Distinguishing tectonic from climatic controls on range-front sedimentation

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ABSTRACT
Geologic and chronometric studies of alluvial fan sequences in south-central Australia provide insights into the roles of tectonics and climate in continental landscape evolution. The most voluminous alluvial fans in the Flinders Ranges region have developed adjacent to catchments uplifted by Plio-Quaternary reverse faults, implying that young tectonic activity has exerted a first-order control on long-term sediment accumulation rates along the range front. However, optically stimulated luminescence (OSL) dating of alluvial fan sequences indicates that late Quaternary facies changes and intervals of sediment aggradation and dissection are not directly correlated with individual faulting events. Fan sequences record a transition from debris flow deposition and soil formation to clast-supported conglomeritic sedimentation by ~30 ka. This transition is interpreted to reflect a landscape response to increasing climatic aridity, coupled with large flood events that episodically stripped previously weathered regolith from the landscape. Late Pleistocene to Holocene cycles of fan incision and aggradation post-date the youngest-dated surface ruptures and are interpreted to reflect changes in the frequency and magnitude of large floods. These datasets indicate that tectonic activity controlled long-term sediment supply but climate governed the spatial and temporal patterns of range-front sedimentation. Mild intraplate tectonism appears to have influenced Plio-Quaternary sedimentation patterns across much of the southern Australian continent, including the geometry and extent of alluvial fans and sea-level incursions.

INTRODUCTION
Tectonism and climate are the primary external processes governing continental erosion, sedimentation and landscape evolution. Tectonic uplift creates elevated terrain and provides increased potential energy to the agents of erosion, such as fluvial systems. Seismic shaking associated with tectonic events may generate rubble and, in mountainous regions, trigger landslides, thereby increasing sedimentary inputs into catchment systems (Keefe, 1994; Allen & Hovius, 1998; Dadson et al., 2004; Quigley et al., 2007a). Climate controls the spatial and temporal distribution of erosional agents (streams and glaciers) and the vegetative cover that protects the landscape from erosion. Climatically induced changes in source catchment palaeo-geography and/or hydrologic regimes may exert a strong influence on sediment generation and transport (e.g. Pederson et al., 2000). In addition, the frequency and magnitude of large floods capable of significantly modifying continental landscapes may be strongly influenced by climate (Molnar, 2001; Molnar et al., 2006). The ability to distinguish tectonic from climatic forcing on landscape evolution hinges on the development of robust geologic and chronometric datasets that may be evaluated in the context of well-dated tectonic events and palaeo-climatic regimes.

Alluvial fans are ubiquitous features of mountainous range fronts worldwide and provide a spatial and temporal record of source catchment erosion and basin sedimentation over geologic time scales (e.g. Bull, 1964, 1991; Ritter et al., 1995; Whipple & Traylor, 1996; Calvache et al., 1997). A primary focus of recent research has been to consider how tectonic and climatic processes influence alluvial fan morphological properties and sedimentary styles, and how fans respond to changes in these external parameters (e.g. Harvey et al., 2005). Tectonic activity is now commonly recognized as the primary controlling factor in dictating alluvial fan properties such as location, setting and morphology, primarily through tectonic influences on drainage basin relief and fan accommodation space (Denny, 1965; Bull, 1977, 1991; Whipple & Traylor, 1996; Allen & Hovius, 1998; Allen & Densmore, 2000; Densmore et al., 2007). Climate appears to have a dominant control in determining alluvial fan sequence stratigraphy, including the distribution of debris-flow, sheetflood and channelized fluvial deposits and fan aggradation–dissection intervals (Bull, 1991; Harvey & Wells, 1994; Harvey, 2004). Early studies on alluvial fans from the southwest USA emphasized the role of catchment lithology on alluvial fan morphology (Bull, 1964, 1991; Hooke & Rohrer, 1977) and sequence stratigraphy (Blair, 1999). However, these interpretations were questioned on the basis of spatial
variability in tectonic activity, which appeared to exhibit a more dominant control on fan geometry (Whipple & Taylor, 1996; Allen & Hovius, 1998). Additionally, the presence of both debris- and stream-flow deposits in individual fans (e.g. Harvey et al., 1999), and debris-flow-dominated fans derived from lithologically distinct catchments (P.A. Allen, pers. comm., 2007), suggests that source catchment lithology alone plays a minimal role in dictating fan stratigraphy. Fanhead aggradation–dissection intervals have also been explained by complex internal responses resulting from the ‘tininnabulation’ of a single perturbation to the fan-catchment system (Humphrey & Heller, 1995), thus complicating the assignment of alluvial sequences to distinct tectonic and climatic events. Additional studies of alluvial fan systems, including chronologic studies, are required both to provide additional insight into the interplay between tectonic, climatic and depositional processes and to assess how landscapes may respond to future tectonism and climate change.

This study focuses on alluvial fans deposited adjacent to the Flinders Ranges of south-central Australia. Although the Australian continent is widely regarded as one of the oldest, flattest, slowest-eroding and tectonically quiescent continents on Earth (T. Widale & Campbell, 2005), the Flinders Ranges are seismically active (Greenhalgh et al., 1994), and contain large areas of relatively high relief and geomorphically youthful terrain (Sandiford, 2003; CElerier et al., 2005; Quigley et al., 2006, 2007b). The coincidence of concentrated historical seismicity, abundant neotectonic structures (Sandiford, 2003; CElerier et al., 2005; Quigley et al., 2006) and dramatic landscape responses to late Quaternary climate change (Williams et al., 2001) imply that Plio–Quaternary alluvial fan sequences are likely to record the impacts of both tectonism and climate change within the region. In order to evaluate the extent to which these processes governed the geomorphic evolution of the modern landscape, we conducted stratigraphic and chronometric studies of the Wilkattana Fans. These results are combined with previous investigations of the fans (Williams, 1973; Quigley et al., 2006), range-bounding faults (Quigley et al., 2006) and catchments (Quigley et al., 2007a) that provided quantitative tectonic uplift and erosion rate constraints. Our results indicate that tectonism exerted a first-order control on long-term sedimentation rates whereas climatic processes exerted first-order control on sedimentary facies distributions and on the timing of individual sedimentation events. The surface response of south-central Australia to neotectonic activity is thus partially reflected in the geometry and extent of Plio–Quaternary alluvial fan sequences.

