	503410/6449190	220	20	1.374 (4527)	4.321 (1322)	3.079 (942)	28	44.1	4.29	360 ± 17	13.65 ± 0.24 (34)	1.43
MU-6	Ophara Quarry/amphibolite	504700/6447111	220	6	1.381 (4527)	4.273 (309)	2.710 (196)	22	94.4	0.00	405 ± 37	13.55 ± 0.25 (31)	1.41

Brackets show number of tracks or lengths counted. Standard and induced track densities measured on mica external detectors (g= 0.5) and fossil track density on internal surfaces.
Apatite ages calculated using zeta = 383.5 for dosimeter glass Corning-5.
*All ages are central ages.

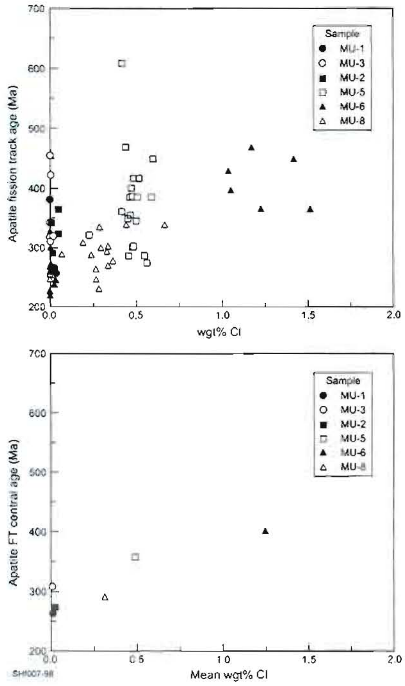

Figure 8: *Plots of apatite fission track age (Ma) versus weight%Cl for individual grains (8a) and central apatite age (Ma) versus mean weight%Cl for each sample (8b). For reference Durango apatite mean chlorine composition is also shown as a vertical dashed line.*

DISCUSSION

SYNTHESIS OF MORPHOTECTONIC EVOLUTION

AFTT Interpretations

Interpretation of the fission track results indicates that the areas sampled experienced cooling episodes during the Palaeozoic and the Tertiary. On the Mundi Mundi Plain onset of a discrete phase of cooling is recorded from the Early Palaeozoic (Cambrian-Ordovician). It is suggested that this cooling was a probable response to kilometre-scale denudation associated with the Delamarian Orogeny. This timing contrasts with that seen in rocks in the Barrier Ranges and west of the Mundi Mundi Fault within the Kantappa Fault block which record a phase of rapid cooling in the Mid-Late Palaeozoic. This cooling episode is possibly related to denudation associated with the tectonism at this time, such as the Alice Springs Orogeny which has also been recognised in central Australia (e.g. Tingate, 1990; Shaw *et al.*, 1991; Dunlap & Teyssier, 1995; Spikings *et al.*, 1997) and areas to the north and west of the study area in South Australia (e.g. Mitchell *et al.*, 1997) or the Lachlan Orogeny recognised in southeastern Australia (e.g. Gray & Foster, 1997).

The disparate temperature-time histories recorded between rocks from the Mundi Mundi Plain and the Barrier Ranges and Kantappa Fault block to the east points to the importance of the Mundi Mundi Fault and western section of the Kantappa Fault as a major geological boundary. To the east a greater amount of denudation has occurred than to the west, such that at the time of onset of Mid-Late Palaeozoic tectonic related cooling, rocks presently exposed to the west were ~40-50°C cooler than those to the east. In terms of the present day geothermal gradient known from the Broken Hill region (~20°C/km) this represents removal of at least 2-2.5 km of section. It is emphasised that because the chlorine content of apatite in samples to the west of the Mundi Mundi Fault is relatively high the samples could have been at an even deeper crustal level at this time, so the calculated amount of denudation should be regarded as a minimum. The present data set does not allow a specific timing to be placed on movement along this fault, however it must have occurred post Late Palaeozoic.

Regolith-Landform Interpretations

The Mundi Mundi range front is located close to the margins of several sedimentary basins that have been evolving throughout the Mesozoic and Cainozoic. The tectonic evolution of these basins has largely been facilitated by reactivation of ancient structures. The tectonic evolution of these basins appear to have had an influence on the morphotectonic evolution of this range front.

