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CHAPTER 8—Neotectonics of southeastern Australia: linking the Quaternary faulting record with seismicity and in situ stress

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The 'snapshot' of active deformation provided by the historical record of seismicity in southeastern Australia correlates with the distribution of faults with significant demonstrable Quaternary displacement. This is most evident in the Mt Lofty and Flinders Ranges, a region of relatively high seismic activity and fault density, as well as the southern Victorian uplands. In the Mt Lofty and Flinders Ranges, faults associated with prominent range-bounding scarps are characterised by reverse-sense Quaternary slip rates in the range 20–150 m/106 y. In comparison, in the Murray Basin, a region of low seismic activity and low fault density, the largest faults have slip rates of less than 15 m/106 y, averaged over the last 5 million years. The modern neotectonic regime can be traced back at least until the terminal Miocene, where it is marked by regional unconformities between Upper Miocene and Pliocene sequences. A terminal Miocene onset for the modern neotectonic regime implicates an important role played by Pacific–Australian plate-boundary forces in defining the unusual pattern of *in situ* stress in southeastern Australia characterised by east–west to southeast–northwest σ_{Hmax}.

KEY WORDS: Australia, faults, *in situ* stress, neotectonics, Quaternary, seismicity.

INTRODUCTION

The historical record of seismicity within continental interiors provides an intriguing 'snapshot' of tectonic activity although it is not always clear how this relates to activity at the longer geological time-scale. For a continental interior remote from plate boundaries, southeastern Australia shows substantial seismic activity (Figure 1). However, there is little understanding of the relationship between the seismicity and the indicators of tectonic activity at geological time-scales (neotectonic structures). This is partly due to an entrenched belief that the Australian continent is tectonically inert. Nevertheless, there is a surprisingly rich neotectonic record in southeastern Australia. The most dramatic evidence is found in the Mt Lofty and Flinders Ranges in South Australia (Figures 2–4), which is also one of the most seismically active parts of the continent. The geomorphology of this region testifies to the profound role of faulting in shaping the landscape, more so than in any other part of the continent, and evidence for the role played by active faults in shaping this region has long been recognised (Sprigg 1945, 1946). To quote Sprigg (1946 p. 341) on the Mt Lofty Ranges: 'At approximately the end of Miocene time the instability of the landmass was again apparent…. Faulting continued actively throughout the Pliocene and Pleistocene times'.

More recently, a number of workers have documented compelling evidence for dramatic Quaternary faulting (Williams 1973; Bourman & Lindsay 1989). Much of the literature documenting this neotectonic activity is old or in obscure journals, with the consequence that it has been largely overlooked by the wider geological community. Moreover, the evidence for neotectonic activity has been further obscured by a tendency for much of the more recent geomorphological literature to emphasise the antiquity of the Australian landscape at the expense of more youthful features (Ollier 1978; Twidale & Bourne 1975). Wittingly or unwittingly, this has contributed to the perception of an ancient landscape largely unaffected by tectonic processes

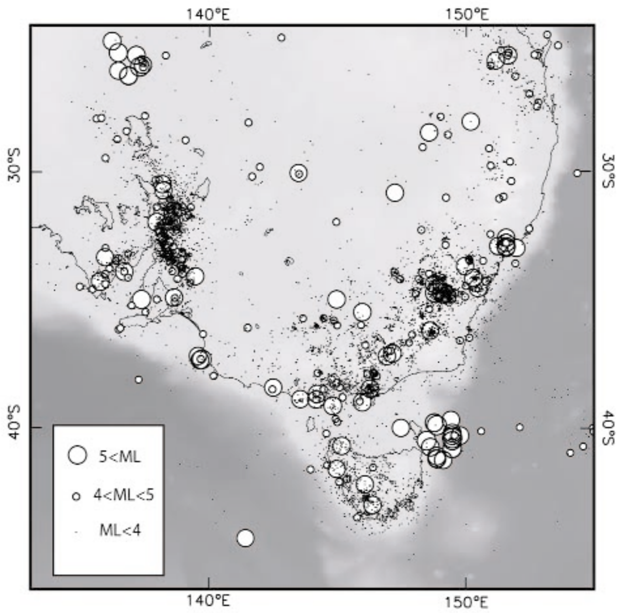

Figure 1 Distribution of seismicity in the southeastern part of the Australian continent, showing distinct concentrations in seismic activity in the Mt Lofty–Flinders Ranges–eastern Gawler Craton region of South Australia, and in a belt trending from the west coast of Tasmania, through south-central Victoria (in the vicinity of the southern uplands), northeast through the eastern highlands to southern New South Wales. Primary data are from Geoscience Australia.

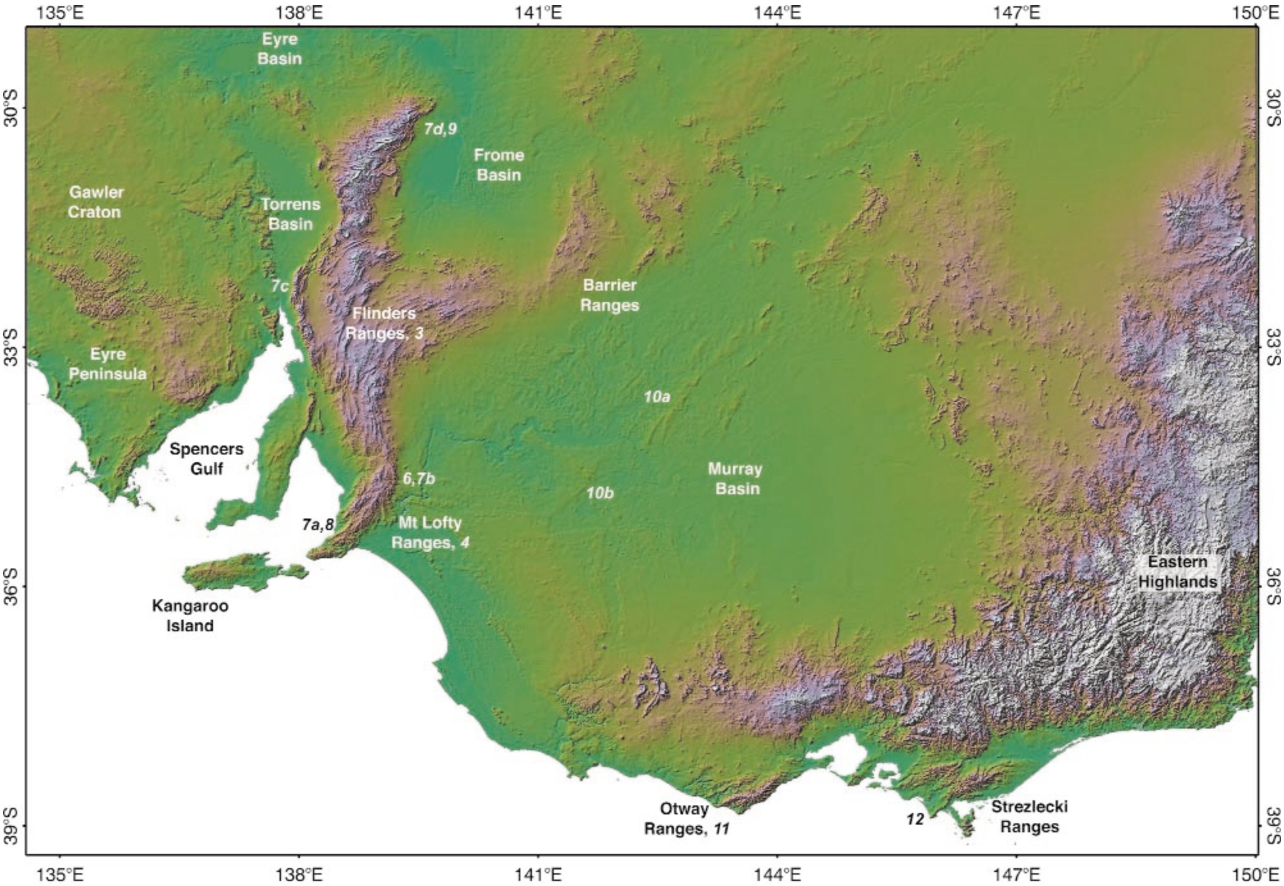

Figure 2 Shaded relief image of the southeastern mainland Australia, showing the location of the main physiographic features and localities referred to in the text. Image derived from the AUSLIG/AGSO 9 s DEM. Numbers refer to Figures of associated localities.

at least since the fragmentation of Gondwana. Therefore, the prime objective of this paper is to draw attention to some of the most emphatic indicators of active faulting, highlighting a few key localities that bear testimony to the rich neotectonic record. The focus is on the distribution, extent and timing of faulting in the Mt Lofty and Flinders Ranges, with a brief excursion across the Murray Basin into the southern Victorian uplands (Figure 2).