**GEOLOGIC SETTING**

**Flinders Ranges**

The Flinders Ranges form part of a north–south trending, rugged upland system extending more than 600 km inland from the southern coast of South Australia to the Lake Eyre Basin (Fig. 1). The ranges contain some of the most topographically rugged terrain in Australia, with local relief exceeding ~600 m and highest elevations of ~1100 m above sea level (a.s.l.). The ranges are flanked by large regions of anomalously low topography (<0–50 m a.s.l.), including internally draining playa lake basins (e.g. Lakes Frome, Eyre and Torrens), a large externally draining continental basin (Murray Basin) and shallow marine gulfs (Spencers Gulf, St. Vincent’s Gulf). The intervening region between Lake Torrens and the Spencer Gulf consists of a discontinuous series of salt pans (Fig. 1).

The bedrock geology of the Flinders Ranges consists of a 5–12-km-thick package of Neoproterozoic to Cambrian rift sediments with minor volcanics (Fig. 2) (Dalgarno et al., 1968) underlain by Palaeoproterozoic metasedimentary and igneous rocks and Mesoproterozoic intrusives (Stevens & Corbett, 1993). These rocks were strongly deformed during the early Palaeozoic into a series of folds that are reflected in the distinctive strike-ridge-dominated topography of the region. Much of the middle to late Palaeozoic was characterized by tectonic quiescence punctuated by mild thermal perturbations associated with the late Palaeozoic Alice Springs Orogeny (Gibson & Stiwe, 2000; McLaren et al., 2002). The region was reduced to a near peneplain in the Mesozoic followed by intermittent periods of fluvial to lacustrine deposition in the Cretaceous, Eocene and Miocene. A transition from low-energy fluvial and lacustrine sedimentation to high-energy gravels and fluvial-lacustrine deposition occurred on the flanks of the ranges in the late Miocene or early Pliocene and has continued to present.

Some workers have suggested that the modern topography of the region was established in the early Cenozoic (e.g. Vevers & Conaghan, 1984). However, other workers have interpreted the transition from low- to high-energy sedimentation in range-bounding sequences to indicate the uplift of the ranges initiated in the late Miocene or Pliocene (Callen & Tedford, 1976). Regionally uplifted and deformed Miocene and Pliocene sedimentary sequences add credence to the hypothesis that a significant component of the present topography relates to post-Miocene tectonism (Alley & Benbow, 1995; Sandiford, 2003). This hypothesis is also supported by the presence of reverse faults that have uplifted the ranges relative to bounding Plio–Quaternary alluvial fan sequences (Sprigg, 1945; Williams, 1973; May & Bourman, 1984; Bourman & Lindsay, 1989; Lemon & McGowran, 1989; Belperio, 1995; Sandiford, 2003; CElerier et al., 2005; Quigley et al., 2006, 2007b). From such features, Sandiford (2003) and Quigley et al. (2006) inferred as much as 30–50% of the present maximum topographic relief between summit surfaces in the ranges and adjacent piedmonts (~800–1000 m) have developed since ~5 Ma.

The spatial distribution and geometry of Plio–Quaternary alluvial fans bounding the Flinders Ranges is highly variable. On the western flank of the ranges, steep alluvial fans with thick depositional sequences have aggraded along steep, linear portions of the range front between Adelaide and the central Flinders Ranges, where young fault activity has been identified (Fig. 1) (Williams, 1973;
Tectonic and climatic controls on sedimentation

May & Bourman, 1984; Bourman & Lindsay, 1989; Lemon & McGowran, 1989; Belperio, 1995; Sandiford, 2003; Quigley & al. 2006). In contrast, alluvial fans with lower gradients and volumes are present in regions with more subdued basement topography and no clearly delineated neotectonic faults, such as the Parachilna area in the central ranges (Fig. 1) (Dalgarno & Johnson, 1966). Gravity surveys suggest that the basement–alluvium interface beneath the steep fans is locally >100 m beneath the surface and slopes gently towards the ranges close to the range front (Preiss & Faulkner, 1984) suggesting flexural control of subsidence of the basin floor (Fig. 3). The basement beneath lower gradient fans commonly reaches the surface outboard of the range front, indicating a shallow basement–alluvium interface. These relationships suggest that neotectonic faulting has exerted a first-order control on the geometry and volume of sedimentary sequences along the front of the western Flinders Ranges.

On the eastern flank of the ranges, Plio–Quaternary fans are commonly uplifted and incised proximal to the range front (Coats, 1973; Sandiford, 2003) with Quaternary alluvial sedimentation centred further outboard towards the basin depocentres. The basement–alluvium interface beneath these fans is commonly shallow and dips gently away from the ranges (Célérier et al., 2005), distinct from the geometry of this interface beneath the western range front fans (Fig. 3c). Célérier et al. (2005) attributed this geometry to low-amplitude (~200–500 m), long-wavelength (~200 km) lithospheric buckling. Importantly, qualitative regional observations from the margins of the Flinders Ranges suggest that differences in alluvial fan geometries relate to differences in the magnitude and style of neotectonic deformation.

In addition to the record of neotectonic activity provided by fault exposures, the Flinders Ranges are historically one of the most seismically active regions in Australia (Fig. 1), with hundreds of small earthquakes recorded.

