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Geomorphic constraints on the Late Neogene tectonics of the Otway Range, Victoria

M. SANDIFORD

School of Earth Sciences, University of Melbourne, Vic. 3010, Australia (mikes@unimelb.edu.au).

A Pliocene strandline system in the Hanson Plain Sands, between the volcanic plains of the Western District and the northern flanks of the Otway Range in southwest Victoria, provides an excellent datum against which to measure Late Neogene fault-related uplift. Individual strandlines that can be traced from elevations of ~120 m near Cobden to ~245 m on the Ferguson Hill structure are displaced across northeast-trending faults and monoclines associated with the Simpson and Ferguson Hill structures. A break in slope in the Otway Range front at elevations of 230–280 m, beneath which drainage incision parallels the trends of the strandlines, probably correlates with the Pliocene coastline on the ancestral Otway Range. By analogy with correlative systems in the Murray Basin, deposition occurred during sea-stands between 0 and 65 m above present-day sea-level, implying uplift of between 175 and 240 m since the Early Pliocene. Enhanced incision parallel to the strandlines, in combination with tilting of fault blocks about northeast axes at a high angle to the strandlines, has facilitated the development of a remarkable rectilinear drainage net. Local inversion of the drainage where it focused basalt flows constrains the age of incision and faulting to greater than *ca* 1 Ma and, most probably, less than *ca* 2 Ma.

KEY WORDS: drainage pattern, geomorphology, neotectonics, Otway Range, uplift, Victoria.

INTRODUCTION

Throughout much of the 20th century, the upland systems of the southeast part of the Australian continent were attributed to relatively youthful, Late Neogene (Plio-Pleistocene) uplift during an event commonly referred to as the 'Kosciusko (now spelt Kosciuszko) Uplift' (Andrews 1910; Browne 1969). However, quantitative dating in the past few decades has clearly shown that much of the topography of the Eastern Highlands was generated in much earlier times associated with the opening of the Tasman Sea (Wellman & McDougall 1974), calling into question the significance of the Kosciuszko Uplift (Young 1974). At present, there is little understanding of the magnitude of Late Neogene topographic generation during the Kosciuszko Uplift.

Understanding the distribution and magnitude of tectonic uplift in the southeast part of the continent in the Late Neogene (i.e. over the past few million years) has a number of important consequences, not the least of which is providing the neotectonic framework for interpreting seismic risk. Perhaps the most convincing evidence for the creation of topographic relief in the southeast part of the Australian continent in the past few million years is provided by a remarkable set of Pliocene strandline systems in the Parilla Sands of the Murray Basin (Brown & Stephenson 1991). These strandlines were deposited during sea-stands up to ~65 m above present sea-level and rise to over 200 m above present sea-level over hundreds of kilometres to the southeast, towards the upland systems of western-central Victoria (Brown & Stephenson 1991) (Figure 1). The causes of this long-wavelength uplift around the periphery of the Murray Basin are unclear, as there is little direct correlation between uplift and faults with demonstrable Late Neogene movement (Figure 1). Roy *et al.* (2000) suggested a connection between uplift and Pliocene–Holocene volcanism in southwest Victoria.

GEOMORPHIC SETTING

This paper focuses on a set of Pliocene strandlines developed in the Hanson Plain Sands, in the region between the volcanic plains in Victoria's Western District and the northwest flanks of the Otway Range (Figure 1) encompassing the drainage basins of the Gellibrand and Curdies Rivers. Digital elevation data acquired by Natural Resources of Victoria (Colac – Gridded Airborne Geophysics Survey) is used together with surveyed elevation data to estimate the tectonic relief generated along the northern flanks of the Otway Range since the deposition of the Hanson Plain Sands relating to Late Neogene faulting.

The Otway Range represents an inverted Cretaceous rift sequence of feldspathic volcanogenic sands. The maximum elevation of the Otway Range is ~670 m with the main range averaging ~500 m, some 350–400 m above volcanic plains of the Western District further north. On the northwest flanks of the Otway Range the Cretaceous sequence is surrounded by a Tertiary sedimentary sequence (including the Paleocene Wangerrip Group, Eocene–Oligocene Nirranda Group and Oligocene–Miocene carbonates of the Heytesbury Group, and the Pliocene Hanson Plain Sands) and Late Pliocene to Holocene basalts of the 'Newer Volcanics'. The imprint of these differing stratigraphic elements is clearly expressed in the geomorphology (Figure 2a). The volcanic plains form a low undulating surface at elevations of 100–150 m characterised by isolated volcanic vents and

