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 (Keefer, 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 palaeogeography 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; Denny, 1965; 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; 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

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variability in tectonic activity, which appeared to exhibit a more dominant control on fan geometry (Whipple & Traylor, 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 'tintinnabulation' 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 (Twidale & 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; Cèlérier et al., 2005; Quigley et al., 2006, 2007b). The coincidence of concentrated historical seismicity, abundant neotectonic structures (Sandiford, 2003; Cèlérier 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 of these processes governed the geomorphic evolution of the modern landscape, we conducted stratigraphic and chronometric studies of the Wilkatana 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. Vincents 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 & Stüwe, 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 fanglomerate 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. Veevers & 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; Cèlérier 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;
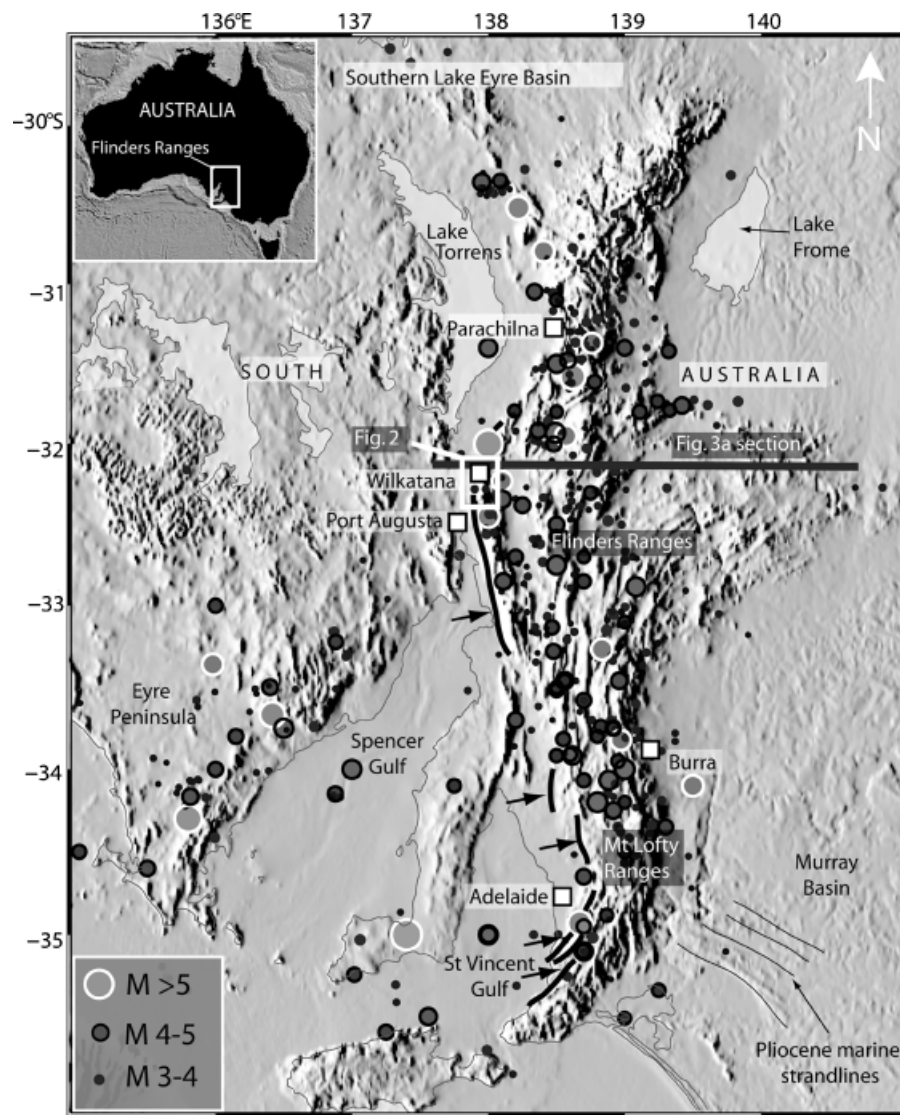
Fig. 1. Shaded digital elevation map of south-central Australia including the Flinders Ranges. Distribution of historical seismicity overlaps with present topographic expression of the ranges, as shown by correspondence between historical earthquake epicentres and topography. Bold arrows denote location 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.