IN SITU STRESS AND SEISMICITY IN SOUTHEASTERN AUSTRALIA

The geodynamic framework for understanding the neotectonic evolution of southeastern Australia is provided by the historical record of seismicity and the *in situ* stress field. In terms of seismicity, the southeast is one of the most active parts of the Australian continent (Figure 1). Records extending back ~150 years show a widespread distribution of earthquakes up to Richter Magnitude (ML) ~6.4 across a zone ~1000 km in width from the eastern seaboard to the Gawler Craton in the west. ML 6 earthquakes are estimated to have a return period of ~29 years (McCue *et al.* 1990) although the largest 20th century earthquake was only ML 5.6 implying a marked temporal clustering of events. Distinct concentrations in seismic activity are recorded in the Mt Lofty–Flinders Ranges–eastern Gawler Craton region of South Australia, and in the belt trending from the west coast of Tasmania, through south-central Victoria (in the vicinity of Port Phillip Bay and the Strzelecki Ranges), northeast through the eastern highlands to southern New South Wales (Figures 1, 2). The intensity of seismic activity in these zones contrasts considerably with the intervening Murray Basin and the cratons to the west.

The *in situ* stress field in the Australian continent (Figure 5) is constrained by both earthquake focal mechanisms and borehole breakouts (Denham *et al.* 1979; Lambeck *et al.* 1984; Denham & Windsor 1991; Hillis *et al.* 1999; Hillis & Reynolds 2000). Greenhalgh *et al.* (1986, 1994) have calculated focal mechanisms for seven earthquakes in the Flinders Ranges, four of which are inferred to have had strike-slip fault mechanisms, and three reverse fault mechanisms. These focal mechanisms define a principal horizontal compression (σ_{Hmax}) of 83 ± 30° (Hillis & Reynolds 2000). In the eastern highlands of Victoria, reverse-fault mechanisms have been resolved for a number of seismic events, and define a southeast–northwest azimuth for σ_{Hmax} (Gibson *et al.* 1981). Hillis and Reynolds (2000) summarised borehole breakout data from two basins along the southeastern margin where the data are considered sufficient to define a statistically significant trend. In the Otway Basin, along the Victorian–South Australian border, the azimuth of σ_{Hmax} derived from breakouts is 136 ± 15°, while in the Gippsland Basin near the southeastern corner of the continent breakouts yields a σ_{Hmax} of 130 ± 20°.

In summary, the southeastern part of the continent is

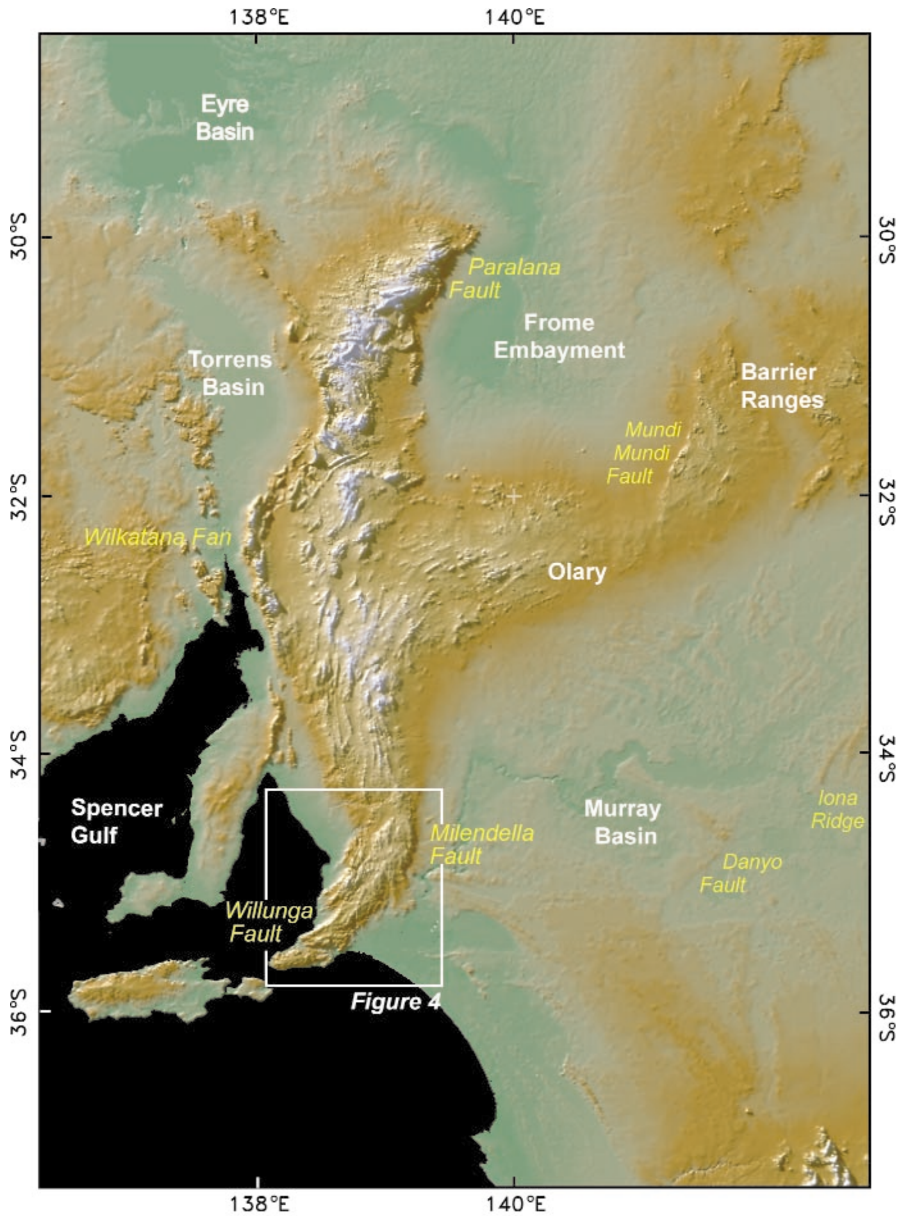

Figure 3 Shaded relief image of the Flinders Ranges, Mt Lofty Ranges and western Murray Basin showing the location of the main physiographic features and localities referred to in the text. Image derived from the AUSLIG/AGSO 9 s DEM.

characterised by a broad zone of east–west to southeast–northwest compression. The 'snapshot' of active deformation provided by the historical record of seismicity is heterogeneous, with marked concentrations in the Mt Lofty and Flinders Ranges and in the eastern half of Victoria. Notwithstanding the fact that the seismic moment in all these regions is relatively low, it seems likely that if the regional variation in seismic activity is representative of the seismic moment distribution at geological time-scales it should be reflected in the neotectonic record. The following sections review some of the most dramatic evidence for Quaternary faulting in the southeastern Australia.