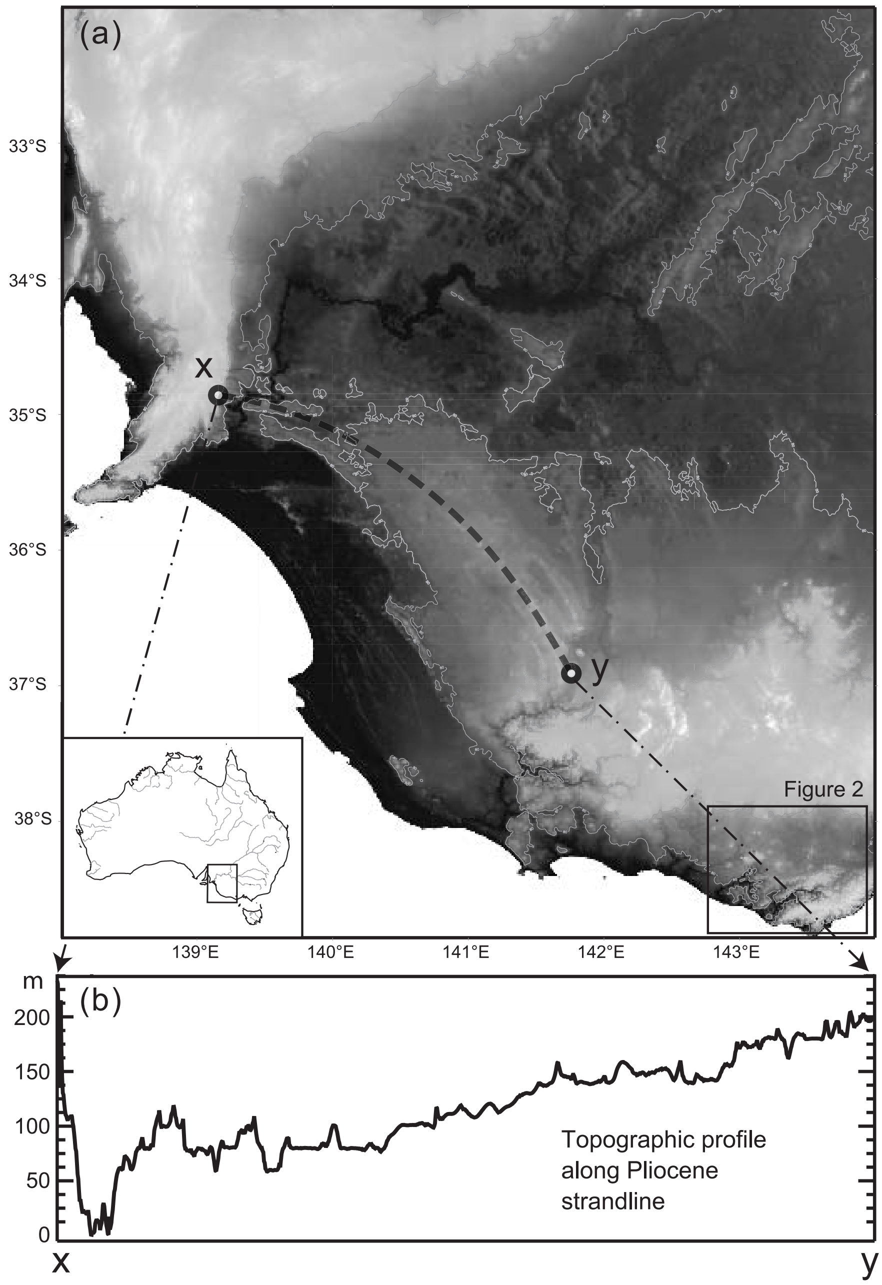
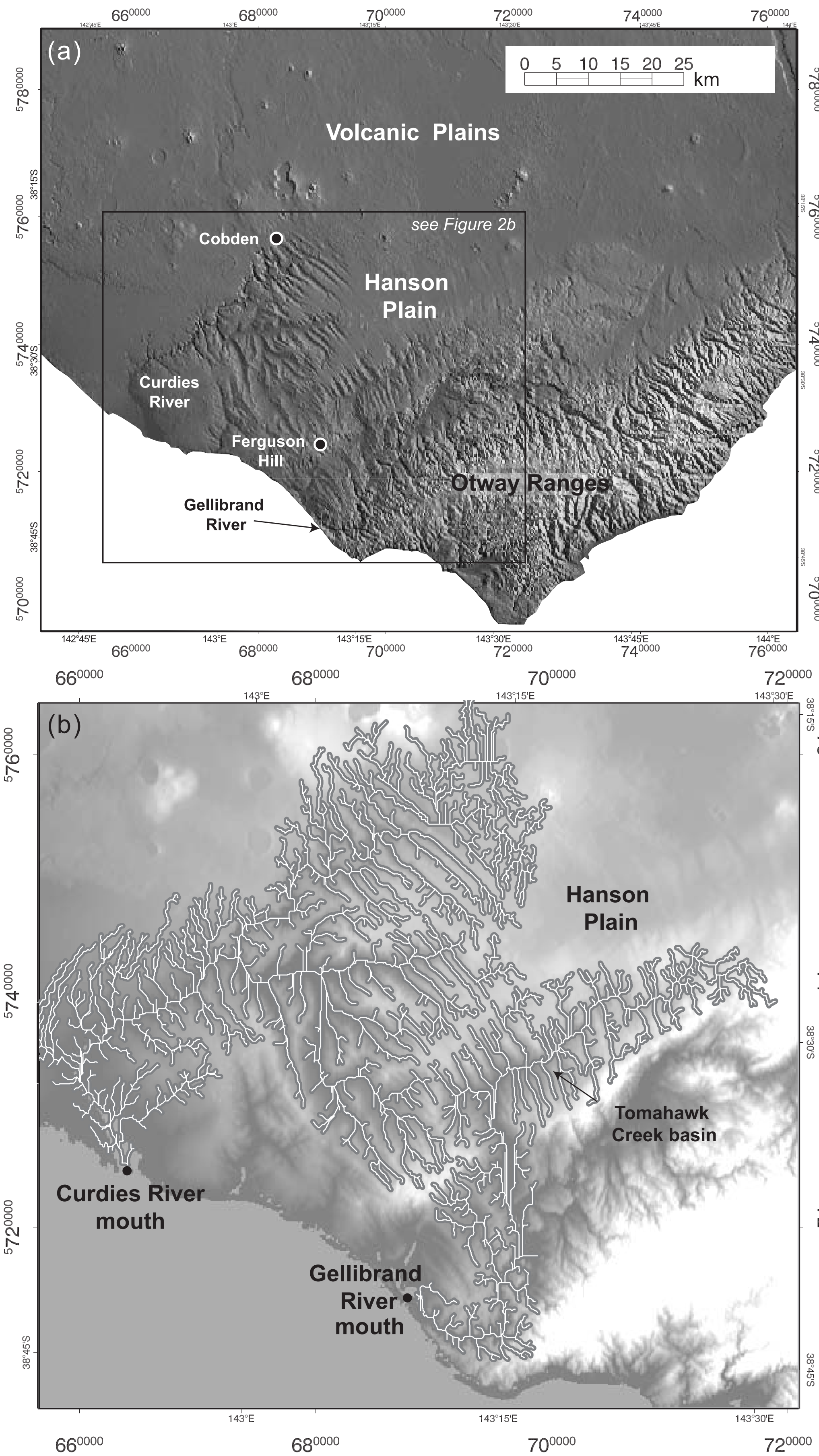


Figure 1 Topography of the Murray Basin, southeast Australia, showing northwest-trending, curvilinear trends of Pliocene strandline systems in the Parilla and Loxton sands (image based on the Geoscience Australia 9-second digital elevation model). Individual strandlines formed during a regression from a sea-stand high ~65 m above present sea-level (Brown & Stephenson 1991; J. M. Bowler pers. comm. 2002). Individual strandlines [as indicated by the dashed line in (a) and corresponding topographic profile in (b)] can be traced to elevations in excess of 200 m above present sea-level on the northwest flanks of the western Victoria highlands, implying long-wavelength, Late Neogene warping of the landscape.

maars. The Tertiary sedimentary sequences along the northwest flanks of the Otway Range are characterised by a distinctive rectilinear drainage network (Figure 2b) incised into a surface (Hanson Plain) that rises from about 120 m above sea level in the northwest to 180 m in the southeast.