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Fig. 1. Shaded digital elevation map of south-central Australia including the Flinders Ranges. Distribution of historical seismicity overlaps with present topographic expression of the ranges, as shown by correspondence between historical earthquake epicentres and topography. Bold arrows denote location of Plio–Quaternary fault scarps and/or steep, linear range fronts along the western side of the Flinders Ranges. These regions also contain voluminous, steep alluvial fans. Location of Figs 2 and 3a section as indicated.
yearly and five magnitude > 5 earthquakes recorded in the past century (Greenhalgh et al., 1994). Approximately east—west-oriented maximum compressive stress orientations derived from focal-plane solutions of historical earthquakes (Clark & Leonard, 2003) are consistent with inferred palaeo-stress orientations determined from Plio-Quaternary faults, indicating that the modern compressional tectonic regime has been in place for at least ~5 Myr (Sandiford, 2003; Quigley et al., 2006) and that the tectonic forces that influenced Plio-Quaternary sedimentation patterns adjacent to the ranges are still active.

Pliocene to Recent deformation appears to reflect increasing stress levels within the Indo-Australian Plate due to increased plate boundary forcing from collision zones with the neighbouring Pacific and Asian plates (Coblentz et al., 1995, 1998; Sandiford, 2003; Sandiford et al., 2004).

Wilkatana area

The Wilkatana area is located within the central Flinders Ranges approximately 40 km north of Port Augusta, South Australia (Fig. 1). The catchments encompass an area...
Fig. 3. (a) E–W topographic cross-section across the central Flinders Ranges. Location of section shown in Fig. 1. Length of section = 275 km. (b) Schematic cross-section of the western range front, showing geometry of the basement–alluvium interface. Base of fans dips gently towards ranges close to range front, indicative of flexural subsidence in response to loading. (c) Schematic cross-section of the eastern range front. Basement–alluvium interface dips gently away from range front, a geometry that Célier et al. (2005) attribute to long-wavelength flexural buckling of the lithosphere in the eastern Flinders Ranges. (d) ASTER satellite image and underlying DEM of the Wilkatana area, showing steep range front topography and voluminous and steep Wilkatana alluvial fans (e)–(g) Geologic and topographic cross-sections of the Wilkatana fans, showing longitudinal fan profiles and estimated thickness of Plio–Quaternary sediment. Constraints on subsurface fan geometry from boreholes and gravity profile (Preiss & Faulkner, 1984).
of $\sim 65 \text{ km}^2$ and locally exhibit as much as $\sim 600 \text{ m}$ of relief between summit surfaces and valley floors. The morphology of the ranges reflects the variable properties of the underlying bedrock. The western sections of the Wilkatana catchments are composed of resistant quartzite and sandstone ridges (Fig. 2) lined with zones of recent rock failure and active scree slopes, implying many hillslopes are at critical angles. The eastern portions of the catchments are composed of dolomite and shale sequences, resulting in broader valley forms and more-rounded lower-relief hillslopes. Superimposed on these lithologically controlled landforms is a general pattern of broader, u-shaped valley systems steeply incised by narrow v-shaped valleys.

The Wilkatana Fans are some of the largest and best-developed alluvial fans in Australia (Williams, 1973), encompassing an area of $>100 \text{ km}^2$. The fans coalesce westward from the Wilkatana range front, where they exit source catchments at elevations of $\leq 290 \text{ m a.s.l.}$ to the Lake Torrens Basin, where they merge with fine-grained alluvial and dune deposits at elevations of $20-30 \text{ m a.s.l.}$ (Fig. 2).

The high-standing western range front flanking the Wilkatana Catchments (Fig. 3) forms one of the steepest and most linear mountain fronts in the Flinders Ranges, with hillslopes locally $>60^\circ$. Elevations of Emeroo Ridge (Fig. 3) decrease southward from $\sim 600 \text{ m a.s.l.}$ between the North and South Wilkatana Catchments to $<400 \text{ m a.s.l.}$ at Depot Creek. Numerous landslide scars and scree slopes are present along the range front and coarse-grained accumulations of poorly sorted scree and talus breccias occur at the base of the front over its entire length (Williams, 1973). These observations suggest that much of the range front is at the angle of repose.

**LATE QUATERNARY FAULTING IN THE WILKATANA AREA**

The Wilkatana range front is defined by a network of east-dipping reverse faults that have displaced the Neoproterozoic bedrock over the adjacent alluvial fan sequences (Fig. 4). The Wilkatana Fault (Williams, 1973; Quigley et al., 2006) is clearly exposed in the incised apaxes of the North and South Wilkatana Fans and is also exposed as a steep to slightly overhanging ridge along the range front between North Wilkatana and Depot Creek (Figs 2 and 3). The fault strikes NNW and varies in dip from 46 to 80° along strike. Quigley et al. (2006) estimated a minimum strike-length of $\sim 13.8 \text{ km}$ from distances between clearly delineated fault exposures. At the incised apex of the North Wilkatana Fan, Emeroo Quartzite has been thrust more than 8 m vertically over adjacent late Paleozoic alluvial sequences (Fig. 4) (Quigley et al., 2006). Fault striations on the fault plane indicate reverse left-lateral displacement. The faulted footwall deposits consist of talus breccias and debris flows that yielded optically stimulated luminescence (OSL) ages of $67 \pm 6$ and $56 \pm 6 \text{ ka}$ overlain by conglomerate that yielded an optical age of $32 \pm 2 \text{ ka}$ (Quigley et al., 2006). Both these faulted footwall sediments and the bedrock hangingwall are blanketed by conglomerate that yielded an optical age of $29 \pm 2 \text{ ka}$. Quigley et al. (2006) interpreted these field-chronologic relationships to indicate at least two major surface rupturing events at this locality, given that the $\sim 15 \text{ m}$ of fault offset parallel to fault striations is highly unlikely to have been generated in a single event. The most recent event is constrained to $ca. 32-29 \text{ ka}$ and associated with a fault displacement of $\sim 4 \text{ m}$, whereas the older event(s) is constrained to $ca. 56-32 \text{ ka}$ and associated with a total fault displacement of $\sim 8-11 \text{ m}$ (Quigley et al., 2006).