EVIDENCE FOR QUATERNARY FAULTING IN THE MT LOFTY AND FLINDERS RANGES

The Mt Lofty and Flinders Ranges form an upland system extending some 800 km inland from the southern coast in the vicinity of the Adelaide (Figure 3). The Flinders Ranges (maximum elevation of ~1200 m) comprise the central and northern parts, north of about 33°S, while the Mt Lofty Ranges (maximum elevation of ~700 m) constitute the southernmost part. The ranges are almost entirely bordered by anomalously low regions with elevations typically less than 50 m asl (above sea level) and frequently below sea level. These lowlands and basins include (to the west) St Vincents Gulf, Spencer Gulf and Torrens Basin, (to the north) the Eyre Basin, (to the northeast) the Frome Embayment and (to the southeast) the Murray Basin (Figure 3). To the east the ranges merge with a broad, low upland system (200–450 m asl) through the Olary district that connects with the Barrier Ranges in western New South Wales (Figure 3). The morphology of the ranges and the surrounding lowlands suggests a regional-scale flexural compensation, as does the fact that the bouguer gravity field is generally higher in the ranges than in the surrounding lowlands (Wellman & Greenhalgh 1988).

The Mt Lofty Ranges are bounded by a set of discrete, curvilinear scarps defining the most dramatic fault-bound landscapes anywhere in the Australian continent (Figures

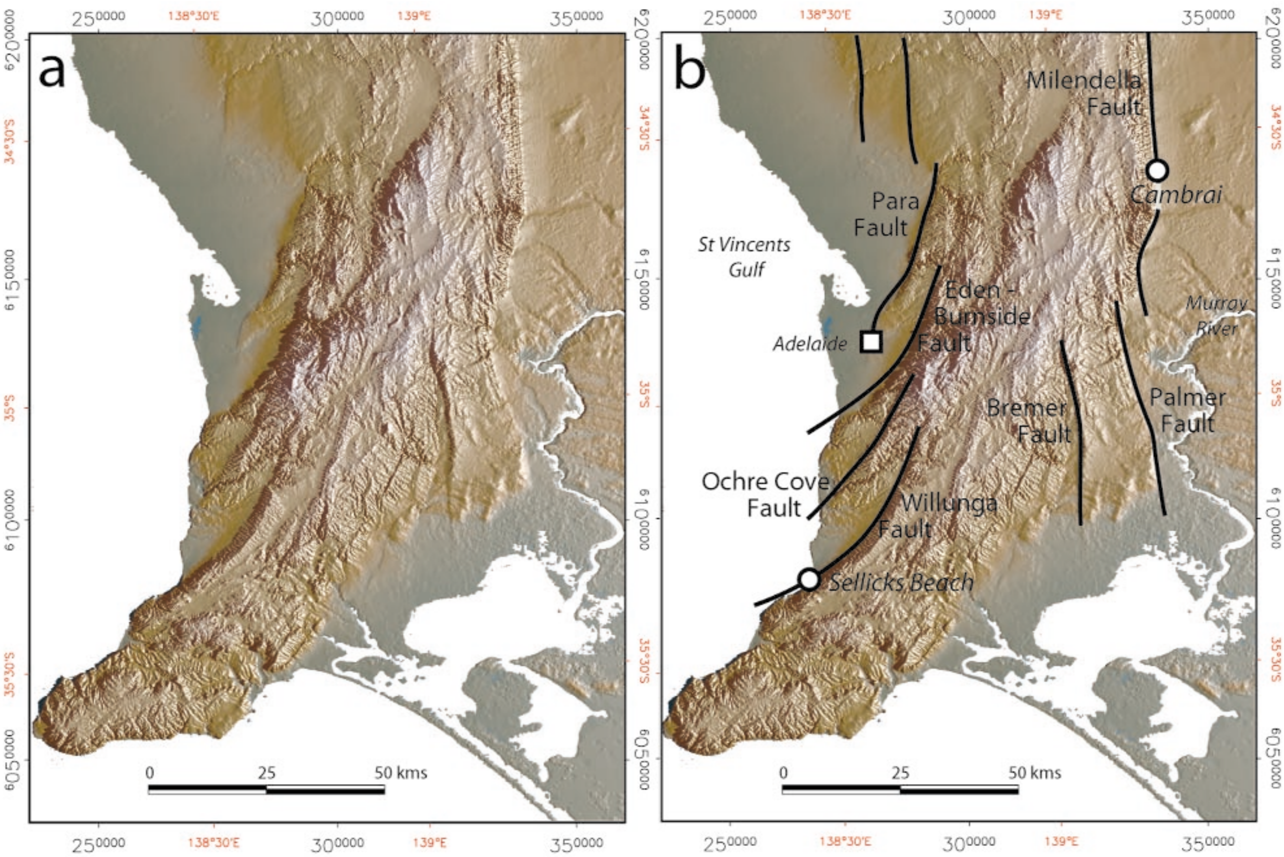

Figure 4 Shaded relief image of the Mt Lofty Ranges and Fleurieu Peninsula, South Australia, showing the main Quaternary faults referred to in the text. Image derived from a 100 m resolution digital elevation data provided by Department of Environment and Natural Resources, South Australia.

4). The main scarps are 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. The lack of degradation of these scarps implicates the profound role that faulting has played in the landscape evolution of this Mt Lofty Ranges (Sprigg 1945; Tokarev *et al.* 1999). The highest topography occurs along the western range front, markedly offset from the main drainage divide (Figure 4). The western scarps are deeply and steeply incised, particularly where the west-flowing rivers cross the axis of maximum topography, such as in the Torrens and Onkaparinga Gorges. Nick points in most valleys remain close to their generative scarps, again testifying to the youthful nature of the drainage systems along the western range front.

The bounding faults associated with the main scarps in the Mt Lofty and Flinders Ranges are largely buried beneath extensive alluvial fans and associated pediments. These fans accumulated episodically, largely during the Quaternary, but are currently being dissected (Williams 1973), resulting in the exposure of the fault planes at a few localities, some of which are described below.

Milendella Fault at Cambrai, eastern Mt Lofty Ranges

The Milendella Fault (Figure 4) is exposed in two ~8 m-high, undercut creek-bank sections near Cambrai (Bourman & Lindsay 1989) (Figure 6a, b). The fault is defined by a west-dipping thrust at the foot of the Milendella scarp, which has a total topographic relief of ~250–300 m from ~380–400 m asl at its crest to 160 m asl at the exposed fault trace to ~80–100 m at the base of the footwall pediments (Figure 7b). The fault juxtaposes metamorphosed Cambrian rocks of the Kanmantoo Group in the hangingwall above a footwall comprising a Lower Miocene limestone (the Mannum Limestone) and a Quaternary sequence comprising mottled ferruginous clay interbedded with coarse conglomerate. The Mannum Limestone, which outcrops as disrupted, rotated and locally overturned lenses, consists largely of bryozoal fragments with a minor (~5 vol%) clastic component. The Quaternary sequence includes a distinctive mottled clay resembling the Ochre Cove Formation (Ward 1966) that elsewhere has been shown to contain the Brunhes–Matuyama palaeomagnetic reversal at ca 780 ka BP, interbedded with angular conglomerates. The total post-Early Miocene throw on the Milendella Fault is at least ~60–90 m, based on the differential displacement of Mannum Limestone in the footwall sequence between the scarp and exposures of stratigraphic equivalents along the Murray River. A slightly greater minimum displacement is indicated further south, in the Bremer valley, where Middle Miocene (ca 16 Ma) Lepidocyclina-bearing Mannum Limestone is reported at ~170 m asl, about 160 m above the elevation of the nearest equivalent exposures some 23 km to the northeast in the Murray Basin (Lindsay 1986). Siliciclastic debris in the Mannum Limestone adjacent to the scarp suggests that deposition occurred close to the

