LANDSCAPE EVOLUTION IN THE MOUNT LOFTY RANGES: IMPLICATIONS FOR REGOLITH DEVELOPMENT

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ABSTRACT

The Mount Lofty Ranges form an upland system dominated by active fault scarps that displace earlier formed planation surfaces characterised by deep weathering and associated regolith formation The main watershed transects older lithology and structure; lies to the east of the highest parts of the upland system, and is characterised by low amplitude relief (~100 m) Many of the largest rivers associated with this watershed cut across the main topographic axis and associated bounding fault scarps. These factors suggest that the evolution of the modern Mount Lofty Ranges and its drainage pattern involved, firstly, the development of relatively low amplitude relief in a deeply weathered peneplain, followed by rejuvenation to form the modern fault-bound topography. Sedimentary successions in the flanking basins suggest that the first tectonic phase occurred in the Middle Eocene to Early Miocene (~43 to14 Ma), while the second tectonic phase occurred after ~5 Ma The latter phase is demonstrably associated with reverse faulting and can be related to the broadly E-W oriented compressional stress field now prevailing in this part of the continent The nature of the tectonic movements associated with the earlier stage are less clear However, they probably relate to an extensional stress regime associated with basin formation along the southern Australian margin in early-Tertiary times

Key words: landscape evolution, South Australia, Mount Lofty Ranges, fault scarp, watershed, digital elevation model

INTRODUCTION

In upland areas, identifying the sequence of events leading to denudation of ancient surfaces and their attendant regolith, forms the prime goal of landscape evolution studies Landscape dissection events can provide age bounds on regolith formation both in upland and adjacent lowlands The Mount Lofty Ranges form a prominent upland system in South Australia, and many models for their evolution have been presented (Benson, 1911; Woolnough, 1927; Fenner, 1930, 1931; Sprigg, 1945, 1946; Campana, 1955; Campana & Wilson, 1954; Brock, 1964; Ward, 1966; King, 1976; Alley, 1969, 1973, 1977; Forrest, 1969; Maud, 1972; Twidale, 1968, 1976a, 1976b, 1983; Daily et al., 1974; Twidale & Bourne, 1975; Milnes et al , 1983, 1985; Bourman, 1989). Most authors point out that the preservation of an uplifted peneplain or planation surface is an essential characteristic of this region and that the summit surface of the Mount Lofty Ranges is part of the original weathered surface. The age of this surface is controversial with estimates ranging from ~200 Ma (Twidale, 1976a, 1976b, 1991, 1994) to Pleistocene (Fenner, 1930, 1931) Bourman's multiple and multicyclic models (1969, 1973, 1989, 1993a, 1993b, 1995) of landscape and laterite development suggest coexistence of various age planation surfaces within the Mount Lofty Ranges. Similar uncertainty surrounds the age of the structures associated with uplift and dissection of the planation surface(s)

In this paper we present an analysis of the watershed and drainage patterns of the Mount Lofty Ranges in order to reconstruct the main morphotectonic events that have shaped this region The sedimentary record in the basins flanking the upland system is used to provide broad time constraints on these events Our analysis has been greatly aided by the availability of a high resolution (100 m) digital elevation model (DEM) provided by the South Australian Department of Environment and Natural Resources (DENR), with visualisation and quantitative analysis of this dataset made possible by the software packages RiverTools (Peckham, 1995), ENVI and IDL

We begin with a general description of the main morphological features of the Mount Lofty Ranges and their associated drainage systems This is followed by a brief review of the stratigraphy of the flanking sedimentary basins, and a discussion of the main factors that have shaped landscape evolution in this region.

GENERAL MORPHOLOGY AND DRAINAGE PATTERN OF THE MOUNT LOFTY RANGES

The Mount Lofty Ranges form an arcuate upland system bounded from adjacent lowlands by discrete, curvilinear fault scarps (Figures 1, 2 & 3). The highest parts of the system are found along the western range front, with the axis of maximum topography markedly offset from the main drainage divide separating west-flowing from east-