Sediments of the Eromanga Basin extend into the Frome Embayment, which underlies much of the Mundi Mundi Plains to the west of the range front. Equivalent sediments extend to the south into the Berri Basin which underlies parts of the Murray Basin (Rogers, 1995), however the extent of these sediments over the Barrier Ranges is not known. The apparent absence of these

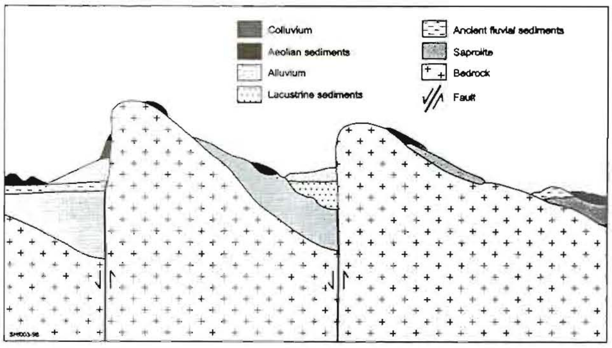

Figure 9: *Cartoon of the morphotectonic setting of regolith types across the Mundi Mundi range front.*

sediments immediately east of the range front suggests that they have either been eroded or else were not extensive in these parts. The expression of the range front at least back into the Palaeozoic, and the contribution of quartzose and high metamorphic grade lithic detritus derived from the Barrier Ranges in the Cretaceous and Tertiary sediments suggests that the sedimentary cover was not extensive to the east of the range front. The situation here appears to be different to that further north in the Fowlers Gap area, where there is some field evidence to suggest that Mesozoic sediments were possibly more extensive across the Barrier Ranges (Gibson, 1997).

The sedimentary record in the adjacent Cainozoic basins may also record features of the regional tectonic history. Sediments of the Lake Eyre Basin extend across much of the area of the Mundi Mundi Plains. Widespread tectonic subsidence began in this basin during the late Palaeocene, continuing throughout the Cainozoic, with a widespread tectonic episode also featuring in the Miocene (Benbow *et al.*, 1995). Structures accomodating Cainozoic tectonism in this basin mostly trend about NW-SE. The similar trend of the Kantappa Fault, which extends across the southeastern margins of this basin, suggests that Cainozoic tectonism along this fault could be related to the evolution of this basin. The Murray Basin extends to the south of the area considered here. Structures accomodating tectonism in this basin mostly trend NE-SW, which is similar to the central section of the Mundi Mundi range front. Tectonic subsidence also began in this basin during the late Palaeocene, and continued throughout the Cainozoic, with a major period of activity in the Miocene (Benbow *et al.*, 1995). Tectonic subsidence in these adjacent basins during the Cainozoic along with inputs of detritus derived from the Broken Hill Block suggest that the Barrier Ranges experienced some of its relative uplift during the Cainozoic. Much of this tectonic movement is most likely to have been accomodated along structures such as the Mundi Mundi and Kantappa faults, corresponding to the continued morphotectonic evolution of the Mundi Mundi range front.

Tectonism appears to have continued up to Recent times along the range front. Thick accumulations of sediments (possibly post-Miocene) against the Mundi Mundi range front may be related to Miocene and younger tectonism. The displacement of pediments and alluvial fan sediments in the piedmont area of the range front, are probably related to young tectonic activity. Wasson (1978) found the youngest, surficial fan units along the Mundi Mundi range front to be less than 16,000 years B.P., however the field setting of the fan units associated with the high level pediments at the foot of the major escarpment appear to be slightly older than these. Strath terraces and knickpoints, particularly along Campbells Creek are also of an uncertain age, however they probably reflect tectonism from the latest Cainozoic. Although historical seismicity is not well recorded in the region, personal accounts of earth tremors from landowners along the range front suggest continued seismicity.

Although the basic structural framework of this region originated at least in the Proterozoic and has been reactivated during the Palaeozoic, any later tectonic activity will most likely reflect driving forces with vector components operating across these structures. Later relative uplift of the range front should therefore reflect a component of compressional forces orientated between E-W and NW-SE along the N-S and NE-SW trending Mundi Mundi Fault and E-W and NE-SW along the N-S and NW-SE trending Kantappa Fault. Stress measurements from within the mines at Broken Hill indicate that the present day axes of maximum compression are orientated close to E-W (Denham *et al.*, 1979; Denham & Windsor, 1991), and are therefore consistent with the orientation of forces required for continued reactivation of this structure. Gibson (1997) however suggests that the later history of movement along structures such as the Mundi Mundi Fault is not related to the present day stress regime, emphasising the very slight ENE trend of some measured stress orientations. It is unlikely however that such a slight northerly vector component to the present stress regime is great enough to dismiss the potential for the present stress regime to contribute to further tectonism along these structures, in particular the Kantappa Fault. Further consideration of the tectonic driving forces throughout the history of morphotectonic evolution is part of an ongoing study in this region.