May & Bourman, 1984; Bourman & Lindsay, 1989; Lemon & McGowran, 1989; Belperio, 1995; Sandiford, 2003; Quigley *et 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 flexurally controlled 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 (Cèlérier *et al.*, 2005), distinct from the geometry of this interface beneath the western range front fans (Fig. 3c). Cèlérier *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
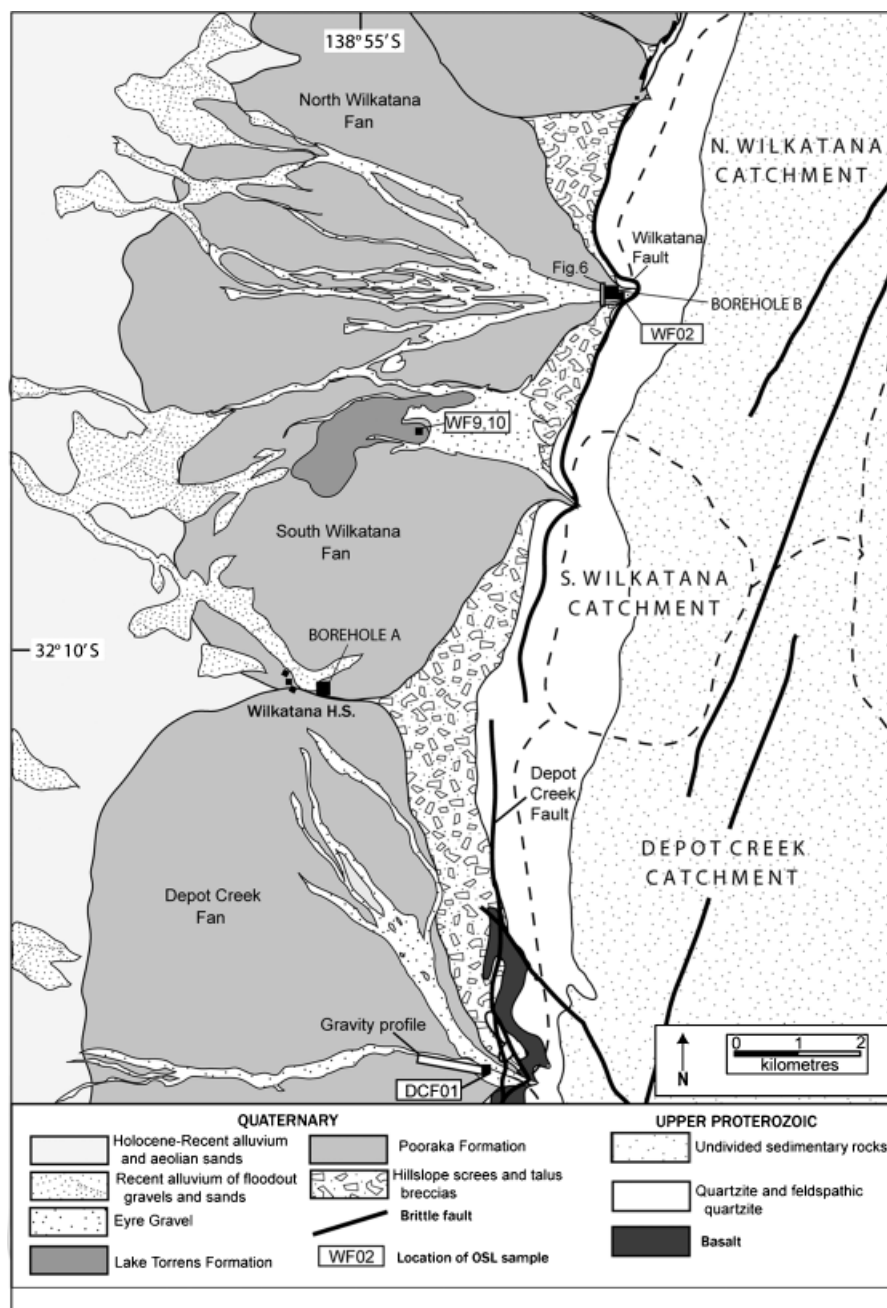
Fig. 2. Simplified geologic map of the Wilkatana alluvial fans and their bedrock source catchments, modified from Williams (1973), Preiss & Sweet (1966) and Dalgarno *et al.* (1968). Location of OSL sample sites, Fig. 3g gravity profile, and Fig. 6 boreholes and cross-sectional fan profile as indicated. Dashed lines denote catchment boundaries, determined from the position of intervening drainage divides. OSL, optically stimulated luminescence.