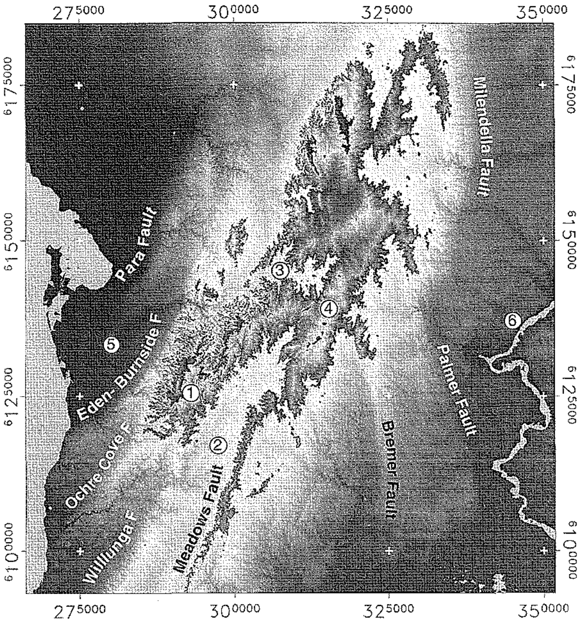

Figure 1: *Density plot of 100 m digital elevation model (DEM) for the Mount Lofty Ranges (original data courtesy of South Australian Department of Environment and Natural Resources) The image has been sliced into three density bands 0-400 m, 400-525 m and > 525 m, with each interval shaded in proportion to elevation Main range defining faults are labelled. Additional reference points are 1 Mount Lofty, 2 Onkaparinga Valley, 3 Torrens Gorge, 4 Mount Torrens, 5 Adelaide, and 6 Mannum. Map units are expressed in Australian Metric Grid (Zone 54) with the image representing an area of 92 x 85 km in size*

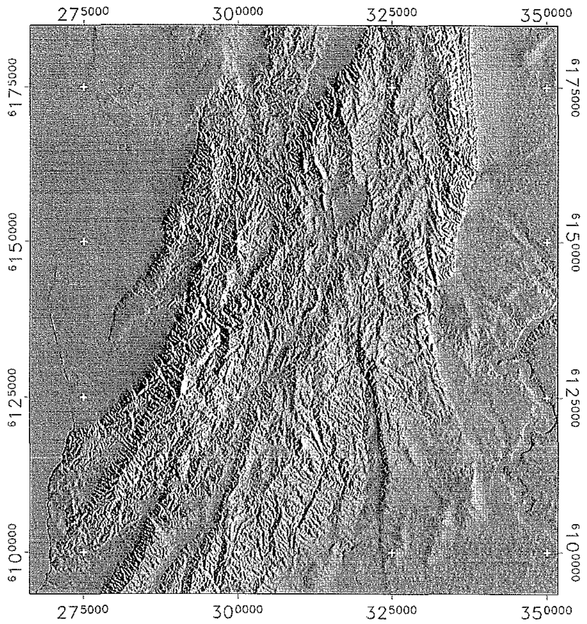

Figure 2: *Shaded relief image of the Mount Lofty Ranges showing the prominent morphostructural control exerted by the bounding fault scarps Illumination is from the east*

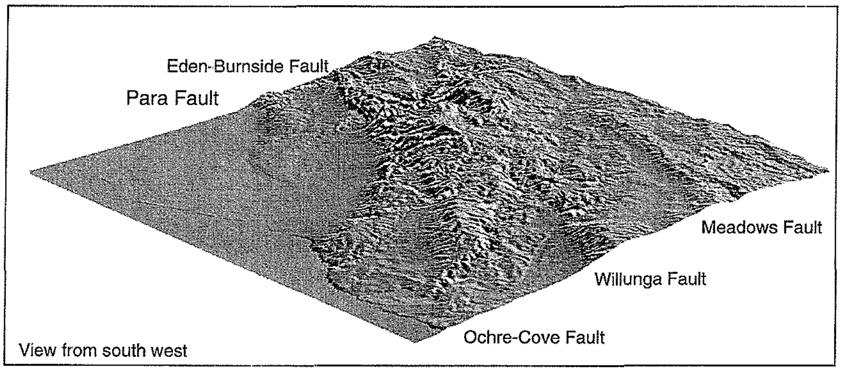

Figure 3: *Perspective view of the Mount Lofty region from the south-west showing the main bounding fault scarps, and associated tilt blocks, along the western range front.*