MINERAL EXPLORATION AND REGOLITH-LANDSCAPE EVOLUTION SIGNIFICANCE

Tectonism along the Mundi Mundi range front has had a major influence on the regional regolith evolution and distribution, and landscape morphology (Figure 9). Tectonism along the range front has controlled the extent of regolith preservation and has been a major driving force behind the production and distribution of transported regolith.

The uplifted western margins of the Barrier Ranges are mostly characterised by exposures of fresh to slightly weathered bedrock with a restricted cover of aeolian, colluvial and minor alluvial valley fill sediments. The lack of regolith material along the Mundi Mundi range front escarpment reflects the low regolith preservation potential for this high relief and steeply sloping landscape setting. Moderately to highly weathered bedrock lithologies are uncommon along the range front, mostly restricted to shear zones, such as along the Umberumberka Shear Zone west of Silverton. To the west of the central section of the range front the Mundi Mundi Plains form a low relief region mostly characterised by a thick sedimentary cover of alluvial fan and aeolian sediments in the upper and surficial parts of the sequence, underlain by fluvial, marine and lacustrine sediments and deep weathering profiles.

These controls on regolith and landscape evolution can be translated into important considerations for models of mineral exploration in the region (Figure 10). Exploration and geochemical sampling strategies will differ depending on morphotectonic setting. For instance along the up-thrusted edge of the range front where exposures of fresh bedrock are dominant, traditional approaches to exploration emphasising bedrock geology are suitable. In the down-tilted areas where regolith profiles are deep and mostly comprise a surficial covering of transported overburden, drilling and regolith sampling techniques would be more important. Most of the Mundi Mundi Plains, and areas to the south and east of Broken Hill are typical of that type of terrain. The morphtectonic evolution has therefore been a fundamental control on the depth to fresh basement across the region, and therefore on the nature of exploration approaches such as the depth of drilling to bedrock.

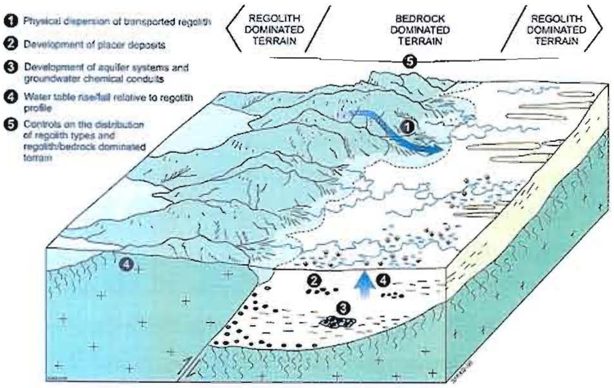

Figure 10: *A summary of morphotectonic controls on mineral exploration.*

Exploration models also require a knowledge of the morphotectonic controls on the composition and style of the transported regolith. For example the morphotectonic evolution of the Broken Hill region has had a control on major changes to the chemical and physical dispersion patterns brought about by changes in the pattern and style of the region's fluvial systems (eg. Hill *et al.*, 1997). The tectonic controls on drainage networks and alluvial fan sedimentation would also need to be considered as part of exploration programs using regolith materials on the Mundi Mundi Plains. Uranium exploration on the Mundi Mundi Plains during the 1970's focussed on the identification and reconstruction of the palaeodrainage networks in this area. This required an understanding of the morphotectonic evolution of the Mundi Mundi range front and its long term controls on the drainage evolution, and sediment supply to the Mundi Mundi Plains area. A continuation of this study will enhance future exploration programs in that area.