The northwest flanks of the Otway Range are drained by tributaries of the Gellibrand River, while the adjacent volcanic plains are drained by the Curdies River. The Scotts and Tomahawk Creeks tributaries of the Gellibrand and Curdies Rivers form a distinctive incised rectilinear drainage network where they drain the Pliocene surface on Hanson Plain (Figure 2b). The drainage net is defined by east-northeast- to northeast-trending trunk streams fed by northwest- to north-northwest-trending tributaries etched beneath the Pliocene surface. Elsewhere on this surface, small amplitude (<5 m), northwest-trending undulations parallel the drainage, as well as radiometric (Figure 3) and magnetic (Figure 4) anomalies, represent either primary stratigraphic thickness variations in the Hanson Plain

Figure 2 (a) Shaded topography of the Volcanic Plains and the Otway Range in Victoria's Western District derived from the 50 m-resolution digital elevation model from Natural Resources of Victoria (Colac – Gridded Airborne Geophysics Survey). This study focuses on the region of Hanson Plain bounded by the Curdies River to the northwest and the Gellibrand River to the southeast. See Figure 1 for location. (b) Rectilinear drainage networks of the Gellibrand (Tomahawk Creek tributary) and Curdies River basins, showing northwest to north-northwest alignment of tributaries and northeast to east-northeast alignment of main trunk streams (see text for discussion).


(a)
0 5 10 15 20 25
km
Volcanic Plains
see Figure 2b
Cobden
Hanson
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River
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(b)
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Tomahawk
Creek basin
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River
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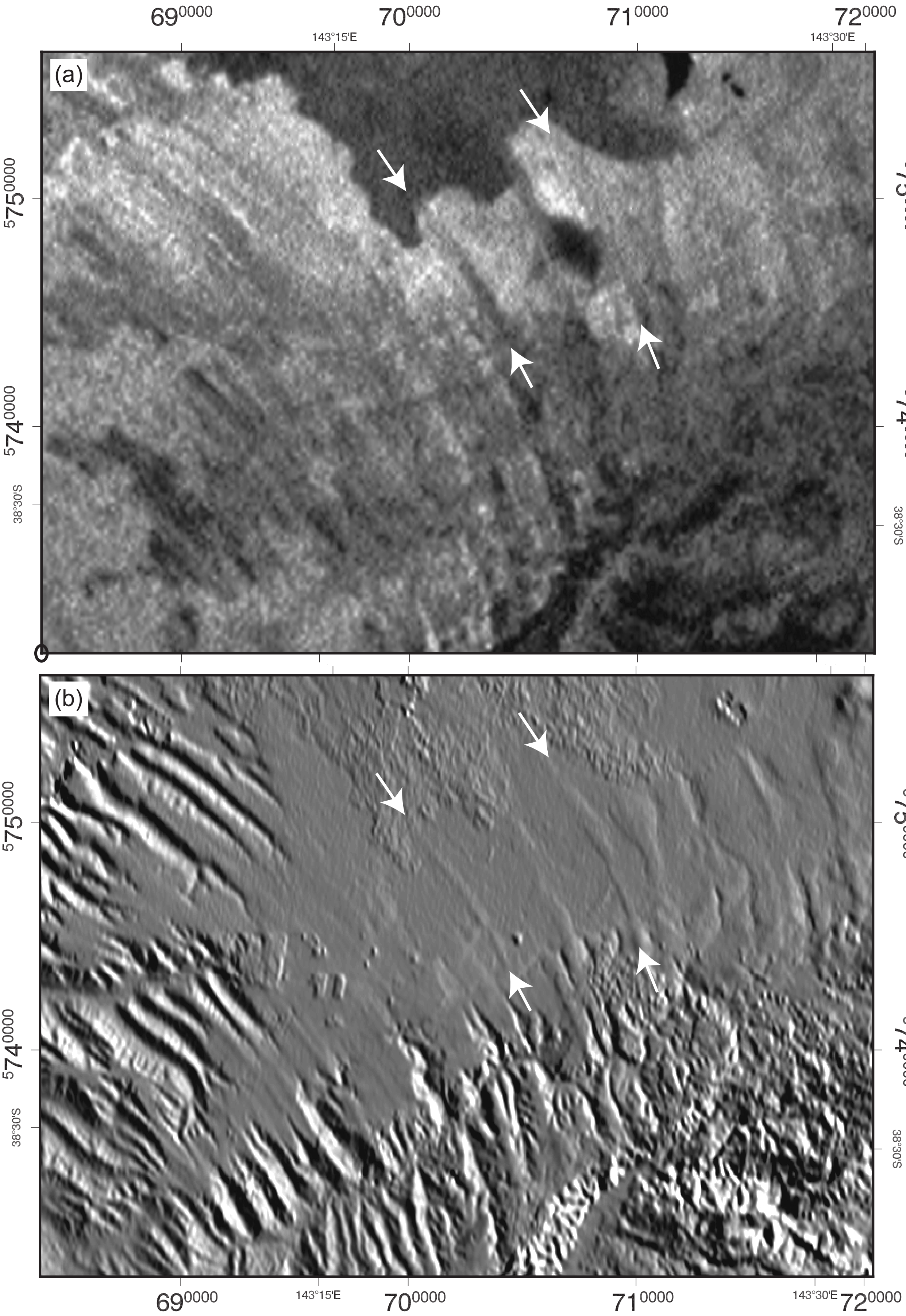

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143°15'E
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Sand, or selective secondary alteration. The depositional setting of the Hanson Plain Sands has been debated. It forms a thin sheet typically no more than 10 m thick (Tickell *et al.* 1992) comprising coarse sand and minor conglomerate. Bock and Glenie (1965) regarded the Hanson Plain Sand as a correlative of the Moorabool Viaduct Formation defined from near Geelong (Bowler 1963), which contains both marine and non-marine facies (M. W. Wallace pers. comm. 2002). Tickell *et al.* (1992) considered it to be largely fluvial with a subordinate marine component, while Dickinson *et al.* (2001) suggested a nearshore marine environment based on lithologies at the type section near Simpson. Noting their crescent-shaped geometry, together with nearshore marine facies, Dickinson *et al.* (2001) interpreted the sands as a regressive barrier sequence analogous to the Loxton–Parilla Sand strandline systems in the Murray Basin (Brown & Stephenson 1991; Kotsonis 1996; Roy *et al.* 2000).

The distinctive geophysical expression of the Hanson Plain Sands can be traced beyond the realm of their obvious topographic expression (Figure 4). To the north of the Curdies River, the magnetic trends of the strandlines show a more northerly trend, implying a change in strike about a northeast-trending axis that passes a few kilometres north of Cobden (Figure 4). The arcuate shapes of the trends on either side of this axis corroborate the notion that these Pliocene sands preserve palaeo-shoreline features, and thus provide an excellent datum to measure subsequent vertical movement.