Approximately 20 m upstream of this location, another segment of the Wilkatana Fault has generated a 4 m high fluvial knickpoint where hangingwall quartzite on the upstream side of the fault has been thrust over the downstream quartzite (Fig. 4). Quigley et al. (2006) estimated the timing of this movement at $ca. 12 \text{ ka}$ based on inferred knickpoint retreat rates, and concluded that more than 12 m of cumulative vertical hangingwall uplift occurred across this segment of the Wilkatana Fault between $ca. 67-12 \text{ ka}$.

The Depot Creek Fault is located beneath the Depot Creek Fan roughly 1 km west of the range front (Figs 2 and 3), where it was identified on the basis of drilling and gravity surveys (Preiss & Faulkner, 1984). The fault has no present surface expression and is blanketed by Paleozoic alluvium. The stratigraphic section overlying the inferred position of the Depot Creek Fault yielded an OSL age of $71 \pm 7 \text{ ka}$ (Table 1), implying that the Depot Creek Fault has remained inactive since that time (Quigley et al., 2006).

The coincidence of the voluminous Wilkatana Fans with the recently active Wilkatana Fault suggests a casual
Table 1. Compiled 14C and optically stimulated luminescence chronology from the Wilkatana Fans

<table>
<thead>
<tr>
<th>Formation or paleosol</th>
<th>Locality</th>
<th>Sample material</th>
<th>Age</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>14C dates</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Eyre Gravel Member 2</td>
<td>Depot Creek</td>
<td>Detrital charcoal</td>
<td>1.8 ± 0.1</td>
<td>Williams (1973)</td>
</tr>
<tr>
<td>Eyre Gravel Member 2</td>
<td>North Wilkatana</td>
<td>Detrital charcoal</td>
<td>1.8 ± 0.4</td>
<td>Williams (1973)</td>
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<tr>
<td>Eyre Gravel Member 2</td>
<td>North Wilkatana</td>
<td>Detrital charcoal</td>
<td>3.1 ± 0.2</td>
<td>Williams (1973)</td>
</tr>
<tr>
<td>Eyre Gravel Member 2</td>
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<td>Detrital charcoal</td>
<td>3.7 ± 0.1</td>
<td>Williams (1973)</td>
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<tr>
<td>Eyre Gravel Member 1</td>
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<td>Detrital charcoal</td>
<td>5.9 ± 0.1</td>
<td>Williams (1973)</td>
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<tr>
<td>Wilkatana palaeosol</td>
<td>Depot Creek</td>
<td>Carbonate nodules</td>
<td>36.1 ± 1.4</td>
<td>Williams (1973)</td>
</tr>
<tr>
<td>Wilkatana paleosol</td>
<td>Dept Creek</td>
<td>Carbonate nodules</td>
<td>39.2 ± 3.6</td>
<td>Williams (1973)</td>
</tr>
<tr>
<td>Wilkatana paleosol</td>
<td>Dept Creek</td>
<td>Carbonate nodules</td>
<td>39.9 ± 1.8</td>
<td>Williams (1973)</td>
</tr>
<tr>
<td>Wilkatana paleosol</td>
<td>Dept Creek</td>
<td>Whole-soil carbonate</td>
<td>36.9 ± 1.3</td>
<td>Williams (1973)</td>
</tr>
<tr>
<td>Wilkatana paleosol</td>
<td>North Wilkatana</td>
<td>Whole-soil carbonate</td>
<td>30.3 ± 0.6</td>
<td>Williams (1973)</td>
</tr>
<tr>
<td>Pooraka Formation debris flows</td>
<td>North Wilkatana</td>
<td>Carbonized wood</td>
<td>&gt; 42.6</td>
<td>Williams (1973)</td>
</tr>
</tbody>
</table>

**Optically stimulated luminescence dates**

<table>
<thead>
<tr>
<th>Localities and dates</th>
<th>Sample material</th>
<th>Age (ka)</th>
<th>Reference</th>
</tr>
</thead>
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<tr>
<td>Pooraka Formation debris flows</td>
<td>Depot Creek</td>
<td>Quartz</td>
<td>71 ± 7</td>
</tr>
<tr>
<td>Pooraka Formation debris flows</td>
<td>North Wilkatana</td>
<td>Quartz</td>
<td>67 ± 6</td>
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<tr>
<td>Pooraka Formation debris flows</td>
<td>North Wilkatana</td>
<td>Quartz</td>
<td>56 ± 6</td>
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<tr>
<td>Pooraka Formation Conglomerate</td>
<td>North Wilkatana</td>
<td>Quartz</td>
<td>32 ± 2</td>
</tr>
<tr>
<td>Pooraka Formation Conglomerate</td>
<td>North Wilkatana</td>
<td>Quartz</td>
<td>29 ± 2</td>
</tr>
</tbody>
</table>

*Faulted.
†Unfaulted.

A relationship between youthful fault activity and fan building. Quigley et al. (2007a) suggested that late Quaternary uplift along the Wilkatana Fault led to an increase in catchment erosion rates due to (a) seismic shaking and liberation of hillslope material via mass wasting, including landsliding, (b) oversteepening range-front hillslopes via uplift relative to the bounding basin and (c) increasing catchment hillslope gradients by generating knickpoints in stream profiles that rapidly propagated upstream through their catchments. These results provide quantitative evidence that localized late Quaternary tectonism led to an increase in bedrock and catchment-averaged erosion rates over a long-term (10 000–100 000 years) time-scale. However, the extent to which tectonic events influenced facies distributions and the timing of aggradation–dissection intervals in the fans were not discussed. The late Quaternary stratigraphy of the Wilkatana Fans, as relevant to distinguishing tectonic vs. climatic processes, is considered below.