Continued tectonism in this region has been important in driving denudation. Stream incision has removed *in situ* regolith materials from much of the catchment areas in the Barrier Ranges and therefore provided a change in sediment composition with time from an initial dominance of resistant and weathered lithologies to the modern dominance of labile and fresh bedrock clasts. The type of materials sampled from these fluvial deposits in different morphotectonic contexts will therefore vary. The onset of tectonism following a tectonic quiesence with extensive preservation of highly weathered materials and resistant lithologies may explain the onset of quartzose and kaolinitic early Tertiary sedimentation in the Murray and Lake Eyre Basins adjacent to this range front. Similar sediments in areas like western Victoria have been very important sources of alluvial gold.

CONCLUSIONS

The morphotectonic evolution of the Mundi Mundi range front has occurred throughout the region's geological and landscape history. Tectonism along the Mundi Mundi and Kantappa Faults have facilitated this long term morphotectonic evolution, suggesting that they are major regional structures. The integration of AFTT with regolith and landscape studies has enabled further constraints to be placed on the long term morphotectonic evolution of this range front.

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Instead, Wasson (1978) preferred to interpret features of the fan morphology and sedimentation within the context of Quaternary climate fluctuations. Radiocarbon dating of fan sequences and palaeosols suggested that fan sedimenation is associated with wetter periods of the Quaternary, and fan incision a feature of drier periods (Wasson, 1978). Tectonic quiesence during the recent evolution of these fans has been recently supported by Hill *et al.* (1994) and Gibson (1997). However, field evidence and interpretations outlined in this study suggest that tectonism continues to contribute some control on the fans and other regolith and landform features in the vicinity of this range front.

METHODS

REGOLITH AND LANDSCAPE STUDIES

In this study a range of regolith and landscape features have been used to account for morphotectonism.

Range Front Morphology

The morphologies of range fronts, in particular the pattern of degradation, have been widely used as an indicator of relative tectonic activity. Mountain or range front sinuosity (Bull & McFadden, 1977) is defined as:

$$S_{MF} = L_{MF}/L_S$$

where S_{MF} is the mountain or range front sinuosity; Lmf is the length of the range front along the foot of the range at the pronounced break in slope; and Ls is the straight-line length of the range front (Figure 2a). This index is used to reflect the balance between erosional forces that tend to cut embayments into a range front and tectonic forces that tend to produce a straight range front more coincident with an active range-bounding fault. The potential value of this index assumes that range fronts associated with active tectonics and uplift are relatively straight, with low values of S_{MF} , whereas if the rate of uplift is reduced then erosional processes will carve a more irregular range front, and S_{MF} will increase. Comparison of range front sinuosity when assessing relative tectonic activity between different range fronts is susceptible to complications due to variations in lithology, structure, drainage-basin spacing and potential changes in climate and uplift with time. The geology of the Mundi Mundi range front has been mapped at a scale of 1:25,000 and therefore reveals lithological variations along it in detail. Also by comparing sections just along the Mundi Mundi range, variations in many of these other variables besides tectonism are reduced. Determination of the sinuosity index is also dependent upon the scale of the image or map from which intial measurements were derived. In this study these calculations were made using RC9 air photographs at a scale of approximately 1:80,000.

Drainage System Modifications

Longitudinal stream profiles have the potential to be powerful tools for detecting subtle perturbations from a graded profile along a river's course. These perturbations may be expressed as "flattening" and "steepening" of stream longitudinal profiles, often caused by changes in stream baselevel or lithological resistance. Perturbations expressed as pronounced channel steepening are referred to as knickpoints (Figure 2b). Knickpoints associated with regional baselevel change due to processes such as tectonic uplift are usually distinguished from lithological controls by anomalous profile steepening for particular lithologies, and also the expression of a particular knickpoint along adjacent stream tributaries with underlying lithologies of different erosive resistance. Stream knickpoints were identified from field study, often after initial discovery from air photo interpretation.

Fluvial Terraces

Stream terraces represent time lines along valleys because they are formed during periods of equilibrium or threshold conditions in the fluvial system. Strath terraces consisting of a thin layer of river sediment overlying a bedrock-cut platform are the terrace type most widely associated with long-term baselevel lowering, such as due to tectonic uplift. In this case stream downcutting may be characterised by brief periods of equilibrium and floodplain construction separated by periods of incision. Four main types of tectonic deformation of fluvial terraces include (Figure 2c):

i. uplift and incision without differential deformation (often described as "valley in valley" incision);
ii. surface faulting;
iii. terrace warping; and,
iv. tilting.