The mapping by Tickell *et al.* (1992) showed that the base of the Hanson Plain sands rises gradually from ~120 m above sea-level near Cobden to the Ferguson Hill structure, some 30 km to the southeast (Figures 5a, b). Prominent steps in this surface occur near Simpson, across a set of *en échelon*, east-northeast-trending monoclinal flexures and surface fault traces with offsets of ~10 m, and along a parallel axis trending east-northeast from Ferguson Hill (Figure 6). The maximum preserved elevation of the Pliocene surface is ~245 m on the Ferguson Hill structure. South of the Ferguson Hill structure, Tickell *et al.* (1992) showed the Hanson Plain Sand to be as low as ~30 m above sea-level in the Gellibrand River valley, although the geophysical signature of the strandline system is missing from these outcrops, implying that they may be younger, reworked deposits. This southern boundary of the Ferguson Hill structure forms part of the Colac Fault zone, with a south-down sense of displacement in this region.

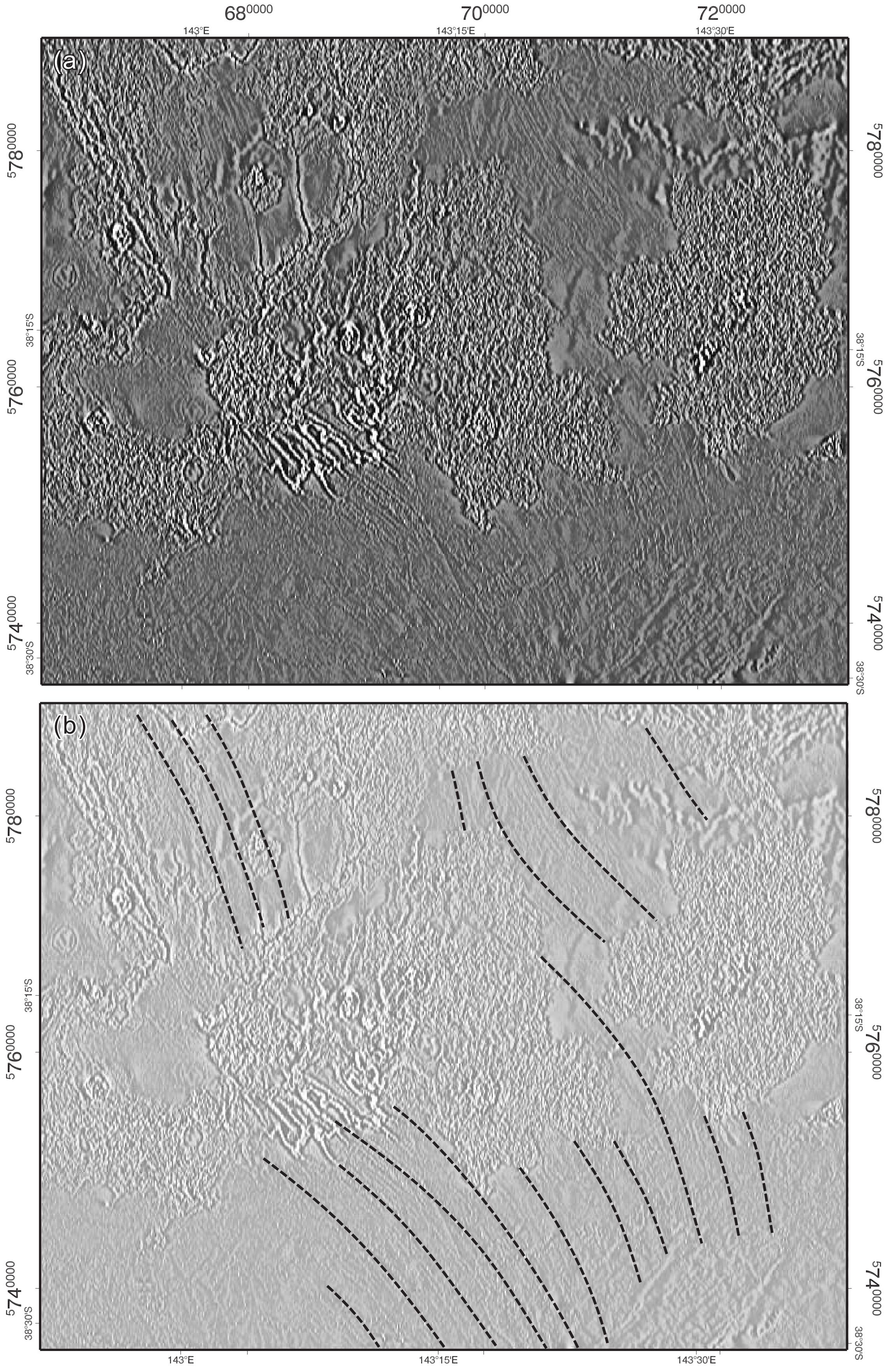
While the Hanson Plain Sand does not outcrop south of the Gellibrand River, several observations constrain its former extent. As suggested by Dickinson *et al.* (2001), the arcuate nature of the strandline systems on Hanson Plain (Figure 4) points to the existence of a land mass further to the south in the vicinity of the present-day Otway Range. On the lower reaches of the northwest flanks of the Otway Range the drainage systems mostly parallel the projected trends of the Pliocene strandlines, suggesting that the drainage has been 'let-down' through the Pliocene surface (Figure 5). The inherited trend is only obvious at elevations below about 230–280 m where there is a significant break in slope (Figure 5b), most plausibly reflecting the trace of the Pliocene shoreline on the ancestral Otway Range.

Figure 3 Detail of airborne radiometrics (a) from Natural Resources of Victoria (Colac – Gridded Airborne Geophysics Survey) showing concordance between radiometric intensity (thorium channel) and small surface undulations (b) with ~5 m amplitude in the Pliocene Hanson Plain Sands. Arrows provide the common reference points between the two panels.

EVOLUTION OF THE CURDIES DRAINAGE NET

The topography of Hanson Plain clearly shows a set of east-northeast-trending fault traces and monoclines that deform the Pliocene surface (Figure 6). Conjugate movement sense on these structures has facilitated uplift of both the Ferguson Hill and Simpson structures, as well as titling of intervening fault blocks (Figure 7). The overall tilt sense is asymmetric, with slopes dipping a few degrees to the north-northwest. The characteristic rectilinear pattern of the Curdies and Tomahawk drainage nets (Figure 2) reflects this interaction of fault-related tilting, focusing drainage along the east-northeast- to northeast-trending trunk streams, and the anisotropic erosion character of the Hanson Plain Sands, aligning tributaries parallel to the northwest-trending strandlines. This anisotropy relates to the selective development of more resistant, ferricrete weathering surfaces on the sandier strandline facies (M. W. Wallace pers. comm. 2002).