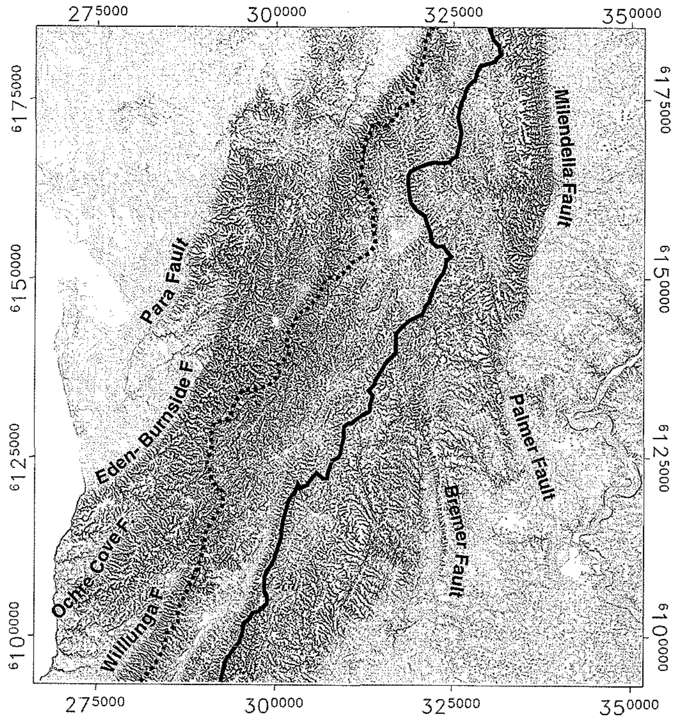

Figure 4: *Image of drainage density (obtained by applying a 5-point laplacian filter to the DEM) The highest drainage densities are found in the marginal regions, with intermediate densities occurring in central part between the major watershed (solid line) and western range The lines of the topographic profiles shown in Figure 6a are indicated by the solid line (main watershed) and the western range front (dashed line)*

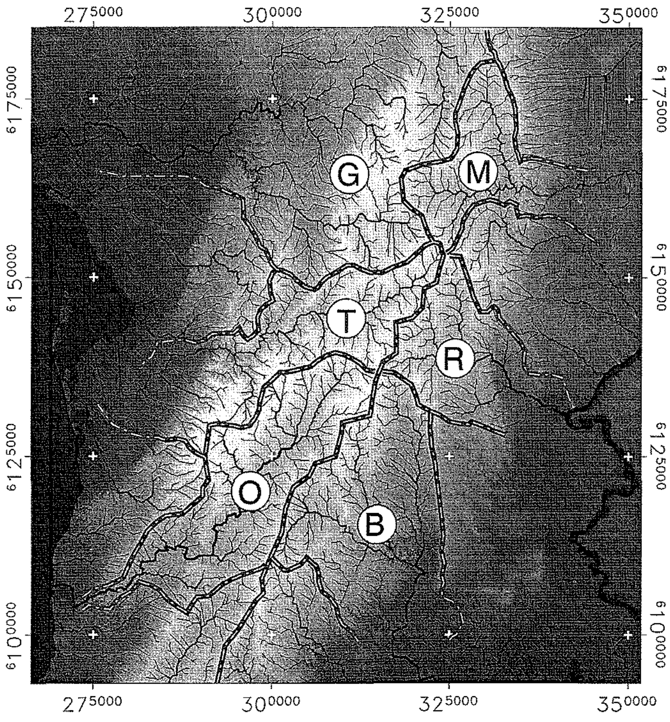

Figure 5: *Image showing the drainage net and drainage basin divides (watersheds) for the Mount Lofty Ranges, superimposed on a grey-scale image of the topography (note that only the main drainage basin divides are shown). The main west-flowing systems comprise (from north to south) the Gawler-Para (G), the Torrens (T) and Onkaparinga (O) systems The main east flowing systems comprise the Marne (M), Reedy (R) and Bremer (B) systems.*

flowing rivers systems (Figures 4 & 5) The western margin of this range is deeply (and steeply) incised, particularly where the west-flowing rivers cross the axis of maximum topography and associated bounding scarps Nick points in many of the river systems remain close to their generative scarps, testifying to the youthful nature of the western range front For example, the knickpoint of the River Torrens profile is now located approximately seven kilometres upstream of the Eden-Burnside Fault Near this fault, the channel of the River Torrens has a gradient of about 7 m/km This increases abruptly upstream to 30 m/km close to the knickpoint Above this point the gradient drops to only 5.5 m/km over a distance of 45 km In these upper reaches, the river flows in a region of subdued, mature relief