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
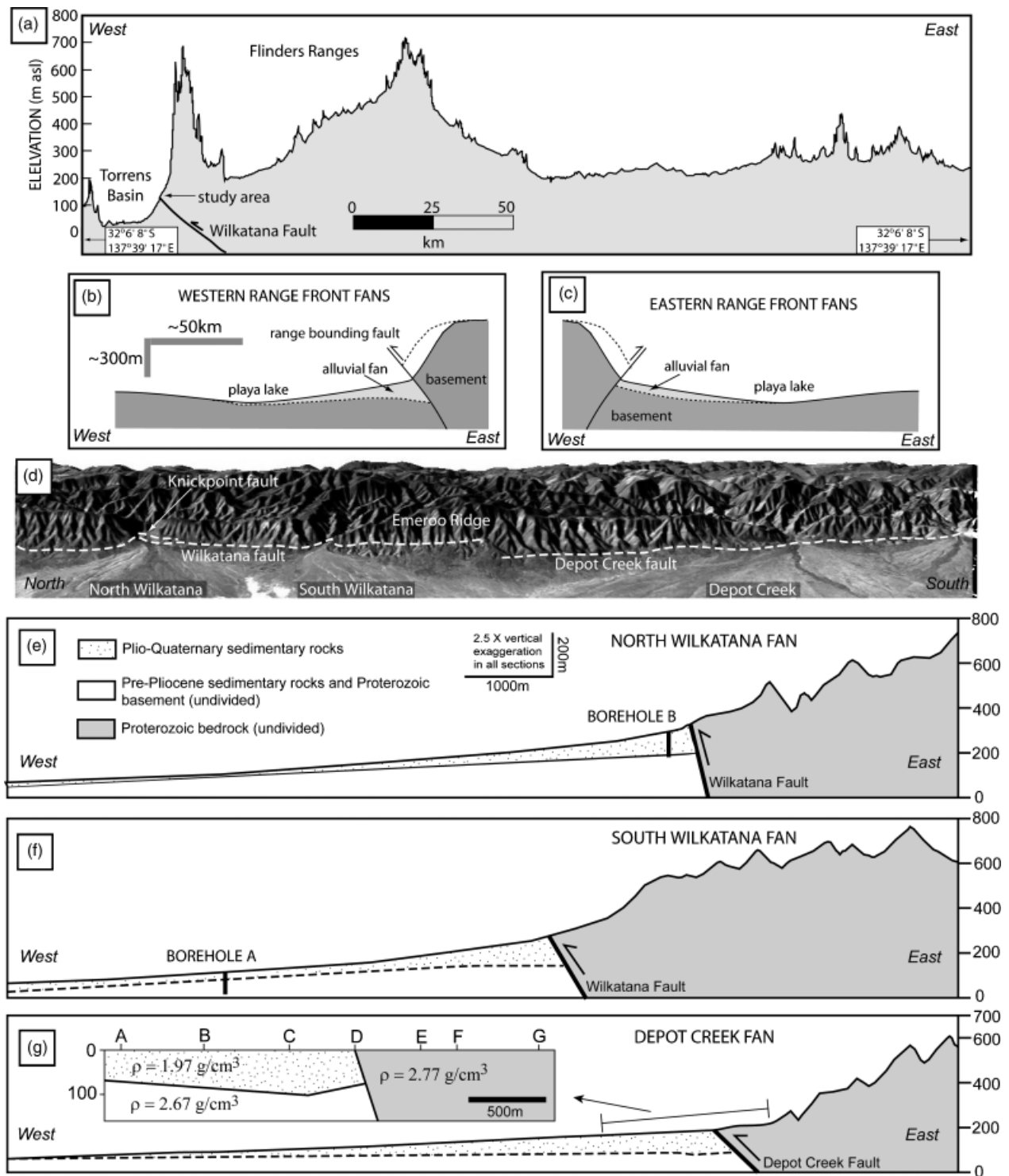
Fig. 3. (a) E–W topographic cross-section across the central Flinders Ranges. Location of section shown in Fig. 1. Length of section = 275 km. (b) Schematic cross-section of the western range front, showing geometry of the basement–alluvium interface. Base of fans dips gently towards ranges close to 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 Cèlérier *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 ∼65 km² and locally exhibit as much as ∼600 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 km². The fans coalesce westward from the Wilkatana range front, where they exit source catchments at elevations of ≤290 m a.s.l. to the Lake Torrens Basin, where they merge with fine-grained alluvial and dune deposits at elevations of 20–30 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°. Elevations of Emeroo Ridge (Fig. 3) decrease southward from ∼600 m a.s.l. between the North and South Wilkatana Catchments to <400 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 apexes 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 ∼13.8 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 Pleistocene 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 ± 6 and 56 ± 6 ka overlain by conglomerate that yielded an optical age of