In the vicinity of Cobden, the Curdies River valley has focused a number of volcanic flows (Figures 8, 9) allowing for an assessment of the timing of incision. This part of the valley is characterised by a prominent set of meanders (Figures 8, 9), with the valley incised some 100 m below the surrounding plain and ~90 m beneath the base of the Hanson Plain Sands (Tickell *et al.* 1992). The Curdies River basalt forms a prominent magnetic anomaly clearly visible at the base of the Curdies River valley between Jancourt and a nest of volcanic centres some 5 km northeast of Cobden. The main flow follows the course of the present valley system around the incised meander bends, with spurs extending a few hundred metres southeast along the tributaries following the trend of the Pliocene strandlines. The present valley form therefore clearly pre-dates the eruption of the Curdies River basalt dated at 1.08 ± 0.02 Ma (Henley & Webb 1990). The airborne magnetics also reveal an older flow, here informally named the Cobden basalt, following the course of an ancestral valley on the northern rim, and some 90 m above the base, of the present Curdies River valley. The Cobden basalt flow comprises a southwest-trending trunk that curves gently along the rim of a pre-existing volcanic dome to the north of Cobden. A number of spurs extend almost 1 km southeast from the main flow along the Pliocene strandline system trend, and reveal the existence of an earlier, low-relief (<10 m) rectilinear drainage only very gently incised into the Hanson Plain surface. While not directly dated, the Cobden basalt is likely to be younger than 2 Ma, the age of the oldest recorded basalt in the vicinity of Cobden (Henley & Webb 1990; Tickell *et al.* 1992). The observations show that the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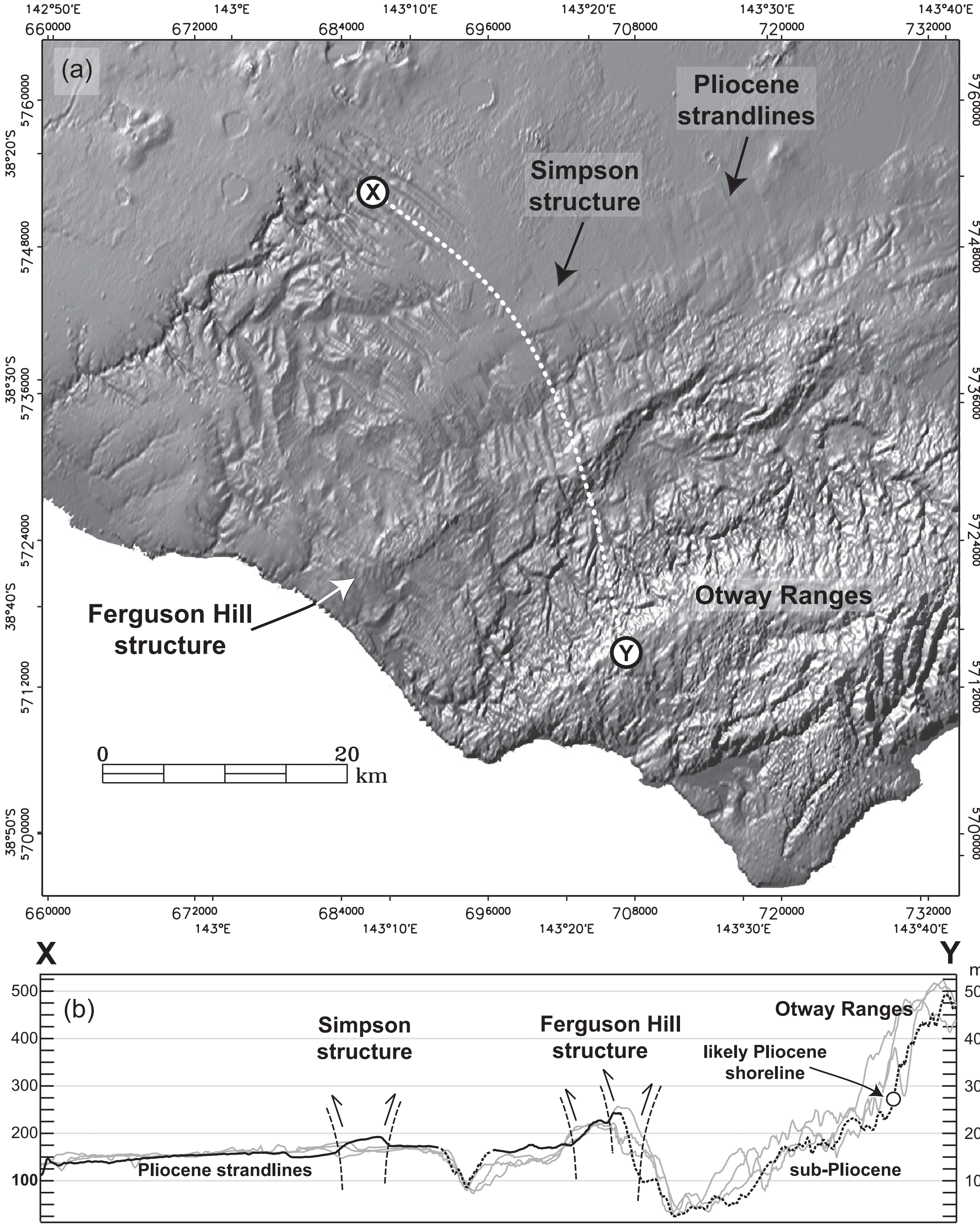
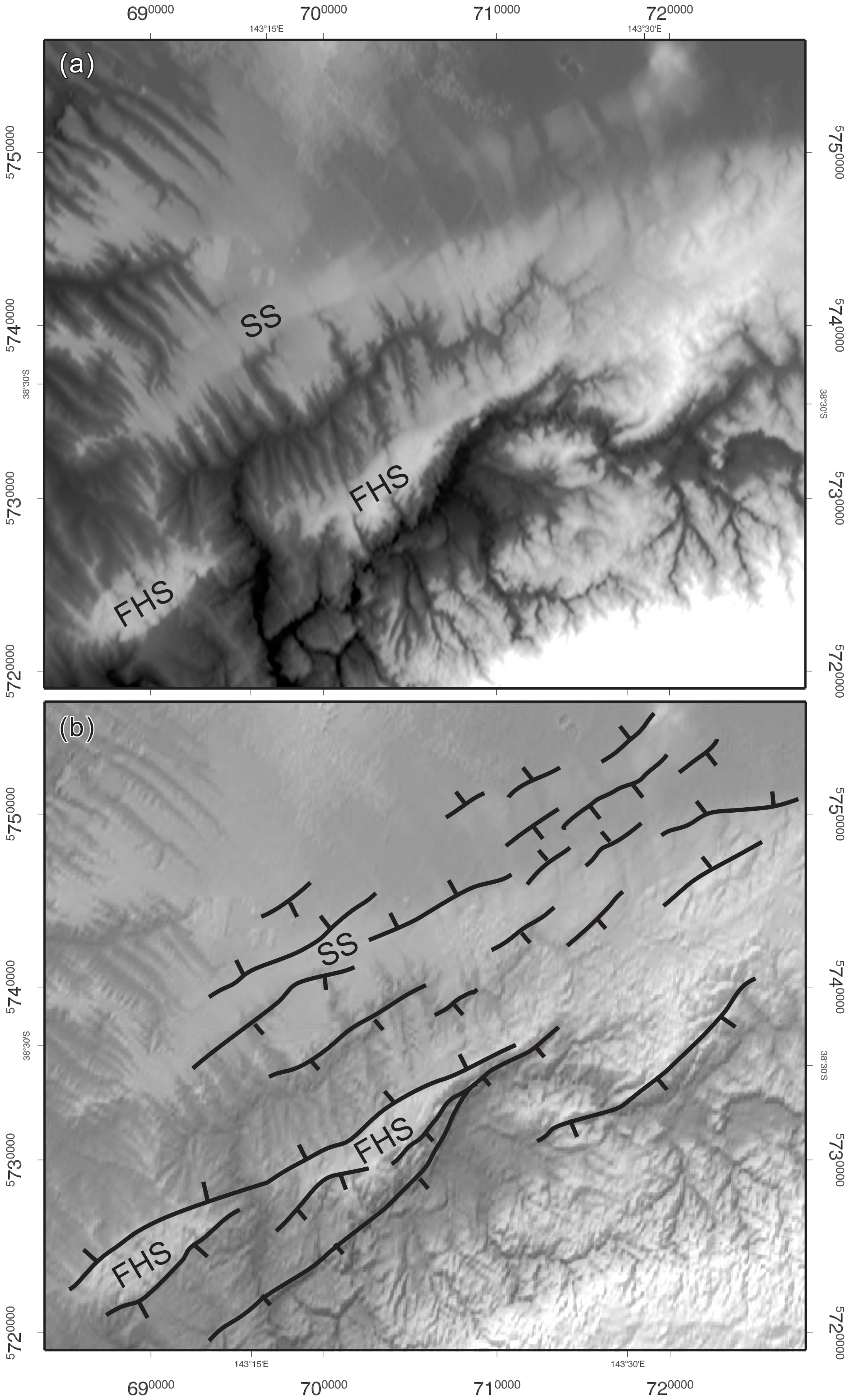