The summit surface forms a broad, elevated tract of land extending north-east from Mount Lofty (Figure 1) It is characterised by average elevations of 500-600 m asl for the western range, 400-500 m asl for the central part and 450-550 m asl in eastern area although the tilted nature of the surface implies both regional and local variations This tilting is clearly shown along the drainage divide forming the northern boundary of the Onkaparinga drainage basin (in part forming the divide with the River Torrens) as shown in Figure 3 & 6b This surface rises gradually from about 250 m along the crest of the Ochre-Cove tilt block, to about 500 m near Mount Lofty The elevation of the summit surface remains more or less constant along the divide north-east of Mount Lofty until it joins the main watershed. Residual pockets of regolith can be found along the entire length of this drainage divide (eg Sprigg, 1945)

The main scarps, associated with the Para, Eden-Burnside, Ochre Cove (or Clarendon) and Willunga Faults on the western range front, and the Bremer, Palmer and Milendella faults on the eastern side of the ranges, define a series of tilted fault blocks (Figures 2 & 3). Particularly prominent features of the Mount Lofty Ranges are the clearly defined bounding fault scarps, indicating that neotectonic fault movements provide a first-order control on the landscape.

The drainage of the Mount Lofty Ranges is divided by a relatively linear regional watershed into west- and east-flowing systems, with west-flowing river systems (ie, those flowing into the St Vincent Basin) dominating the upland In the south, this watershed follows a prominent ridge parallel to the Meadows Fault Further north, the watershed is more irregular and crosses the summit surface towards the eastern part of the ranges Drainage density, which provides a measure of the average length of river streams to unit area (Horton, 1945), shows systematic variations across the Mount Lofty Ranges (Figure 4) allowing the recognition of three distinct drainage density domains, namely:

- high drainage density domains are directly linked to scarps and slopes, particularly along the western range front, and reflect the high erosional energy associated with steep relief,
- intermediate drainage density domains are mainly located in the central part of the Mount Lofty Ranges between the major watershed and western range
- low drainage density domains are mainly associated with low elevations in the bounding basins

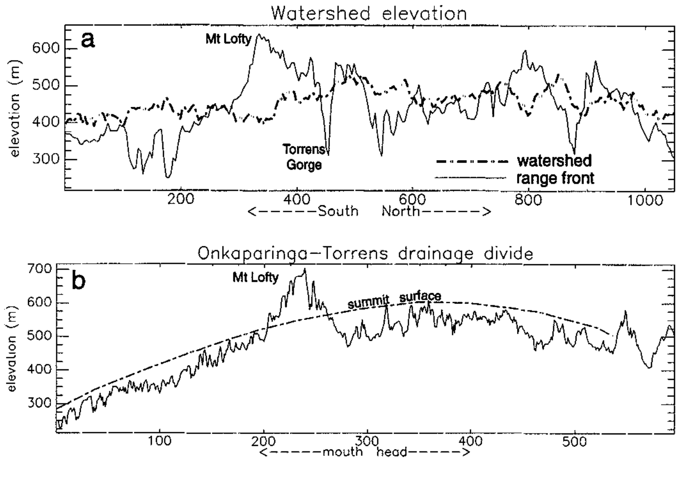

Figure 6 *(a) Topographic profiles along the main watershed (dashed line) and the western range front (solid line), as shown in Figure 4*

(b) topographic profile along the Torrens-Onkaparinga drainage divide showing the tilted form of the summit surface with Mount Lofty forming an erosional remnant rising above this surface

Because of the relatively low drainage density in the watershed areas, these regions are most likely to preserve the oldest landforms, and are thus important in understanding the sequence of landscape evolution In the analysis of the factors controlling the location and origin of watersheds it is necessary to evaluate the relative roles of inherited lithology and structure versus differential uplift/subsidence (ie , neotectonic controls) The regional watershed is dominated by a gently undulating planation surface (Figure 6), with narrow chains of erosional remnants rising above this surface giving a total relief of about 100 m over ~90 km from south to north The following lines of evidence suggest that the main watershed was not linked with the physical properties of rocks, or the inherited structure, of the substrate on which it was formed:

- firstly, the watershed crosses a variety of lithologies ranging from quartzite (Undalya Quartzite) through to biotite schist (Kanmantoo Group), which would be expected to show significantly different erosional resistance It should be noted that much of this watershed is actually composed of deeply weathered regolith, implying that the basement lithology did not provide a primary control on the location of the watershed
- secondly, the watershed crosses the main tectonic fabric of the Adelaide Fold Belt; including a tectonic window of Mesoproterozoic metamorphic basement and the Nairne Fault (which is a major Palaeozoic structure separating the Adelaide Geosyncline from the Kanmantoo Trough)