**WILKATANA ALLUVIAL FANS**

The Wilkatana Fans have been variably incised to depths of ≤ 10 m by modern and palaeo-stream channels, exposing a late Quaternary sedimentary sequence consisting of five distinct stratigraphic units. The lowestmost unit (Pooraka Formation; Williams, 1973) consists of a series of mudstones, clayey silts and sands with volumetrically minor beds of clast-supported river gravels (Fig. 5). The mudstones, silts and sands contain coarse, poorly sorted, subangular quartzite and feldspathic sandstone clasts and are interpreted as debris flow deposits (Williams, 1973; Quigley et al., 2006). These deposits pass laterally into talus breccias at the base of the range front (Williams, 1973). Quigley et al. (2006) obtained OSL ages of ca. 71–56 ka from intercalated alluvial gravel lenses within debris flows at the apex of the North Wilkatana and Depot Creek Fans (Table 1). Elsewhere in the region, the Pooraka Formation yields thermoluminescence ages as old as 116 ± 6 ka (Bourman et al., 1997).

The Pooraka Formation is over lain by a dark-red coloured, calcareous, 1–2-m-thick palaeosol designated as the Wilkatana Palaeosol (Williams, 1973). Carbonate nodule and whole-soil carbonate samples collected from the Wilkatana Palaeosol at North Wilkatana and Depot Creek yield 14C ages clustering between 25 and 35 14C kyr BP (Williams, 1973), calibrated to ca. 30–40 cal kyr BP (Table 1). The Wilkatana Palaeosol is variably overlain by a series of interbedded, clast-supported, coarse-grained fluvial conglomerates (Pooraka Conglomerate; Fig. 5a). The conglomerates contain subrounded to rounded, lenticular, pebble- to boulder-sized quartzite, sandstone, limestone and shale clasts within a sandy matrix. Deposits occur in highly channelized forms, implying that deposition of this unit occurred primarily within a network of braided streams.

Near the apex of the North Wilkatana Fan, these conglomerates directly overlie debris flows (Fig. 4). Two OSL ages of 31 ± 2 and 29 ± 2 ka were obtained from conglomeritic beds at this location (Table 1) (Quigley et al., 2006).

On more distal reaches of the alluvial fans, the Wilkatana Palaeosol and Pooraka Conglomerate are overlain by loessic clayey silt deposits. An ~2.5-m-thick section through these deposits reveals a series of five incipient palaeosols interspersed with aeolian silt and pelletal clay (Fig. 5b). Palaeosols indicate soil-forming intervals and aeolian deposits indicate dune building. Local fluvial reworking of the aeolian deposits is indicated by the presence of laterally discontinuous alluvial gravel lenses of up to 0.4 m thickness. We correlate this sequence with the Lake Torrens Formation of Williams.
The Wilkatana Fans have been deeply incised and partially re-filled by a series of conglomeratic terrace deposits (Eyre Gravel; Fig. 5c and d). These deposits are arranged in a braided network of abandoned channels and terraces and are lithologically equivalent to the modern deposits composing the Wilkatana stream beds, containing a mixture of subrounded boulder- to sand-sized material derived from throughout the catchments. The depth of dissection and height of fan terraces decrease basinward until they pass laterally into modern floodout deposits (Williams, 1973). Williams’ (1973) chronology was correlated with the T2 to T5 Eyre Gravel terraces identified in the North Wilkatana Fan. As many as six distinct terraces were identified in the apex of the North Wilkatana Fan (Figs 5d and 6). Williams’ (1973) chronology was correlated with the T2 to T5 terraces (Fig. 6).

Stratigraphic and facies relations within the Wilkatana Fans indicate a progressive change in depositional regime from (1) debris flow-dominated sedimentation and alluvial fan building (≥ ca. 56 ka), to (2) soil formation and landscape stability (ca. 40–30 ka), to (3) high-energy, braided stream-dominated, conglomeritic sedimentation (≤ ca. 32–29 ka), to (4) low-energy fluvial sedimentation and aeolian activity, to (5) high-energy, braided stream-dominated, conglomeritic sedimentation (ca. 6 ka to Recent).

The overall transition from debris flow to conglomeritic sedimentation is interpreted to indicate a gradual change in the composition in the source region from a soil-mantled to bedrock-dominated landscape (e.g. Bull, 1973) on the basis of similar lithological characteristics and stratigraphic position.

Fig. 5. Field photographs of the stratigraphic units composing the Wilkatana alluvial fans. (a) Pooraka Formation debris flow unit overlain by the Pooraka Conglomerate in the North Wilkatana Fan (b) Fine-grained fluvial and aeolian deposits and intercalated palaeosols. Location of OSL sample sites as indicated (c) Conglomeritic Eyre Gravel channel incised into Pooraka Formation (d) T2–T5 Eyre Gravel terraces identified in the North Wilkatana Fan. OSL, optically stimulated luminescence.
This transition pre-dated the ca. 30 ka event along the Wilkatana Fault. However, conglomerates continued to aggrade after ca. 30 ka, implying that changes in the facies of range-front sedimentary deposits were ‘out-of-synch’ with the discrete tectonic events dated by Quigley et al. (2006). Notably, this transition occurred within the Depot Creek Fan despite an apparent absence of post ca. 7 ka tectonic activity there. In addition, the formation of cut-and-fill terraces from ca. 6 ka to Recent significantly post-dates the most recent surface-rupturing event along the Wilkatana Fault. Together, these observations suggest that processes other than those associated with discrete tectonic uplift events led to the observed age and facies distributions in the Wilkatana Fans. OSL ages were obtained from the Lake Torrens Formation and Eyre Gravel sections. Sample WF09 was collected from the lowermost loessic clayey silt layer beneath the uppermost palaeosol in the Wilkatana Fault. However, conglomerates continued to aggrade after ca. 30 ka, implying that changes in the facies of range-front sedimentary deposits were ‘out-of-synch’ with the discrete tectonic events dated by Quigley et al. (2006). Notably, this transition occurred within the Depot Creek Fan despite an apparent absence of post ca. 7 ka tectonic activity there. In addition, the formation of cut-and-fill terraces from ca. 6 ka to Recent significantly post-dates the most recent surface-rupturing event along the Wilkatana Fault. Together, these observations suggest that processes other than those associated with discrete tectonic uplift events led to the observed age and facies distributions in the Wilkatana Fans. OSL ages were obtained from the Lake Torrens Formation and Eyre Gravel in order to place additional temporal constraints on the sedimentation history of the Wilkatana Fans and gain greater clarity into the origin of these distributions.