In this study, uplift and incision without differential deformation have been identified from within the range front area.

Alluvial Fans and Pediments

Although influenced by a range of factors such as climate, alluvial fans have been recognised as sensitive indicators of morphotectonic activity (e.g. Bull, 1964; Hooke, 1967). Alluvial fan morphology reflecting a strong tectonic control on sedimentation typically feature extensive fanhead deposition of fan segments indicating high rates of range front uplift relative to both the rate of stream-channel downcutting in the range, and to fan deposition. If the rate of uplift of the range front is less than or equal to the rate of downcutting of the stream in the range, then fanhead trenching may occur and deposition is shifted downfan. The relationship between fan size and catchment area also has the potential to characterise tectonic setting, with a larger fan size to catchment area ratio expected in areas with a major contribution from active tectonism controlling fan development. This may become complicated because other variables besides tectonism may also influence fan size and catchment area relationships, such as differences in bedrock lithology (and hence erodibility) of stream catchments, climate and catchment topography. The highly heterogeneous range of bedrock lithologies across the Broken Hill region limits the ability of alluvial fan size to catchment area ratios to exclusively recognise tectonic controls. Some general observations of apparently anomalous relationships however are made here, usually in association with other indicators of active tectonism.

The relationships between alluvial fans and pediments along range fronts have been considered in many studies (e.g. Bull, 1984; Dohrenwend, 1994; Bourne & Twidale, 1998). Pediment development is often associated with long-term tectonic stability, whereas extensive alluvial fan development is usually a feature of tectonically active range fronts (Figure 2d). A pediment is a gently sloping erosion surface developed across bedrock that may be thinly veneered with regolith. As faultline escarpments retreat with time, a pediment will develop, extending downslope from the base of the range front (Bull, 1984; Dohrenwend, 1994). Although the surface of pediments may include irregularities, their general slope usually decreases away from the range front approaching a concave upward profile decreasing in slope towards the local baselevel (usually within the adjacent sediment covered plains). Tectonic activity along the range front will displace earlier formed pediment slope profiles so that they are no longer in their original landscape setting. Regolith on the pediment (such as alluvial fan units) will be similarly displaced. The identification of such features may give some indication of tectonic activity, particularly where several "stacked" pediment profiles can be identified along a single faultline escarpment profile and sedimentary units may be correlated across tectonic dislocations. These features may then be used in a similar way to strath terraces as indicators of tectonism, however the significance of their genesis and slope morphologies are less well understood.

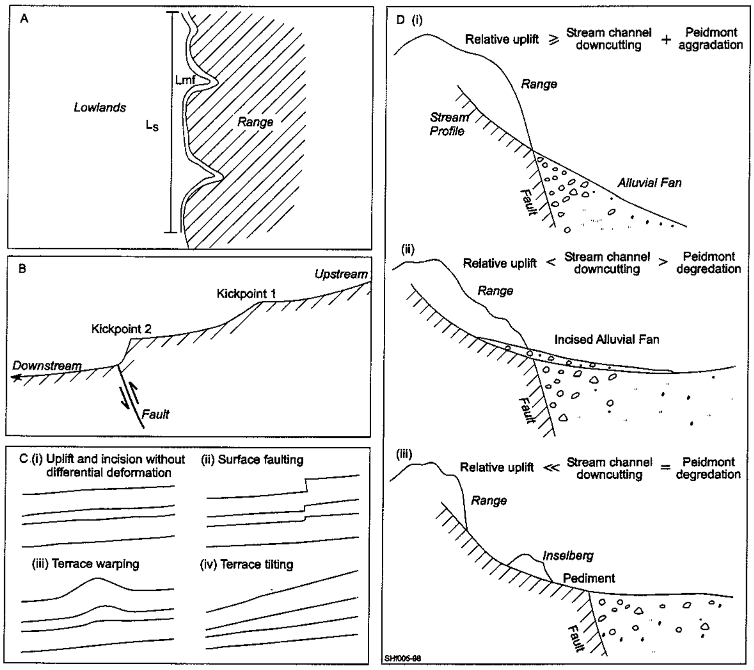

Figure 2: *Regolith-landform evidence for morphotectonic activity used in this study. a) range front sinuosity; b) stream knickpoints; c) tectonic deformation of fluvial terraces (after Keller & Pinter, 1996); d) alluvial fan and pediment development of typical of different uplift rates and rates of local base-level processes for formation of: (i) thick alluvial fans next to the rangefront; (ii) entrenched alluvial fans; and (iii) undissected pediments (after Bull, 1984).*