Figure 5 Detail of the topographic features in the vicinity of Hanson Plain (a), with elevation profiles along individual strandlines (b), emphasising the positive structural relief of the Simpson and Ferguson Hills structures. The Pliocene surface rises gently from ~130 m in the northwest, to ~245 m on the Ferguson Hills structure. A prominent break in slope at elevations of ~230–280 m along the northern flanks of the Otway Range (b) is the probable position of the Pliocene shoreline on the ancestral range front.

Figure 4 First vertical derivative of the total magnetic intensity (a) derived from airborne magnetics, Natural Resources of Victoria (Colac – Gridded Airborne Geophysics Survey). The magnetic signature of the Pliocene systems shows up in remnant outcrops between basalt flows to the north of Hanson Plain, with the arcuate pattern of the anomalies (b) supporting their formation as shoreface deposits (Dickinson *et al.* 2001) (see Figure 3).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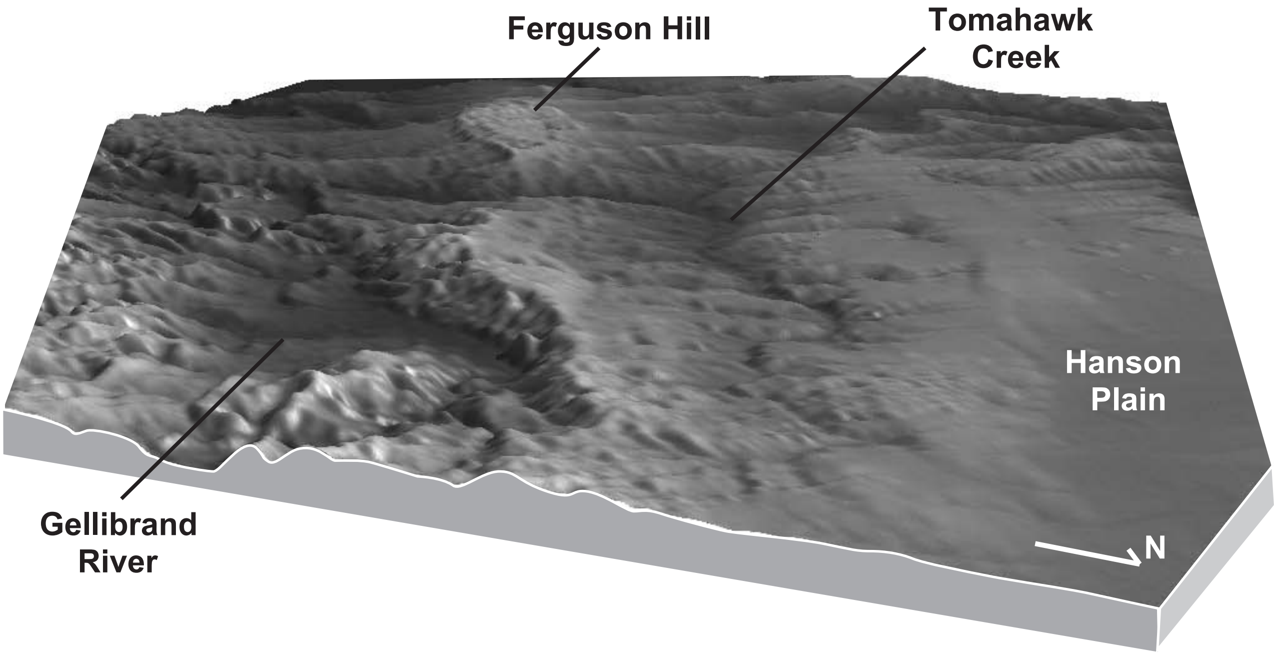


Figure 7 Oblique view (looking west-southwest) showing the tilting of the 'Hanson Plain' surface to the northwest of the Ferguson Hill structure into the Tomahawk Creek drainage basin.

apparent meanders in the Curdies Valley reflect a drainage 'inversion' following eruption of the Cobden basalt, associated with incision against the edge of the southeast-trending spurs (Figures 8, 9). The age constraints cited above imply that the major incision of the Curdies River valley occurred in the interval 2–1 Ma.