Fig. 4. Field photograph of the Wilkatana Fault as exposed at the mouth of the North Wilkatana Catchment, from Quigley et al. (2006). Fault displaces Pooraka Fm debris flows (≥ 56 ka) and ∼32 ka Pooraka Fm Conglomerate but is draped by ∼29 ka Pooraka Fm Conglomerate.

32 ± 2 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 ± 2 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 ∼15 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 ka and associated with a fault displacement of ∼4 m, whereas the older event(s) is constrained to ca. 56–32 ka and associated with a total fault displacement of ∼8–11 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 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 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 Pleistocene alluvium. The stratigraphic section overlying the inferred position of the Depot Creek Fault yielded an OSL age of 71 ± 7 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 ^{14}C and optically stimulated luminescence chronology from the Wilkatana Fans

Formation or paleosol	Locality	Sample material	Age	Reference
[14]C dates			*Calibrated ^{14}C age* (cal kyr BP)	
Eyre Gravel Member 2	Depot Creek	Detrital charcoal	1.8 ± 0.1	Williams (1973)
Eyre Gravel Member 2	North Wilkatana	Detrital charcoal	1.8 ± 0.4	Williams (1973)
Eyre Gravel Member 2	North Wilkatana	Detrital charcoal	3.1 ± 0.2	Williams (1973)
Eyre Gravel Member 2	North Wilkatana	Detrital charcoal	3.7 ± 0.1	Williams (1973)
Eyre Gravel Member 1	Depot Creek	Detrital charcoal	5.9 ± 0.1	Williams (1973)
Wilkatana palaeosol	Depot Creek	Carbonate nodules	36.1 ± 1.4	Williams (1973)
Wilkatana paleosol	Depot Creek	Carbonate nodules	39.2 ± 3.6	Williams (1973)
Wilkatana palaeosol	Depot Creek	Carbonate nodules	39.9 ± 1.8	Williams (1973)
Wilkatana palaeosol	Depot Creek	Whole-soil carbonate	36.9 ± 1.3	Williams (1973)
Wilkatana palaeosol	North Wilkatana	Whole-soil carbonate	30.3 ± 0.6	Williams (1973)
Pooraka Formation debris flows	North Wilkatana	Carbonized wood	>42.6	Williams (1973)
Optically stimulated luminescence dates			*Optical age* (ka)	
Pooraka Formation debris flows	Depot Creek	Quartz	71 ± 7	Quigley *et al.* (2006)
Pooraka Formation debris flows	North Wilkatana	Quartz	67 ± 6	Quigley *et al.* (2006)
Pooraka Formation debris flows	North Wilkatana	Quartz	56 ± 6	Quigley *et al.* (2006)
Pooraka Formation Conglomerate*	North Wilkatana	Quartz	32 ± 2	Quigley *et al.* (2006)
Pooraka Formation Conglomerate†	North Wilkatana	Quartz	29 ± 2	Quigley *et al.* (2006)

*Faulted.
†Unfaulted.

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 lowermost 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 thermoluminesence ages as old as 116 ± 6 ka (Bourman *et al.*, 1997).