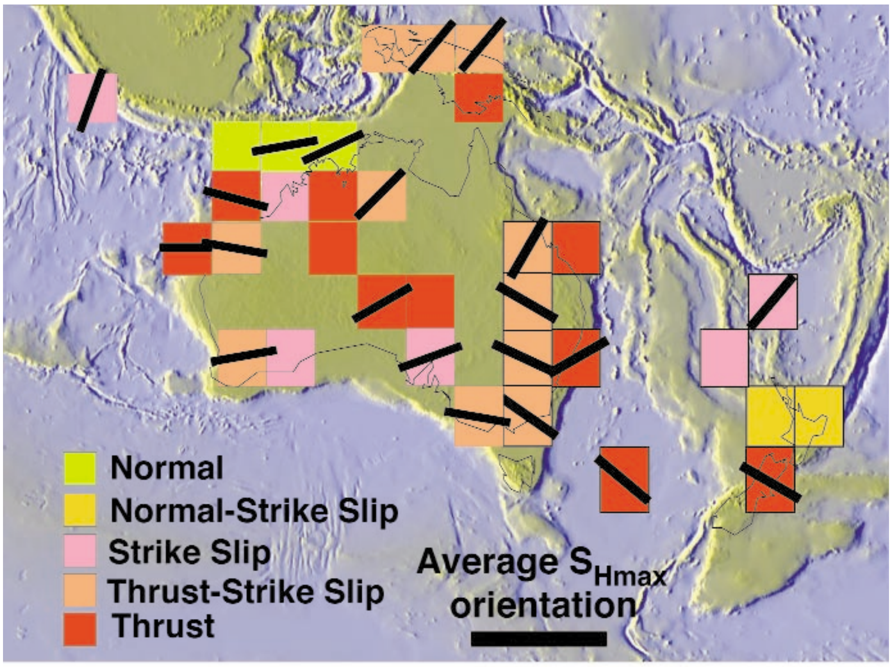

Figure 5 Synthesis of the in situ stress field for the Australian region (adapted after Coblentz *et al.* 1998).

Miocene shoreline, and thus some of ~300 m present-day relief across the scarp is likely to have pre-dated the Early Miocene. At Cambrai, the Quaternary sequence is reported to have a thickness ~30 m (Mills 1965). The exposure shows that the fault places basement above the entire Quaternary sequence, implying a minimum displacement over the last ~1 million years of at least 30 m.

Sellicks Beach, Fleurieu Peninsula

The Willunga scarp is exposed in spectacular profile at Sellicks Beach (Figure 4), where marine processes have eroded sea cliffs up to 50 m into the alluvial fan, with a number of deep canyons penetrating through the footwall across the fault trace (May & Bourman 1984; Lemon & McGowran 1989). The canyon exposures include a near-complete ~60 m-thick section through the alluvial fan which comprises conglomerate and ferruginous clay equivalent in age to those at Cambrai. These sequences unconformably overly the Oligocene – Lower Miocene Port Willunga Formation (equivalent of the Mannum Limestone), locally with very high-angle discordance (Figure 8a). A near-vertical fault contact between weakly metamorphosed Cambrian sedimentary rocks and the Quaternary has an exposed relief of ~50 m. Reverse-fault motion is indicated by steep east-dipping fault traces in the hangingwall sequence within metres of the main fault trace (Figure 8b). A prominent wave-cut bench in the footwall limestone sequence ~4–5 m asl (Figure 8a) is attributed to the ca 120 ka BP last interglacial high sea stand (May & Bourman 1984). Further south, correlative interglacial benches in the hangingwall of the Willunga Fault are up to 12 m asl (Bourman *et al.* 1998), implying a time averaged vertical displacement ~50–70 m/10^6 y. This estimate is independently corroborated reported elevation differences of ~130 m in the Lower Pleistocene (ca 1.7 Ma) Burnham Limestone along the eastern margin of the St Vincents Basin (Belperio 1995; Bourman *et al.* 1998). The differential elevation of the Port Willunga Formation between the Myponga Basin (on the hangingwall block: Figure 6a) and the St Vincents Basin (the footwall block) suggests a post-Early Miocene displacement of ~240 m (Tokarev *et al.* 1999). The presence of locally abundant basement clasts in the Port Willunga Formation fringing the Willunga scarp suggests some relief must have existed during the Oligocene and/or Early Miocene. Consequently, the present-day ~360–400 m scarp relief (Figure 7a) most probably exceeds the total post-Early Miocene displacement.

Wilkatana Fan, western Flinders Ranges

The western bounding fault of the central Flinders Ranges is exposed in Wilkatana Creek where it exits the ranges and incises the Wilkatana Fan (Figure 3) to depths of 15 m (Williams 1973). At this locality, a steep east-dipping fault plane at the foot of the bounding escarpment places a hangingwall comprising Neoproterozoic quartzite above Quaternary outwash gravels of the Wilkatana Fan (Figure 7c). Fault surfaces with 2–3 m reverse-sense offsets occur within the fanglomerate, while Williams (1973) estimates the total Quaternary movement along the bounding fault to be ~50 m. Williams (1973) attributed the major aggradation of Wilkatana fanglomerates of the Pooraka Formation to the interval 35–30 ka BP based on ^{14}C dates. However, this is near the limit of ^{14}C dating and should be considered a minimum age. More recent estimates place the age of the Pooraka Formation in the range ca 120–30 ka BP (Bourman *et al.* 1998). Long-term slip rates along the western bounding fault of the central Flinders Ranges of the order of ~20–30 m/10^6 y are indicated by these constraints.

Paralana Fault, northern Flinders Ranges

A number of fault exposures are known from the northern Flinders Ranges (Figure 3) along Paralana scarp, which separates the northern Flinders Ranges from the Frome

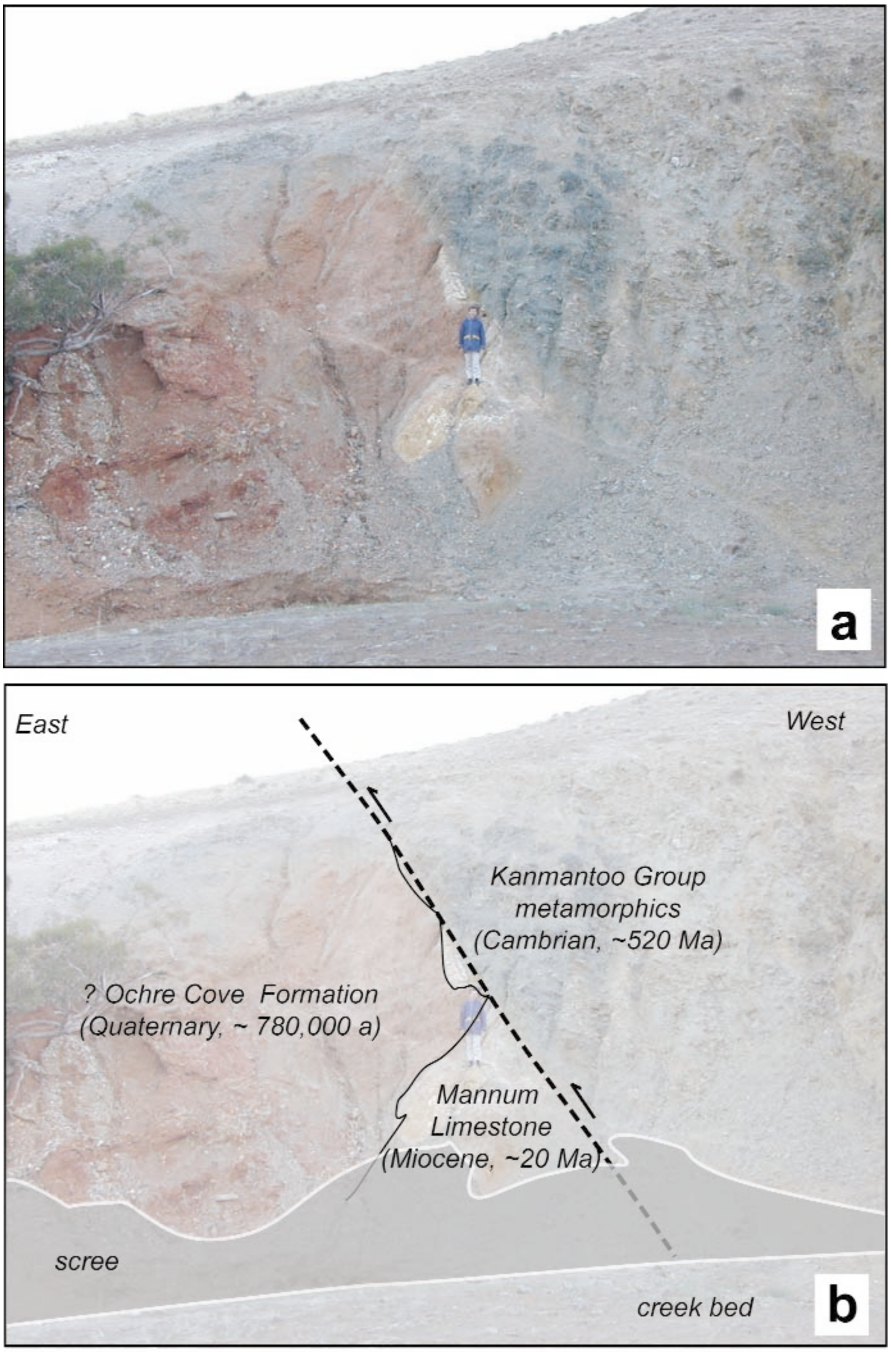

Figure 6 Photograph (a) and outcrop interpretation (b) of the Milendella Fault exposure near Cambrai, in the eastern Mt Lofty Ranges (AMG 338800E 6165900N Zone 54), first described by Bourman & Lindsay (1988). The view is looking south along the north–south-trending fault. See text for further discussion. Figure for scale.