APATITE FISSION TRACK THERMOCHRONOLOGY (AFTT)

Background

The spontaeous nuclear fission of ^{238}U over geological time in uranium-bearing minerals such as apatite causes the formation of linear zones of radiation damage known as fission tracks When formed in apatite, the tracks have a fairly constant mean length of 16±1 (m (Gleadow *et al.*, 1986). The tracks can be made visible by a chemical etching procedure on a polished surface of the mineral so that they can be observed and measured by optical microscopy The number of tracks that have accumulated in a mineral can be related to the uranium content and time over which they have been quantitatively retained (ie a measure of geological age). Fission tracks possess a fundamental property which forms the basis of their use in thermochronology When exposed to elevated temperatures the radiation damage formed by the tracks is progressively repaired or annealed, over a temperature interval which is characteristic for each particular mineral In the case of apatite, this temperature interval typically occurs above ~100°-120°C for geological heating times of the order of 106 years or more Some annealing in apatite occurs even down to ambient surface temperatures, but below ~60°C this is relatively insignificant Hence, the temperature interval between ~60°C and ~100°-120°C is often referred to as the apatite fission track partial annealing zone In this zone, increasing temperatures cause progressive annealing resulting in track shortening, reduced track density, and a reduction in the fission track age (Gleadow et al , 1986; Green *et al.*, 1989) It follows that at temperatures >~100°-120°C total annealing results in the reduction of the fission track age to zero For apatite, this general picture is complicated by the fact that chemical composition is well known to be an important factor in determining the annealing behaviour of fission tracks in apatite and the temperature at which tracks will be totally annealed In chlorine-rich apatites, fission tracks have been completely annealed at temperatures 30o-40oC higher than in fluorine-rich apatites (eg Green *et al.*, 1986; O'Sullivan & Parrish, 1995; Kohn & Foster, 1996)

New tracks continuously form throughout geologic time, so the apparent fission track age and the distribution of track lengths in an apatite sample reflects the integrated thermal history of the rock (Gleadow *et al*, 1986; Green *et al.*, 1989) In this study, data have been interpreted using the principles of apatite fission track response described by Green et al (1989) These are based on an empirical kinetic description of laboratory annealing data in Durango apatite [~0 43 wt% Cl] (Green *et al*, 1986; Laslett et al., 1987) Thermal-history interpretations are based on a quantitative treatment of annealing achieved by forward computer modelling (Green *et al.*, 1989) of track shortening and age evolution The model by Laslett et al (1987) for annealing of fission tracks in apatite gives predictions that are consistent with geological constraints on annealing behaviour, as explained by Green *et al.* (1989) More recently, Gallagher (1995) has automated this procedure to give a forward modelling approach which combines a Monte-Carlo simulation of numerous possible thermal histories, with statistical testing of the outcome against the observed fission track measurements A genetic algorithm that is "self learning" is also used to provide rapid convergence to an acceptable fit.

Methods

Nine samples from locations shown in Figure 1 from the Mundi Mundi range front area were processed and analysed as a part of a AFTT pilot study for the region. Samples were collected from areas where bedrock crops out along both sides of the Mundi Mundi range front This included samples from the southern end of the range front, and also from the north particularly across the area where the Kantappa Fault crosses the Mundi Mundi Fault to assess differences in tectonic histories across these structures

Samples were crushed and ground, and apatite concentrated by conventional heavy liquid and magnetic techniques Grain mounts were prepared following the procedures outlined in Moore *et al* (1986) and Kohn et al. (1995) Irradiations were carried out in a well thermalised neutron flux in the X-7 position of the HIFAR reactor at Lucas Heights, NSW Fission tracks in each mount were counted under transmitted light using a Zeiss Axiotron microscope with a dry objective at a magnification of 1250x Where possible, 20 grains were counted on each mount For a further description of fission track counting methods see Green (1986)

Fission track ages were calculated using the zeta calibration method and standard fission track age equation (Hurford & Green, 1982) Errors were calculated using the techniques of Green (1981) For all samples the "central age" (Galbraith & Laslett, 1993), which is essentially a weighted-mean age, is reported The observed age spread is determined statistically using the Chi-square test (Galbraith, 1981) which indicates the probability that all grains counted belong to a single population of ages A probability of <5% is evidence of an asymmetric spread of single grain ages. Such a spread in individual grain ages can result either from inheritance of detrital grains from mixed detrital source areas, or from differential annealing in apatite grains of different compositions (Green *et al.*, 1989).