An important insight into the regional watershed is provided by the observation that for much of its length it is lower than the main topographic axis along the western part of the Mount Lofty Ranges (Figure 6a) This is particularly the case for the Torrens River which exits the upland system through the steeply incised Torrens Gorge cut into the Eden-Burnside fault scarp Since the major west-flowing rivers cross the western range front, the watershed must formerly have been higher than western ranges The notion that the regional watershed formed earlier, and probably much earlier, than the main uplift of the western ranges is supported by the preserved deeply weathered planation surfaces along the regional watershed In addition, the depth of weathering and the degree of regolith preservation on the western range summit surface is much less than on the major watershed These factors suggest that the regional watershed and its associated drainage pattern reflect primarily neotectonic movements associated with differential uplift of the eastern part of the ranges relative not only to the flanking basins, but also to the now higher, western Mount Lofty Ranges

STRATIGRAPHIC RECORD OF FLANKING BASINS

The lowlands to the west (St Vincent Basin) and to the east (Murray Basin) of the Mount Lofty Ranges, as well as a number of intramontane basins, have been sites of deposition during the Tertiary (Cooper, 1985; Brown & Stephenson, 1991; Lindsay & Alley, 1995; Rogers et al , 1995) In these basins, two distinct depositional packages may be distinguished The first is Middle Eocene through to Middle Miocene (~43 to 14 Ma), and the second is a Late-Cainozoic package from the Early Pliocene (~5 Ma) through to the present Both packages reflect specific features of the neotectonic regimes

The early Tertiary record shows a sudden onset of deposition with a transgressive system passing from non-marine clastics into carbonate-dominated marine successions, and deposition terminating abruptly at about 14 Ma (McGowran, 1989; 1991; McGowran et al., 1997) This interval correlates with regional subsidence of the southern margin of the Australian continent as a consequence of the rapid increase in spreading rate between Australia and Antarctica at about this time (Cooper, 1985) However intraplate uplift and subsidence were the result of epeirogenic movements widespread throughout South Australia, as described by Veevers (1984, p 146) with reference to Wopfner et al (1974)

The late Tertiary (essentially Quaternary) stratigraphic record comprises fine-medium grained clastics, minor carbonates, and significant coarse fan-glomerates restricted to the flanks of the modern topography This package, including Pliocene shallow marine deposits, lies with a low angular unconformity on the early Tertiary deposits, following an approximately eight million year interval of erosion and non-deposition This deformation and subsequent depositional hiatus may represent the transition to, or onset of, a new tectonic regime

Fluctuating climatic conditions also played an important role in the development of fan-glomerates which are ubiquitous along the range fronts but are now being actively dissected For example Williams (1973), attributes alluviation of the fan-glomerates and development of the associated piedmont plains on the western flanks of the Flinders Ranges (~300 km north of the Mount Lofty Ranges) to brief periods of high-rainfall and stream discharge, during an otherwise, cool late Pleistocene (~35,000 BP) This contrasts with the modern, warmer environment characterised by generally low-stream discharge associated with active dissection of the fan systems

The implications of the stratigraphic record for the development of the relief in the Mount Lofty Ranges have been the subject of a considerable diversity of opinion, with much of the interpretation dependent on relatively poorly understood intramontane basin sequences On the assumption that the intramontane basins are largely preserved intact rather than as structural, fault-bound, relicts, Benbow et al (1995, pp 213-215) have argued that the local relief in the Late Oligocene through Middle Miocene was generally similar or even greater than today However, it is difficult to reconcile these observations with the lack of any coarse clastics or deformation of sediments One unequivocal line of evidence relates to the offset of Mid-Tertiary marine sequences between the intramontane and flanking basins For example, the top of the Port Willunga Formation in the Hindmarsh Tiers Basin (on the Fleurieu Peninsula immediately south of the Mount Lofty Ranges) is at ~220 m above sea level, whereas it is buried to at least 150 m below sea level immediately north of Adelaide which implies at least ~370 metres of differential displacement in the late Tertiary This differential displacement probably coincides with the record of marginal uplift indicated by a generally low-angle unconformity between the two Tertiary depositional cycles, and is of the same order as the known, late-Tertiary displacements on the range-bounding faults. Bourman and Lindsay (1989) reported evidence of Tertiary movements along these faults and demonstrated pronounced post-Middle Miocene tectonism in eastern as well as the western edges of the Mount Lofty Ranges Our latest reconstructions of the pre-Tertiary surface indicated a vertical displacement of about 500 m along the south part of Willunga Fault.