**OSL CHRONOLOGY OF FAN SEQUENCES**

**Theory**

OSL is now commonly used for dating sedimentary deposits from a variety of aeolian and fluvial environments (e.g. Stokes, 1999; Olley et al., 2004). When quartz grains within a sedimentary sequence are buried, they begin to accumulate a trapped-charge population that increases in a measurable and predictable way in response to the ionizing radiation dose to which the grains are exposed (Aitken, 1998). Exposure to sunlight releases the light-sensitive trapped charge and resets the OSL signal. This process is commonly referred to as ‘zeroing’ or ‘bleaching’. The time lapsed since quartz grains were last exposed to sunlight can be determined by measuring the OSL signal from a sample, determining the equivalent radioactive dose ($D_e$) that this represents and estimating the rate of exposure of the grains to ionizing radiation since they were buried (‘dose rate’, $D_t$) (Aitken, 1998). From these parameters, the burial age of well-bleached grains can be determined (Burial age = $D_t/D_e$).

The accuracy and precision of OSL ages are partially controlled by the contribution of unbleached grains within a sample (Olley et al., 1999; Murray & Olley, 2002) and this influences which depositional environments will yield the most reliable results. Sedimentary deposits that are likely to have had adequate solar exposure and effective bleaching before deposition and burial are preferred targets for OSL dating; most notably aeolian sequences. In other settings such as alluvial fans, where transport and deposition times may be rapid, the potential for incomplete bleaching is increased. OSL dating of alluvial deposits has recently been aided by the emergence of new methodologies allowing the effective dating of single grains of quartz, which provide information on the degree of partial bleaching within a sample (Olley et al., 2004). This technique was used previously to determine OSL ages of alluvial sequences within the study area and in other parts of the Flinders Ranges (Quigley et al., 2006).

**Methodology**

In this study, we used single-grain OSL dating to determine the depositional age of two samples from the Lake Torrens Formation (Fig. 3b) and one sample from the Eyre Gravel (Fig. 5c). Samples were collected by driving 50-mm-diameter opaque stainless-steel tubes into cleaned sediments. Sample WF09 was collected from a grey loessic clayey silt layer beneath the uppermost palaeosol in the Lake Torrens Formation. Sample WF10 was collected from the lowermost loessic clayey silt layer at this site, which overlies the Wilkatana Palaeosol and Pooraka Formation. Sample WF02 was collected from the base of a ~2.5-m-thick channelized alluvial terrace disconformably inset into the Pooraka Formation near the apex of the North Wilkatana Fan. Detailed mapping of the terrace sequences indicate that the sample was obtained from a T4 Eyre Gravel terrace (Fig. 6).

Sediments were processed under subdued red light, with the 90–125 μm quartz fraction extracted for dating using standard procedures (e.g. Galbraith et al., 1999). A single-aliquot regenerative-dose protocol was used to calculate $D_e$ (Murray & Roberts, 1998; Galbraith et al., 1999; Murray & Wintle, 2000). Approximately 100 aliquots per sample, each composed of single grains of quartz, were pre-heated at 240 °C for 10 s and optically stimulated for 2 s at 125 °C by green (532 nm) light from a solid-state laser beam attached to an automated Risø TL-DA-15 apparatus. Ultraviolet luminescence was detected using a photomultiplier tube with a 7.5 mm U-340 filter. Samples were then given applied doses using a calibrated $^{85}Sr$/$^{90}Y$ β-source and re-stimulated to record their regenerative OSL signals. OSL sensitivity changes in the quartz crystals between the natural and regenerative cycles were monitored after each optical stimulation using test doses of 10 Gy following a 160 °C cut heat.

Output from the Risø apparatus was analysed using Analyst version 2.12 software (Duller, 1999). OSL data were corrected for any sensitivity changes and dose-response curves constructed using six regenerative dose points. $D_e$ values were obtained from the intercept of the regenerates dose-response curve with the natural luminescence intensity. $D_e$ values for aliquots in each sample typically displayed normal frequency distributions, suggesting effective resetting of the luminescent traps before deposition. Optical ages were thus derived from weighted mean $D_e$ using the central age model of Galbraith et al. (1999) and is shown in Table 2.

K, U and Th concentrations were measured using instrumental neutron activation analysis (INAA) by Becquerel Laboratories, Menai, New South Wales, and converted to beta dose rates using the conversion factors of Adamiec & Aitken (1998). A β attenuation factor of 0.93 ± 0.03 (Mejdahl, 1979) was assumed. γ dose rates were

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measured in the field using a portable spectrometer and converted to dry values by oven-drying sediment from the sample location. Internal dose rates were also assumed to be 0.03 $\mu$Gy ka$^{-1}$ based on previous measurements of Australian quartz (e.g. Thorne et al., 1999; Bowler et al., 2003).

Cosmic-ray dose rates were determined from established equations (Prescott & Hutton, 1994), allowing for sample depth, sediment density and site altitude and latitude. Present-day field-moisture contents of the sediments were considered broadly representative of long-term averages and used to correct attenuation of $\beta$ and $\gamma$ rays by water (Aitken, 1998).