Embayment to the east. This scarp face is characterised by some of the steepest, most deeply dissected relief in southern Australia, with an antecedent drainage system forming Yudnamutana Gorge incised some 600 m beneath the 800–850 m asl 'Freeling Heights' surface (Figure 7d). Exposures of the Paralana Fault near the foot of the bounding scarp show low-angle (<45°) contacts comprising a hangingwall sequence of Proterozoic metamorphic rocks thrust over unmetamorphosed sediments of the Frome Embayment (Belperio 1995). One of the most dramatic exposures occurs at Lady Buxton Mine (Figure 9a), where Neoproterozoic marble is thrust over ferruginous sandstone and conglomerate along a shallow (~30°) west-dipping surface. While the age of the footwall sedimentary rocks at Lady Buxton Mine are not well constrained, several lines of evidence suggest that there has been significant recent displacement on the Paralana and associated faults. Shallow west-dipping reverse faults with several metres displacement occur within some of the highest level conglomerates of the Paralana fans (Figure 9b), implying reverse motion post-dates the most recent phase of fan aggradation, elsewhere dated at 120–30 ka BP (Williams 1973; Bourman *et al.* 1998). This interpretation is corroborated by reports from Mt Babbage that basement rocks have been thrust over colluvium that may be as young as Holocene (Belperio 1995). In the last 250 000 years, the depocentre of the saline facies of Lake Frome has migrated towards the Flinders Ranges (J. Bowler pers. comm. 2001) transgressing across the alluvial-fan facies as a flexural response to changes in the tectonic loading across the bounding faults

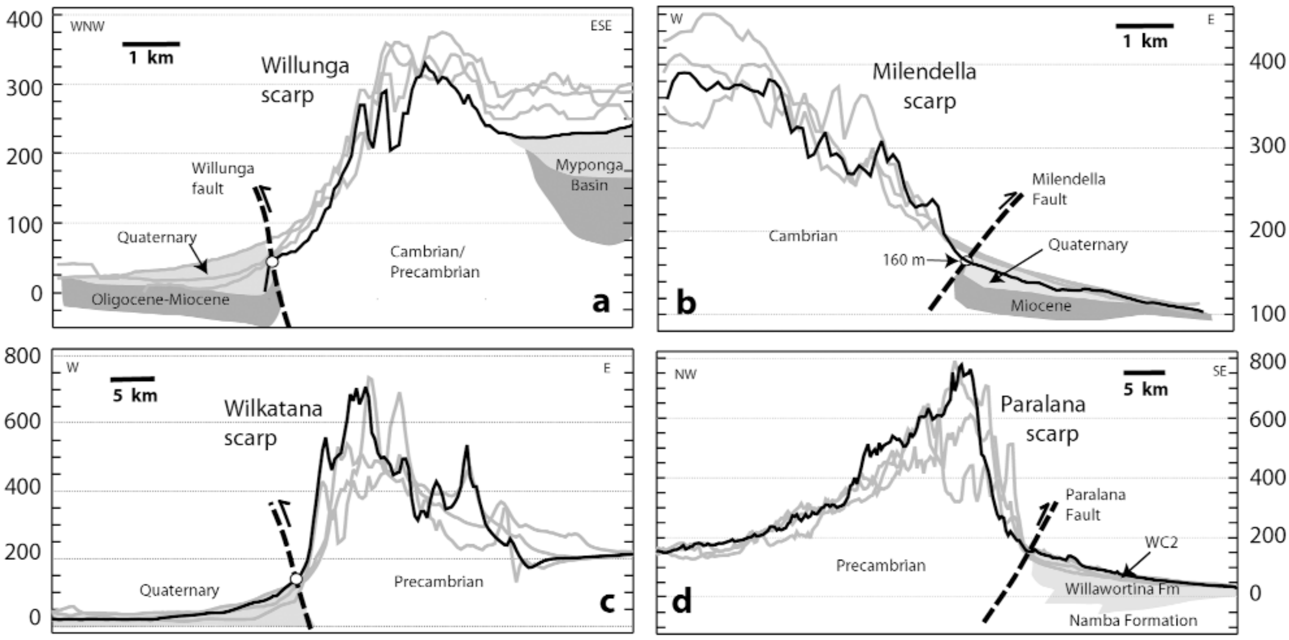

Figure 7 Topographic profiles and stratigraphic relationships across the scarps at the four localities described in the text. Original data for (a, b) from DENR 100 m DEM shown in Figure 4, and for (c, d) from AUSLIG/AGSO 9 s DEM shown in Figure 3. Stratigraphic thicknesses and extent are only approximate.

in this interval. More indirectly, the Neogene sedimentary record of the Frome Embayment points to the existence of widespread low-energy, lacustrine facies (Namba Formation) in the Middle–Late Miocene, with coarse clastics (Willawortina Formation) first appearing in the latest Miocene to Pliocene (Callen & Tedford 1976). On this basis Callen & Tedford (1976 p. 153) considered that: 'the uplift of Flinders Ranges occurred at earliest during Late Miocene times, continued through the Pliocene into the Quaternary… Prior to this, at least during the Cainozoic the Flinders Ranges were virtually non-existent…'.

While this interpretation is undoubtedly a simplification (M. Sheard pers. comm. 2001), the observations cited above implicate ongoing, Late Neogene tectonism as having contributed substantially to the present topographic relief in the northern Flinders Ranges. In the footwall sequence, the Willawortina Formation attains a thickness of in excess of 140 m, extending to at least 60 m below sea level (Callen & Tedford 1976), and thus the total relief on present day pre-Willawortina surface exceeds 800 m (Figure 7d). The thickness of the Willawortina Formation provides a minimum bound on Late Neogene Paralana Fault displacement, giving a time-averaged rate of at least ~30 m/10^6 y. An upper bound of ~160 m/10^6 y would apply assuming Callen and Tedford's (1976) hypothesis that all the topography has been built since the end of the Miocene.

Summary

In summary, the evidence from the various localities cited above points to a relatively consistent story of significant Quaternary faulting along the length of the Flinders and Mt Lofty Ranges, with time-averaged slip rates on the major range bounding faults of 30–100 m/10^6 y over the last 1–5 million years. In view of this, it is perhaps surprising that the direct exposures of the faults in the Mt Lofty and Flinders Ranges appear to be so limited. Indeed, some workers have argued that the scarcity of fault exposures argues against significant pervasive Quaternary faulting (Belperio 1995). It is important to note that in the cases cited above, fault exposure is largely due to locally enhanced erosion, such as the undercutting of incised meander bends (as at Cambrai and Paralana) or canyon formation associated with marine incursion (as at Sellicks Beach). Importantly, even at these localities the evidence for faulting becomes extremely obscure at distances of more than just a few metres from the exposures. The reason for this probably relates to the fact that: (i) the thickness of sediment deposited during the last major stage of fan building significantly exceeds the subsequent characteristic fault displacement; and (ii) the unconsolidated nature of the fans is not conducive to the preservation of surface fault breaks for any significant period of time.