DISCUSSION

Relating the stratigraphic record to the geomorphic history outlined above suggest a two stage landscape evolution model:

- An older, Middle Eocene to Middle Miocene stage is recorded in the Tertiary successions of the flanking St. Vincent and Murray Basins The initiation of subsidence here reflects a change from tectonic quiescence to an epeirogenic tectonic regime associated with predominantly negative tectonic movements of low amplitude. These movements were primarily responsible for the initiation of the bounding basins. The obvious feature of the Mount Lofty Ranges that may be associated with this interval is the development of the regional watershed and its associated deeply weathered surface and well preserved regolith. The drainage system at this time apparently developed on a residual undulating low landscape The absence of coarse clastics, in the bounding basins implies that faults scarps (if existing) were low amplitude
- A younger, Early Pliocene-Recent, stage is marked by the appearance of sharply defined and high-standing relief, and development of coarse clastics in the flanking basins During this stage a major uplift of about 500 m was focussed along the western edge of the Mount Lofty Ranges This uplift disturbed the equilibrium profile of the earlier-formed, west-flowing rivers. The bigger rivers such as Torrens, Para and Gawler had enough energy to cut valleys into the uplifting western range Numerous, newly formed short, steep creeks along the western slope are evidence of relatively recent uplift of this area

The age of summit surfaces and associated regolith of the Mount Lofty Ranges has always been controversial This summit surface, and other erosional residuals, are remnants of a widespread peneplain which had apparently occupied much of southern South Australia including the Gawler Craton, Mount Lofty Ranges as well as St Vincent and the western Murray Basins (Benson, 1911; Woolnough, 1927; Twidale, 1991, 1994). The existence of a gently undulating and deeply weathered surface beneath the Cenozoic deposits is confirmed by the results of drilling and geophysical investigation in the basin areas (Miles, 1952; Boeuf & Doust, 1975; Deighton et al, 1976; Brown & Stephenson, 1991) The analysis presented in our paper suggests that this surface developed up until the mid-Eocene when low amplitude neotectonic movements, associated with localised uplift of the eastern Mount Lofty Ranges and subsidence in the bounding basins, resulted in the initiation of the drainage system. The amplitude of relief remained subdued up until about 5 Ma, and very active regolith formation continued well into the late Tertiary Regolith development had been strongly dependent on fluvial landsculpting The best conditions for continued development and preservation of the regolith took place in the eastern part of the Mount Lofty Ranges around the regional watershed during the whole history of landscape evolution.

The central part of the Mount Lofty Ranges between the major watershed and the western range had only partially good conditions for regolith preservation and development because of fluvial erosion from the Middle Eocene to the Middle Miocene However the post- Pliocene uplift of the western range preserved the central part from active erosion and allowed deep weathering to continue Climatic and sealevel changes obviously played important roles in the landscape evolution and associated regolith development of the Mount

Lofty Ranges but they are beyond the scope of this paper

So far, few studies have explored the connection between landscape evolution in the Mount Lofty Ranges and the regional stress regime governing the neotectonic evolution of the southern part of the continent From the perspective of regolith formation, this may have important regional consequences, since changes in the regional stress regime may be associated with landscape forming events over much of the continent The recent (post ~5 Ma) uplift of the Mount Lofty Ranges is demonstrably associated with reverse fault motions (Bourman & Lindsay, 1989) and thus can be related to the regional E-W to WNW-ESE compressive stress field that operates through much of the south eastern part of the continent Coblentz et al (1995) attribute this stress field to plate boundary forces, associated with changes in the relative motion of the Australian and Pacific plates at about 5 Ma The nature of the neotectonic movements associated with the earlier stage are less clear However, they probably relate to an extensional stress regime associated with basin formation along the southern Australian margin in early-Tertiary times, following the earlier separation of Australia and Antarctica.

In summary it is clear that neotectonic movements in the Mount Lofty Ranges were neither uniform in space nor through time This was fundamental to landscape evolution and to the formation and preservation of the regolith

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