Results

Optical ages of 18 $\pm$ 1 and 25 $\pm$ 2 ka were obtained from the uppermost and lowermost loess layers of the Lake Torrens Formation, respectively (Fig. 5b; Table 2), indicating that aeolian and low-energy fluvial deposition occurred in the Wilkatana region during the last glacial maximum (LGM, ca. 24–18 ka; Bard, 1999). WF09 dates one of the last major phases of landscape instability in the region associated with deflation of fine-grained deposits from the Lake Torrens Basin. WF10 constrains the initiation of aeolian activity subsequent to deposition of the Wilkatana Palaeosol. The Lake Torrens Formation section preserved on the South Wilkatana Fan may correlate with seif dune deposits from the Lake Torrens Basin (Williams, 1973).

The Eyre Gravel T4 terrace sample yielded an optical age of 4.2 $\pm$ 0.5 ka (Table 2, Fig. 6). This age is within error of the calibrated $^{14}$C age of 3.7 $\pm$ 0.1 cal kyr BP obtained by Williams (1973). The age of the T4 terrace is therefore interpreted as 4.2 $\pm$ 0.6 ka, consistent with the interpretations that the higher elevation T5 terrace is older and the lower elevation T2 and T3 terraces are younger (Fig. 6). Compilation of OSL and $^{14}$C terrace ages (Fig. 6) suggests that the most recent depositional mode of episodic cut-and-fill sedimentation persisted from deposition of the T6 terrace sometime before ca. 6 ka until the formation of the T1 terrace sometime after ca. 2 ka. Punctuated depositional events occurred at 59 $\pm$ 0.1 ka (T4), 4.2 $\pm$ 0.6 ka (T3), 31 $\pm$ 0.2 ka (T3) and 1.8 $\pm$ 0.4 ka (T2) (Williams, 1973; Table 1).

DISCUSSION

Climatic influences on fan sequence stratigraphy

The Wilkatana Fans provide a record of changing depositional facies and fluctuating intervals between sediment accumulation and erosion throughout the late Pleistocene and Holocene. These changes occurred at time intervals independent of discrete tectonic events, implying that the
Table 2. New optically stimulated luminescence data and optical age estimates from the Wilkatana Fans

<table>
<thead>
<tr>
<th>Locality</th>
<th>Water content (%)</th>
<th>Depth (m)</th>
<th>Water 4</th>
<th>Depth 4</th>
<th>K (%)</th>
<th>Th (ppm)</th>
<th>U (ppm)</th>
<th>Optical age (ka)</th>
<th>Equivalent dose (Gy ka⁻¹)</th>
</tr>
</thead>
<tbody>
<tr>
<td>WF02 Eyre Gravel</td>
<td>2 ± 1</td>
<td>2.5</td>
<td>213 ± 0.04</td>
<td>7.59 ± 0.06</td>
<td>0.04 ± 0.09</td>
<td>0.08 ± 0.08</td>
<td>0.15 ± 0.02</td>
<td>2.85 ± 0.09</td>
<td>12 ± 1.3</td>
</tr>
<tr>
<td>WF09 Lake Torrens</td>
<td>5 ± 1</td>
<td>1.64 ± 0.02</td>
<td>7.15 ± 0.06</td>
<td>1.37 ± 0.03</td>
<td>0.06 ± 0.01</td>
<td>0.15 ± 0.06</td>
<td>0.28 ± 0.05</td>
<td>2.30 ± 0.07</td>
<td>4 ± 1</td>
</tr>
<tr>
<td>WF10 Lake Torrens</td>
<td>5 ± 1</td>
<td>2.01 ± 0.02</td>
<td>8.09 ± 0.07</td>
<td>1.47 ± 0.03</td>
<td>2.0 ± 0.01</td>
<td>1.78 ± 0.06</td>
<td>0.92 ± 0.06</td>
<td>0.26 ± 0.02</td>
<td>2.77 ± 0.08</td>
</tr>
</tbody>
</table>

**Notes:**
- Bold equivalent sedimentation age estimates from the Wilkatana Fans.
- Estimated time-averaged moisture contents, based on measured field water values (% dry weight).
- Obtained by INAA (Resured Laboratories, Menai).
- Derived from INAA radionuclide concentration measurements using the conversion factors of Adamec and Aitken (1998), corrected for attenuation by water.
- Calculated using the equation of Prescott & Hutton (1994), based on sediment density, time-averaged depth and site latitude, longitude and altitude.
- Including a 2% systematic uncertainty associated with calibration of the laboratory γ-source.

Spatial–temporal distribution of range-front sedimentation and erosion was more likely governed by an aspect of climate. Deposition of the Pooraka Formation debris flows in the late Pleistocene suggests derivation from a source catchment composed primarily of fine-grained sediment with localized exposures of quartzite and sandstone bedrock. This material was sourced from a landscape markedly different from the contemporary bedrock landscape, which generates coarse conglomeratic sediment containing a mixture of bedrock clast types within modern stream channels. Debris flow deposits are interpreted to reflect sedimentation during episodic, high-magnitude flooding of a soil-mantled landscape. Such episodic events may have eventually removed sufficient material from source catchments to strip hillslopes of accumulated regolith, resulting in a bedrock landscape similar to present.

C isotopic ratios in fossil emu eggshells collected within the region suggest abundant monsoonal C₄ grasses from ca. 65 to 45 ka, interpreted to indicate significant climatic oscillations punctuated by episodic, high-magnitude rainfall events (Johnson et al., 1999). A general trend of increasing aridity occurred in the region in the late Quaternary (Bowler, 1976; Hesse et al., 2004). Frequent climatic oscillations and increasing aridity probably maintained a landscape where surface processes (i.e. soil production) could not keep pace with the soil-stripping events associated with floods. The oldest age of the conglomeratic alluvial facies (Pooraka Conglomerate) is interpreted to mark the time at which the transition from a soil-mantled to bedrock landscape was firmly established (ca. 30 ka), although the transition is likely to have occurred as early as the last debris flow deposit (ca. 56 ka). Similar transitions from debris flow to conglomeratic sedimentation are observed throughout Australia (Wasson, 1979) and in other arid to semi-arid settings of other continents (e.g. Bull, 1991; Harvey & Wells, 1994; Calvache et al., 1997), suggesting that the transition from soil mantled to bedrock-mantled landscapes may have reflected a widely distributed landscape response to global climate change.