BROADER NEOTECTONIC RECORD OF SOUTHEASTERN AUSTRALIA

In view of the evidence outlined above for the role played by Quaternary faulting in shaping the Mt Lofty and Flinders Ranges, it is apposite to consider how widespread this record is across southeastern Australia. The following section reviews some evidence pertaining to the distribution and extent of Quaternary faulting in the Murray Basin and the southern Victorian uplands.

Murray Basin

The Murray Basin forms a lowland system extending across much of the interior of southeastern Australia

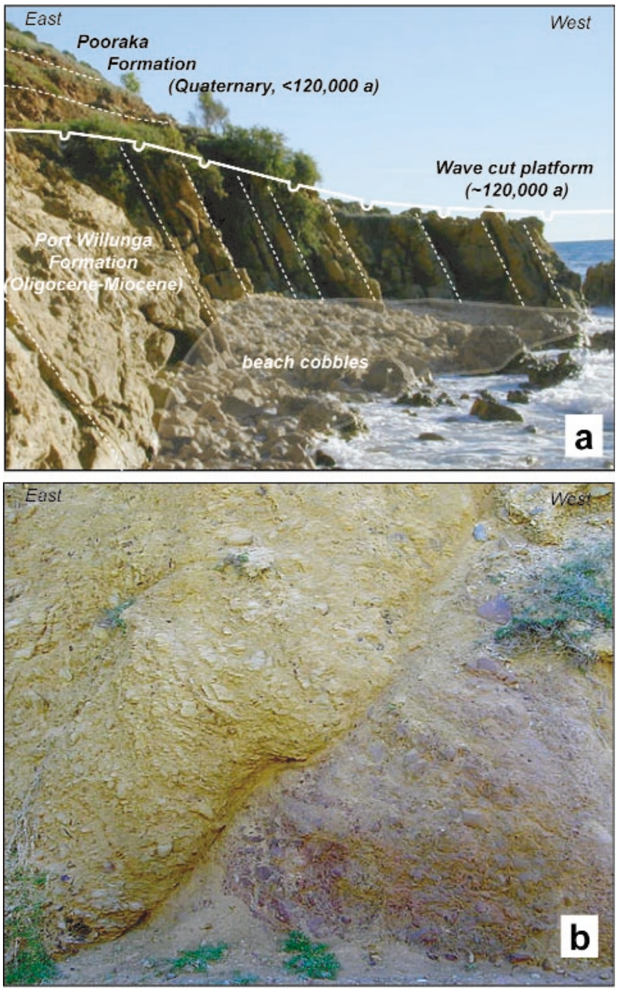

Figure 8 Willunga Fault locality at Sellicks Beach, Fleurieu Peninsula (AMG 262400E 6082900N Zone 54). (a) ca 120 ka BP wave-cut platform some 4–5 m asl in steeply dipping Oligocene – Early Miocene limestones of the Port Willunga Formation overlain by boulder conglomerates of the Pooraka Formation in the footwall of the Willunga Fault. Field of view is ~18 m across. (b) Inferred splay of the Willunga Fault showing reverse fault motion within brecciated Cambrian basement. Field of view is ~3 m across. In both cases the view is to the south-southwest.

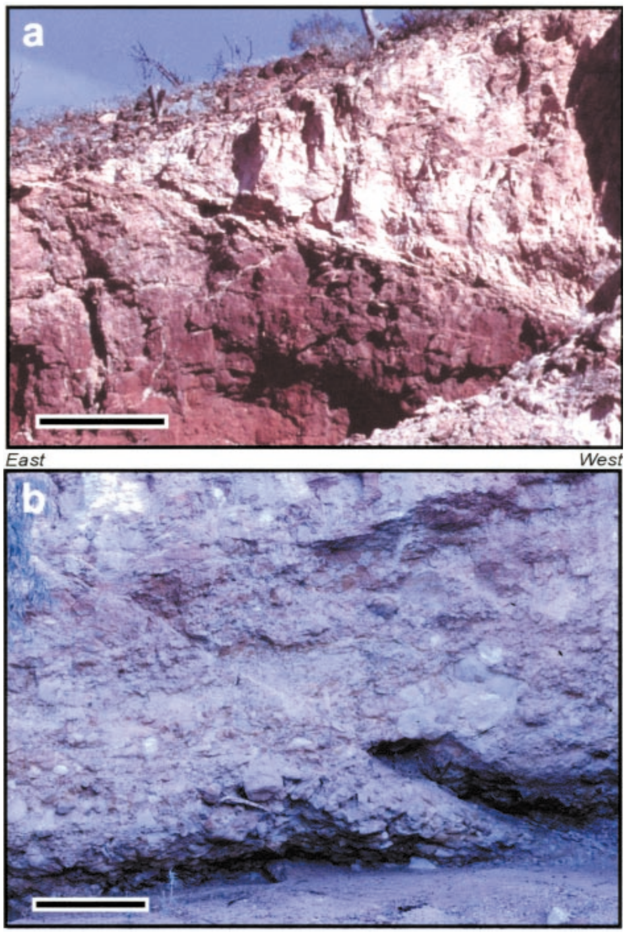

Figure 9 Paralana Fault exposures, northern Flinders Ranges. (a) Low-angle reverse fault placing Neoproterozoic marble (Wywyana Formation) above unmetamorphosed ferruginous sandstone and gravel of unassigned age (AMG 350440E 6656240N Zone 54). (b) Reverse fault cutting fanglomerate sequence in incised fan 3 km north of Paralana Hot Springs (AMG 358930E 6666200N Zone 54). In both cases the view is to the south and the bar scale is ~1 m.

(Figure 2). The basin records sedimentation, in part marine, through much of the Tertiary (Brown & Stephenson 1991) implying that it has formed a persistent topographic low at least since 50 Ma. The last phase of sedimentation commencing in the earliest Pliocene, and continuing to the present day, is recorded in a remarkable sequence of ~170 stranded shoreface deposits formed during Milankovitch-cycle highstands as sea level regressed from an Early Pliocene high of ~65 m asl (Sprigg 1959, 1979; Kotsonis 1996). The strandlines preserved in the Loxton and Parilla Sands provide a remarkable datum against which to measure subsequent tectonic activity. In the interior of the basin, the subdued topography on individual strandlines testifies to a low density of post-Pliocene structures with the Quaternary fault density very much lower than in the Flinders and Mt Lofty Ranges. Nevertheless, a record of small-scale faulting is preserved by a number of events that dammed the Murray River, most obviously with the mid-Pliocene deposition of the Blanchetown Clay and, more recently, with the Cadell Fault (Brown & Stephenson 1991).

The digital elevation models (Figures 2, 3) show a prominent set of low-amplitude northeast-trending ridges in the central part of the basin, known as the Neckarboo, Iano and Danyo ridges. Topographic profiles across these ridges (Figure 10) show an asymmetry consistent with their formation as hangingwall uplifts on steep west-dipping reverse faults with total displacements of 50–75 m. Roy *et al.* (2000) demonstrated that the Neckarboo and Iona ridges were initiated during earliest Pliocene sedimentation, with their emergence acting to concentrate heavy-mineral placer deposits. Movement has continued into the Quaternary giving a time-averaged slip rate of ~10–15 m/10^6 y on the associated faults.

Around the Murray Basin, the Pliocene strandlines rise up to several hundred metres towards the surrounding upland systems. For example, Brown and Stephenson (1991) reported the Parilla Sands at elevations of up to 300 m in western Victoria, some 250 m above its inferred depo-

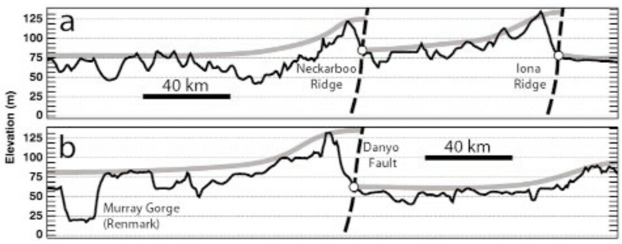

Figure 10 Topographic profile along the trend (NW–SE) of Pliocene strandlines across the (a) Neckarboo and Iona Ridges in the southwest New South Wales and (b) the Danyo Fault in northwest Victoria (see Figure 2 for locations). Original data AUSLIG/AGSO 9 s DEM. Position and orientation of faults is inferred.

sitional elevation. In western Victoria, this uplift has been attributed at least in part to a broad doming associated with Late Pliocene volcanism (Roy *et al.* 2000). However, as discussed below, there is strong evidence that the differential uplift recorded in southern Victorian upland systems is due primarily to fault-related neotectonic displacements rather than volcanic doming.