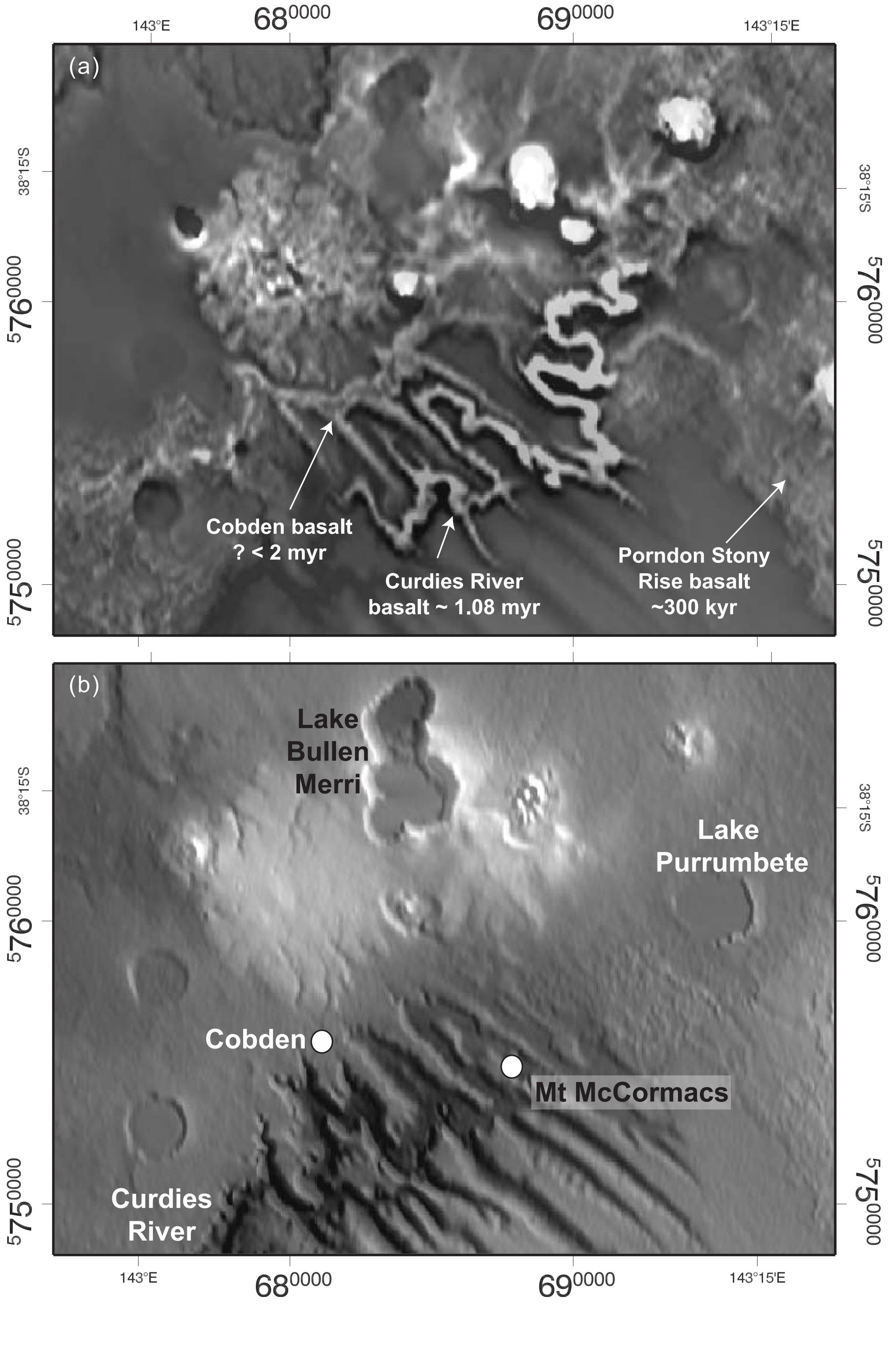
Inasmuch as the present relief in both the Curdies and the Gellibrand drainage basins is a consequence of tilting of fault blocks, faulting must have occurred mainly prior to 1 Ma. Indirect evidence for most of the observed fault slip occurring after *ca* 2 Ma is provided by a comparison between the Curdies River and Tomahawk Creek drainages. Noting that the two drainages show similar relief, it seems reasonable to assume that their incision was contemporaneous (i.e. in the period 2–1 Ma). The main northwest-trending tributary in Tomahawk Creek clearly cuts across the topographic axis of the Ferguson Hill structure (Figures 5–7), to which it therefore appears to be antecedent. Given that the Hanson Plain surface deformed by the Ferguson Hill structure was demonstrably horizontal early in the Pliocene (at least along the trend of the strandlines), such antecedence suggests that the incision of the valley systems across the Ferguson Hill structure accompanied the tectonic activity. Thus the assumption that the incision of Tomahawk Creek and Curdies River was coeval implies that the faulting responsible for the present topographic relief of the Ferguson Hill structure also occurred in the interval 2–1 Ma.

Figure 6 Detail of topography (a) and surface deflections associated with fault traces and monoclines (b) around the Ferguson Hill and Simpson structures.FHS, Ferguson Hill; SS, Simpson.

IMPLICATIONS FOR NEOTECTONIC EVOLUTION OF THE OTWAY RANGE

The Pliocene strandline system on Hanson Plain provides an excellent datum for evaluating subsequent vertical displacements. The strandlines rise over 100 m from near Cobden in the northeast to the Ferguson Hill structure in the southeast, where they may have been displaced by as much as 200 m across the Colac Fault (Tickell *et al.* 1992). By analogy with the Murray Basin, where strandlines have formed during a regression from a sea-stand high of 65 m above present-day sea-level at *ca* 6 Ma to near present-day sea-level at 2 Ma (Brown & Stephenson 1991; J. M. Bowler pers. comm. 2002), these observations imply a total uplift on the Ferguson Hill structure of between 175 and 240 m. The recognition that the Eastern Highlands were constructed prior to, or early in, the Tertiary (Wellman & McDougall 1974) has cast doubt on the credibility of the 'Kosciuszko Uplift'. The geomorphology of Hanson Plain clearly testifies to Late Neogene faulting, probably most intense in the Late Pliocene and Early Quaternary prior to 1 Ma. As such, this region provides one of the few definitive estimates of Late Neogene uplift in southeast Australia that can be clearly related to the so-called 'Kosciuszko Uplift' event. This estimate of ~175–240 m of Late Neogene, fault-related uplift for the Otway Range, compares with the estimate of Late Neogene tectonic relief generation in the Mt Lofty Range some 500 km further west (Sandiford in press).