The deposition of coarse sedimentary sequences from ca. 71 to 56 ka (Pooraka Formation), ca. 32 to 29 ka (Pooraka Conglomerate) and ca. 6 to 2 ka (Eyre Gravel) indicates the occurrence of episodic, high-discharge flood events capable of transporting coarse material over these time intervals. Conversely, palaeosol development from ca. 40 to 30 ka indicates a prolonged period of landscape stability and an absence of large flood events. The accumulation of finer-grained sedimentary sequences including aeolian material within the fans from ca. 25 to 18 ka also indicates low-stream discharges and low discharge variability during the LGM, consistent with studies from elsewhere in the Flinders Ranges (Williams et al., 2001). C isotope signatures of emu eggshells (Johnson et al., 1999) support both the interpretations of decreased rainfall variability during the LGM and increased stream discharge and variability in the mid-Holocene, implying the inferred climate-related changes were regional in extent.
The Eyre Gravel terraces within the Wilkatana Fans record punctuated high-stream discharge events superimposed on an overall pattern of fan dissection. This suggests a cycle whereby coarse material continually accumulates within catchment systems (as is evident in the modern environment; Fig. 7) and is episodically flushed to alluvial fan systems when the stream-power threshold required to transport bedload is breached. The Wilkatana creeks must transport this material in order to incise into bedrock. Holocene incision thus fundamentally depends on the recurrence of large-magnitude floods. Pre-Holocene tectonic uplift undoubtedly enhanced the ability of Wilkatana creeks to incise by maintaining steep downstream gradients and therefore increasing the stream power of these flood events. However, the timing of these sequences does not reflect tectonic events.

We suggest that the depositional ages of the Eyre Gravel cut-and-fill terraces provide a proxy for the temporal distribution of large-magnitude floods in the mid to late Holocene. This indicates a large flood-recurrence interval of one flood per 1370 ± 300 years between deposition of the T₃ and T₂ sequences. Such datasets might form the basis for future flood predictions, although additional mapping and chronology from other alluvial sequences in the region should be obtained to test this hypothesis.

Plio-Quaternary tectonics, regional sedimentation patterns and sea-level incursions

The sedimentary records preserved in alluvial fans adjacent to the Flinders – Mt Lofty Ranges provide insights into the interplay between Plio-Quaternary tectonics, subsidence and sedimentation patterns. As described above, steep, voluminous alluvial fans have accumulated adjacent to parts of the ranges that have been subjected to hangingwall uplift along reverse faults and related footwall flexural subsidence. Thin, more dissected alluvial fans have accumulated adjacent to parts of the ranges that appear to have been subjected to broader uplift expressed by long-wavelength lithospheric buckling (Calèrier et al., 2005). These relationships indicate that the modes of tectonism exerted a strong influence on the volume and morphology of alluvial fans throughout the region, primarily through an influence on accommodation space (Silva et al., 1992; Viseras et al., 2003).

The sedimentary basins adjacent to the Flinders – Mt Lofty Ranges also provide insight into the interplay between Plio-Quaternary tectonics, sedimentation and eustasy. Early Pliocene marine strandlines in the western Murray Basin (Fig. 1) are presently at elevations up to 120 m a.s.l., suggested to reflect Pliocene sea-level highstands of 40–50 m above present coupled with at least 80 m of regional tectonic uplift (Miranda, 2007). However, internally draining basins including Lake Torrens lack Cenozoic marine sediment (Johns, 1968), indicating that Pliocene marine incursions did not breach the topographic barriers between these basins and the ocean. Large regions of the modern topographic divide between Lake Torrens and the Spencer Gulf are below 40 m, implying that Pliocene sea-level highstands should have encroached into these low-lying regions if the present surface topography was static since the Pliocene. However, because this region does not contain marine sedimentation, we infer that the region between the Spencer Gulf and Torrens Basin, into which the Wilkatana alluvial fans have been deposited, has undergone mild Pliocene subsidence on the order of several tens of metres. The opposing vertical movements of the major basins flanking the Flin-
CONCLUSIONS

The Wilkatana Fans provide a record of the spatial–temporal distribution of alluvial fan building and associated facies changes in the late Quaternary. The well-constrained tectonic and climatic history of the area provides a robust context in which to interpret these records. Tectonic uplift increased sedimentary inputs into the Wilkatana Fans via increasing catchment gradient and relief, increasing catchment sediment input and increasing footwall ‘accommodation space’ in response to tectonically induced footwall basin flexural subsidence. The mode of tectonism exerted an influence in the volume and geometry of alluvial fans throughout the region. However, both facies changes and sediment aggradation–dissection cycles were out-of-sync with dated tectonic events, implying that an aspect of climate was responsible for their compositional and temporal distributions. Rapidly oscillating and increasingly arid late Pleistocene climates produced a landscape that was highly susceptible to regolith-stripping episodes from \( > \text{ca. 71 ka} \) to \( < \text{ca. 55 ka} \), as indicated by aggraded debris flow deposits. Progressive regolith erosion culminated with the transition to a bedrock landscape by \( \text{ca. 32 ka} \), as indicated by the deposition of conglomeratic units markedly distinct from earlier debris flow deposits. Lower total rainfall and rainfall variability at the LGM was reflected by low-energy fluvial sedimentation and aeolian deposition within the fans. Holocene cut-and-fill terraces mark the return of punctuated, high discharge flood events capable of transporting coarse material. The age of these sequences may be used as a proxy for large-magnitude flood recurrence in the mid–late Holocene and quite possibly to provide estimates of large flood recurrence in the future.

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REFERENCES


Tectonic and climatic controls on sedimentation


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