Southern uplands of Victoria

The southern uplands of Victoria include the Otway Ranges to the southwest of Melbourne and the Strezlecki Ranges to the southeast (Figure 2). Direct evidence for the impact of Quaternary faulting in shaping these ranges is best illustrated on the northwest side of the Otway Ranges, where Pliocene strandline systems equivalent to those of the Murray Basin onlap onto the ranges (Dickinson *et al.* 2001a) (Figure 11). In this region, the geomorphic expression of these strandlines has been greatly accentuated by erosional landsculpting resulting in the development of a dramatic trellised drainage net. Since the strandlines provide a horizontal datum at the depositional time (Early–Middle Pliocene: Tickell *et al.* 1992) when sea level was less than 65 m above present-day sea level (Kotsonis 1996), they provide an extraordinary insight into the more recent tectonic activity. Profiles along individual strandlines rise from less than 120 m to ~250 m on the range flank, stepping over a series of small faults and monoclinal flexures with displacements of the ~10–50 m. Discrete structural highs, clearly visible in the landscape, forming the Simpson and Ferguson Hill 'anticlines' are bound by an east-northeast-trending array of en échelon faults and monoclines (Tickell *et al.* 1992) (Figure 11). The largest of these faults, the Colac Fault on the south side of the Ferguson Hill 'anticline', has a throw estimated at ~50 m. The maximum elevation of the preserved strandlines coincides with a prominent break in slope at ~250–300 m on the northwestern flanks of the Otway Ranges, beneath which the incised valleys follow the trend of the Pliocene strandlines further north. This break in slope almost certainly reflects the position of the Pliocene coastline implying that the ranges have experienced ~200–250 m of post-Middle–Late Pliocene uplift. Importantly, the uplift increases away from the axis of Late Pliocene–Quaternary volcanism centred on a low-lying (~100–150 m) region to the north of Figure 11. Consequently, the great proportion of the 200–250 m Late Pliocene–Quaternary uplift of the Otway Ranges can be attributed to fault-related neotectonic movements, rather than volcanic doming. To the southeast of the Otway Ranges, the correlative Pliocene is restricted to submarine sections to depths of ~140 m (Dickinson *et al.* 2001). This submarine Pliocene sequence exhibits a seismic character consistent with terrestrial deposition (Mallet & Holdgate 1985) implying the fault/faults on southeastern side of the Otway Ranges accommodate up to 350 m of movement, giving a cumulative, time-averaged displacement of at least ~100 m/10^6 y.

The Strzelecki Ranges in south Gippsland form an incised set of discrete uplifted blocks bound by a set of northeast–southwest- and east–west-trending structures (Figure 2), in one of the most seismically active parts of southeastern Australia (Figure 1). While quantitative constraints on the displacement history of these faults are not yet available, evidence for recent movement is indicated near Cape Liptrap, by kink-bands in cemented dune limestones (Figure 12). These limestones correlate with ca 120 ka BP interglacial sequences that fringe much of the southern coast of Australia, making these amongst the youngest tectonic structures documented from within the Australian continent.

DISCUSSION

The recognition of a rich neotectonic record in southeastern Australia has important implications for a number of questions relating to the current geodynamic state of the Australian continent, some of which are addressed below.

The 'snapshot' of active deformation of southeastern Australia provided by the historical seismic record is markedly heterogeneous. As documented above, the most active seismic areas (Flinders Ranges, southern uplands of Victoria) correspond to regions of relatively high Quaternary fault activity, both in terms of fault spacing and time-averaged slip rates. In these regions, a significant proportion of the current topography can be attributed to Neogene tectonic activity, with major range-bounding faults having slip rates of the order of 20–100 m/10^6 y averaged over the last 3–5 million years. In contrast, seismically quiet regions of southeastern Australia such as the Murray Basin, are characterised by a more subdued Quaternary faulting record. In the Murray Basin this record is discernible largely because of the preservation of a widespread strandline system that provides an unambiguous datum against which to measure subsequent vertical displacements. This correlation between historical seismic activity and the Quaternary faulting record lends credence to the notion that the 'snapshot' of active deformation provided by the historical record of seismicity does in fact provide a first-order insight into the deformation rates at geological time-scales. In turn, this suggests that there is much to be learned from the neotectonic record in terms of understanding seismic risk across southeastern Australia.

The complex *in situ* stress field in the Indo-Australian contrasts with the other fast moving, 'compressional' plates such as the North American and South American plates (Zoback *et al.* 1989; Zoback 1992; Richardson 1992). The