While there are no documented exposures of the Late Neogene faults that deform the Pliocene sequences in the vicinity of Hanson Plain and Ferguson Hill, several lines of evidence suggest that the faulting mechanism was likely to be reverse. First, the active seismicity across southeast Australia has yielded mainly reverse-fault and strike-slip earthquake mechanisms, with principal horizontal stress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basalt ~ 1.08 myr
Porndon Stony
Rise basalt
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Curdies
River

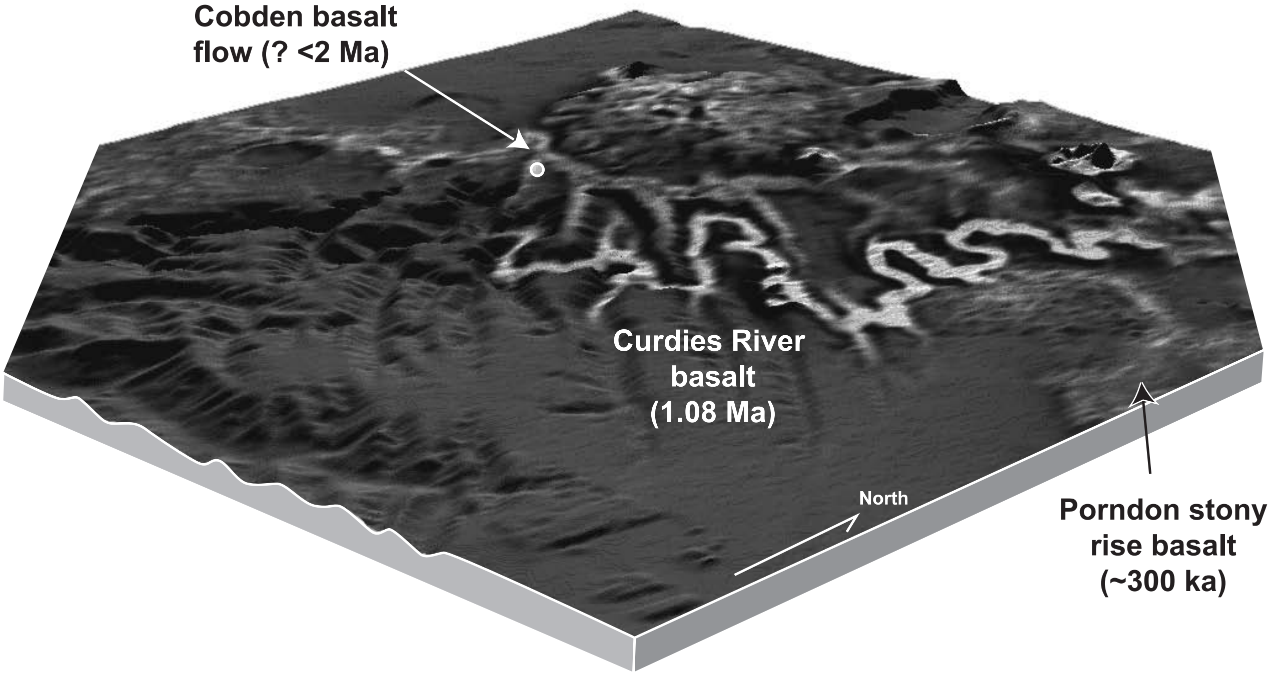

Figure 9 Oblique view (looking to the northwest) of the area appearing in Figure 8, showing the basalt flows associated with the Curdies River valley near Cobden.

trajectories varying from east–west in the vicinity of Adelaide to southeast–northwest in the Eastern Highlands (Gibson *et al.* 1981; Greenhalgh *et al.* 1986; Sandiford in press). Borehole breakouts in the offshore Otway and Gippsland basins confirm that the southeast–northwest S_{Hmax} orientation is widespread across southern Victoria (Hillis & Reynolds 2000). With regard to the contemporary stress field, the north-northeast-striking faults bounding the Otway Range are therefore presently in thrust-fault mode. The best-documented Quaternary faults in southeast Australia are from the Mt Lofty Range near Adelaide (Bourman & Lindsay 1989; Tokarev *et al.* 1999; Sandiford in press). These faults strike between north and northeast, are clearly reverse in nature, and have post-Early Pliocene displacement of the order of 100 m (Sandiford in press).

As pointed out by Dickinson *et al.* (2001; 2002), the neotectonic record of southern Victoria includes an episode of significant structuring prior to the deposition of the Hanson Plain Sands in the interval 8–6 Ma. In the region considered in this paper, this episode is evidenced by the fact that the Hanson Plain Sands onlap progressively older Tertiary units exposed towards the core of the Ferguson Hill structure at Ferguson Hill (Tickell *et al.* 1992). This terminal Miocene structuring seems to herald the onset of the modern neotectonic regime reflected in Late Neogene faulting as well as the contemporary seismicity (Sandiford in press). This regime can be allied to a change in the relative plate motion between the Pacific and Australian Plates at *ca* 6.4 Ma (Walcott 1998) that instigated the building of the Southern Alps in New Zealand, and reflects a general increase in stress levels within the Australian Plate associated with changes in the plate-scale force balance, through a variety of processes, commencing in the Eocene (Sandiford *et al.* 1995).

Figure 8 (a) Total magnetic intensity from Natural Resources of Victoria (Colac – Gridded Airborne Geophysics Survey) and (b) shaded topography of Curdies River near Cobden. The prominent magnetic intensity high in the Curdies River valley is the 1.08 Ma Curdies River basalt (Henley & Webb 1990). This flow follows the incised meander bends in the Curdies River and extends a little way up some of the tributaries. It parallels an older flow (informally named the Cobden basalt) indicated by a slightly more subdued magnetic high now forming the crest of the northwest valley wall, implying inversion of an earlier formed valley system. The etching of the current valley system against the inverted topography reflects the general southeast up-tilting of the landscape associated with rejuvenation of the Otway Range in the period 2–1 Ma.

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