Lengths of confined tracks were measured using the procedure outlined by Green (1986) Only fully-etched and horizontal "confined tracks" were measured (Laslett *et al*, 1982) in grains with polished surfaces parallel to prismatic crystal faces. Measurements were made under similar conditions to those employed for age determinations Suitable track lengths were measured using a projection tube and a digitising tablet calibrated using a stage micrometer As many tracks as possible were measured from each sample

Chlorine values of 92 apatite grains for which fission track ages had been previously determined were determined from seven samples were determined on a JEOL JXA-5A electron microprobe analyser at Geotrack International Pty Ltd The microprobe was run at an accelerating voltage of 15kV, defocussed beam size of 15-20 (m and beam current of 29nA, and samples calibrated using the Durango apatite standard. For values <0 02% Cl errors are about ±100%, for values of ~0.10%Cl errors are about ±25% and for values ~1% Cl errors are about ±15%

RESULTS

Regolith and Landform Features

The regolith and landform features along the Mundi Mundi range front can be sub-divided into two main sections: i) along the Mundi Mundi Fault trend; and, ii) along the Kantappa Fault trend in the north

Features Along the Mundi Mundi Fault Trend

The Mundi Mundi Fault extends for over 150 km, along most of the western edge of the Barrier Ranges, from the Thackaringa Hills in the south and west of Corona homestead in the north (Figure 1) Its orientation varies along its length from approximately N-S south of Umberumberka Creek to approximately NE-SW between Umberumberka Creek and Cartwrights Creek, and north of Cartwrights Creek its trend is approximately N-S

A regional NW-SE topographic profile across the Mundi Mundi range front near Umberumberka Creek reveals a sharp increase in elevation corresponding to the Mundi Mundi fault line escarpment with a gradual decrease in elevation towards the southeast. Elevation of hill crests and ridge tops gradually decreases from over 400m immediately to the east of the range front to less than 200 m in the central Barrier Ranges near the city of Broken Hill. Further to the southeast the topography is complicated by the influence of other structures and lithological controls along the Springs, Mulculca and Redan Faults This topographic profile suggests the existence of a tilted fault block with relative movements of upthrusting along the Mundi Mundi Fault and downtilting towards the southeast. It is not clear whether the upland summit surfaces represent a tilted palaeosurface Mawson (1912) suggested that concordant summits and upland surfaces in the Barrier Ranges may represent remnants of a land surface originating in the Mesozoic The limited sedimentary and regolith preservation across the higher landscape elements of this area however makes regional correlations purely speculative The apparent upland surface represented by concordant summits with limited regolith preservation may have originated in part as an etch-surface exhumed after regolith stripping across the region In areas experiencing less relative uplift, stripping appears to have been less extensive and weathering profiles are preserved beneath an extensive sedimentary cover such as beneath the Mundi Mundi Plains and in the Balaclava region, south of Broken Hill

A detailed section across the Mundi Mundi range front may be subdivided into two separate escarpments: i) the main escarpment; and, ii) a minor escarpment, providing a step in the slope profile of the piedmont zone of the main escarpment (Figure 3)

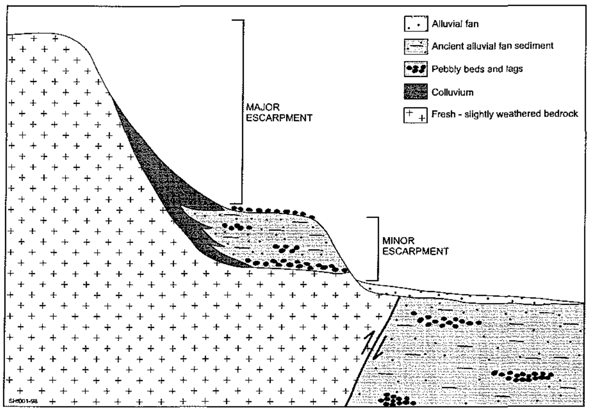

Figure 3: *Section across the Mundi Mundi range front escarpments.*

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