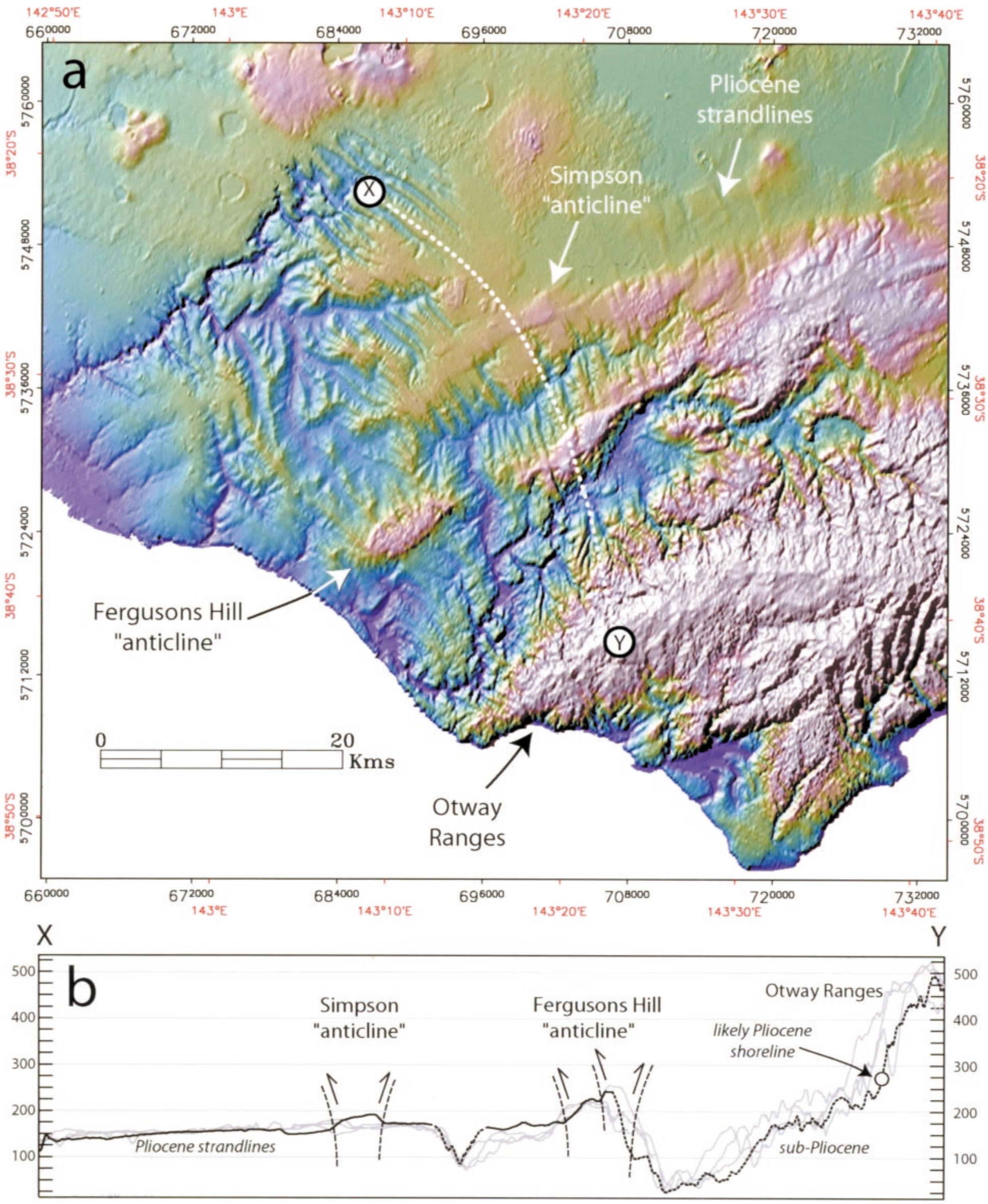

Figure 11 (a) Shaded digital elevation map of the northwest slopes of the Otway Ranges, southwest Victoria. (b) Topographic profile along Pliocene strandline across the Simpson and Fergusons Hill structural highs. These structural highs are defined by a ENE-trending en échelon array of faults cutting the Pliocene strandlines. Elevation of these horizontal Pliocene datum planes, now rises from <120 m to the northwest of Cobden to ~260 m on the Ferguson Hill structure in the southeast, ~200 m higher than at deposition. Strandlines have been differentially etched to produce a trellised drainage. The former onlapping of the Pliocene strandlines onto the northwest flanks of the Otway Ranges is suggested by a prominent break in slope at ~250 m, beneath which the incised values follow the trends of the Pliocene strandlines. An important implication is that the Otway Ranges have witnessed ~200 m of post Middle–Late Pliocene uplift (see text for further discussion).

Figure 12 A candidate for Australia's youngest mesoscopic tectonic structure: kink bands in dune limestone where the western boundary fault of the Liptrap Peninsula, South Gippsland, intersects the coast (AMG 404200E 5699900N Zone 55). The dune systems along the southern coast date to last interglacial high sea stand at ca 120 ka BP. Field of view is ~1 m wide. Photograph courtesy of Andrew Gleadow.

main feature of the Indo-Australian intraplate stress field is the broad arcuate trend from north–south σ_{Hmax} in India through east–west σ_{Hmax} in the central Indian Ocean to western margin of the continent and, finally northeast–southwest trends in northern Australia (Coblentz *et al.* 1998). This trend seems to implicate an extremely important role played by the collisional torques generated in the Himalaya and New Guinea in balancing the driving torques associated with subduction and/or ocean lithosphere cooling (Coblentz *et al.* 1995, 1998; Sandiford *et al.* 1995). However, the east–west to southeast–northwest σ_{Hmax} trend in the southeastern part of the continent cannot easily be related to any such balance and its origin remains enigmatic. Two distinct hypotheses have been proposed for this component of the stress field. Coblentz *et al.* (1995) suggested that it relates to interactions along the Pacific–Australian plate boundary and, more specifically, to the torques associated with the generation of the Southern Alps of New Zealand. In contrast, Zhang *et al.* (1996, 1998) have shown that broad east–west compression in eastern Australia may result from the density structure associated with the development of the eastern Australian margin, which exhibits a classic rift-related escarpment, although it is unlikely to account for the southeast–northwest σ_{Hmax} orientation inferred for much of Victoria. While the *in situ* stress field undoubtedly represents an interaction of both plate-boundary torques and intraplate density variations (Coblentz *et al.* 1994), as well as regional variations in rheological properties of the lithosphere, the relative importance of these two mechanisms in controlling the southeastern Australian *in situ* stress field may be resolved with reference to the geologic record, in as much as they each imply very different temporal evolutions. The Southern Alps of New Zealand have been built since the latest Miocene due to a change in the relative velocities of the Pacific and Indo-Australian plate at about 6 Ma (Norris *et al.* 1990; Walcott 1998). Prior to that time this boundary was characterised by transtension to strike-slip motion, and thus broad compression in southeast Australia arising from Pacific plate interactions should be no older than terminal Miocene. In contrast, the eastern Australian margin was built during the opening of the Tasman Sea commencing in the Mesozoic, and thus a stress-field associated with the construction of this margin must have persisted throughout most of the Tertiary.

The record of Quaternary faulting in southeastern Australia on north–south- to northeast–southwest-trending faults is consistent with the contemporary *in situ* stress determinations showing east–west to southeast–northwest σ_{Hmax} (Denham *et al.* 1979; Denham & Windsor 1991; Hillis *et al.* 1999; Hillis & Reynolds 2000). Consequently, constraints on the time of initiation of this faulting record are relevant to the hypotheses concerning the origin of the *in situ* stress field. This faulting record can be traced back to at least until the earliest Pliocene. For example, in the Murray Basin the faults associated with the Iona and Neckarboo ridges have been active since the earliest Pliocene (Roy *et al.* 2000). In the interval 8–6 Ma, the various basins around southeastern Australia experienced significant inversion (Dickinson *et al.*, 2001, in press) with a corresponding transition in the nature of basin-fill from mainly carbonate to siliciclastics, most dramatically evidenced by the unconformity at Sellicks Beach (Figure 8a). In part, the 'visibility' of this inversion event, which is evident in many seismic profiles from the Gippsland and Otway Basins (Dickinson *et al.* 2001, in press), has been greatly augmented by erosion associated with a global, terminal Miocene, regression (Haq *et al.* 1988). However, the local removal of up to 1 km of section on structurally controlled highs (Dickinson *et al.* 2001) is evidence of significant tectonism at this time, with the implied deformation rates significantly greater than those implied by the subsequent Pliocene–Quaternary faulting record. In the Otway and Gippsland Basins, the axis of the terminal Miocene inversion structures parallels the younger onshore Pliocene–Holocene structures, implying formation under a stress regime that was comparable with the *in situ* stress field, in the interval 8–6 Ma.

The marked inversion of the offshore basins along the Victorian coast and, to a lesser extent, the interior basins, together with the associated changes in character of basin fill points to a significant change in the tectonic regime in southeastern Australia during the terminal Miocene. In terms of the hypotheses about the origin of the *in situ* stress regime this would seem to implicate an important role played by Australian–Pacific plate interactions, at least in terms of stress magnitudes. The initial response to the establishment of the modern stress regime appears to have been characterised by substantial, regional-scale tilting, with localised uplift and erosion, now best preserved by regional unconformities in offshore basins, perhaps reflecting readjustment of existing fault networks and associated discontinuities to the new stress regime. Subsequent ongoing displacements, probably at significantly lower rates, have continued to deform the landscape through to the present day, where the deformation is now manifest in the historical record of seismicity. These observations suggest that the neotectonic record of southeastern Australia captures an 'event' initiated in the terminal Miocene followed by ongoing, but less intense, deformation through to modern times. In South Australia, the term 'Sprigg's Orogeny' is proposed to encapsulate the ongoing processes that have built the upland systems of the Flinders and Mt Lofty Ranges to their present elevation. In a broader historical context, this neotectonic activity is almost certainly allied to the Late Pliocene to Pleistocene 'Kosciuszko Uplift' in the eastern highlands (Andrews 1910; Sprigg 1945). If it is correct to attribute this neotectonic record to the changes in Australian–Pacific plate interactions at ca 6 Ma, then it has important implications for the nature of the intraplate response to changes in plate-boundary interactions. The change in Australian–Pacific plate interactions at this time is apparently marked by a relatively abrupt transition from one steady displacement regime associated with strike-slip motion across the plate boundary at the present site of the Southern Alps of New Zealand to another steady regime characterised by transpression (Walcott 1998). The neotectonic record of southeastern Australia suggests that this transition in plate-boundary kinematics propagated as a tectonic 'event' involving minor, but nonetheless important, strain accommodation several thousand kilometres into the Australian plate with an initial response reflecting enhanced slip on existing discontinuities as they adjusted to the change in the stress regime.

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