The Pooraka Formation is overlain 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 ^{14}C ages clustering between 25 and 35 ^{14}C 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
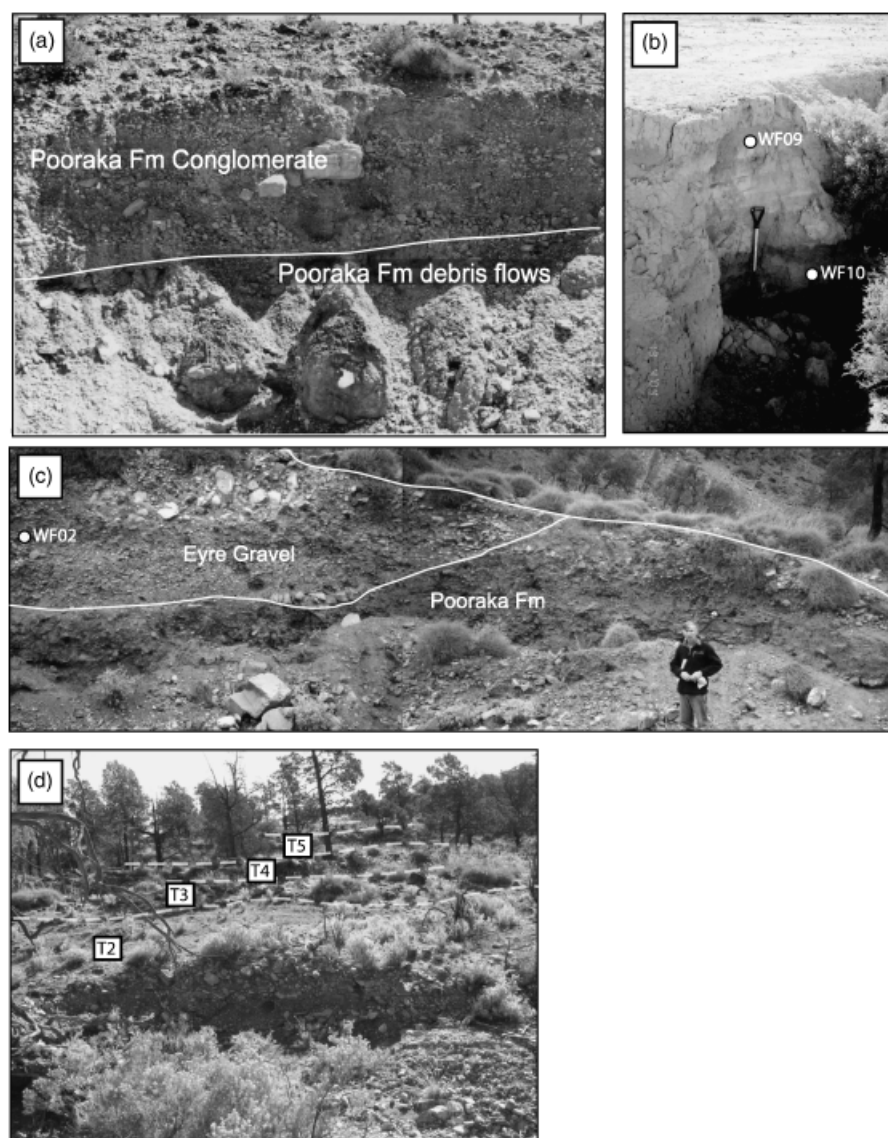
Fig. 5. Field photographs of the stratigraphic units composing the Wilkatana alluvial fans. (a) Pooraka Formation debris flow unit overlain by the Pooraka Conglomerate in the North Wilkatana Fan (b) Fine-grained fluvial and aeolian deposits and intercalated palaeosols. Location of OSL sample sites as indicated (c) Conglomeritic Eyre Gravel channel incised into Pooraka Formation (d) T_2–T_5 Eyre Gravel terraces identified in the North Wilkatana Fan. OSL, optically stimulated luminescence.

(1973) on the basis of similar lithological characteristics and stratigraphic position.

The Wilkatana Fans have been deeply incised and partially refilled 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) recognized two pervasively developed terraces within the fans and classified the highest terrace deposit as Eyre Gravel Member 1 (^{14}C age of 5.1 ± 0.1 kyr BP; calibrated in Table 1) and the lowest as Eyre Gravel Member 2 (^{14}C age of 3.4 ± 0.1 to 1.8 ± 0.4 kyr BP;

calibrated in Table 1). 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 T_2 to T_5 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 ($\geq$ *ca*. 56 ka), to (2) soil formation and landscape stability (*ca*. 40–30 ka), to (3) high-energy, braided stream-dominated, conglomeritic sedimentation ($\leq$ *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,

1991). 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*. 71 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 (the 'dose rate'; D_r) (Aitken, 1998). From these parameters, the burial age of well-bleached grains can be determined (Burial age $= D_e/D_r$).

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. 5b) and one sample from the Eyre Gravel (Fig. 5c). Samples were collected by driving 50-mm-diameter opaque stainless-steel tubes into cleaned sections. 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 T_4 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 ^{90}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 regenerated 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 Nouth 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
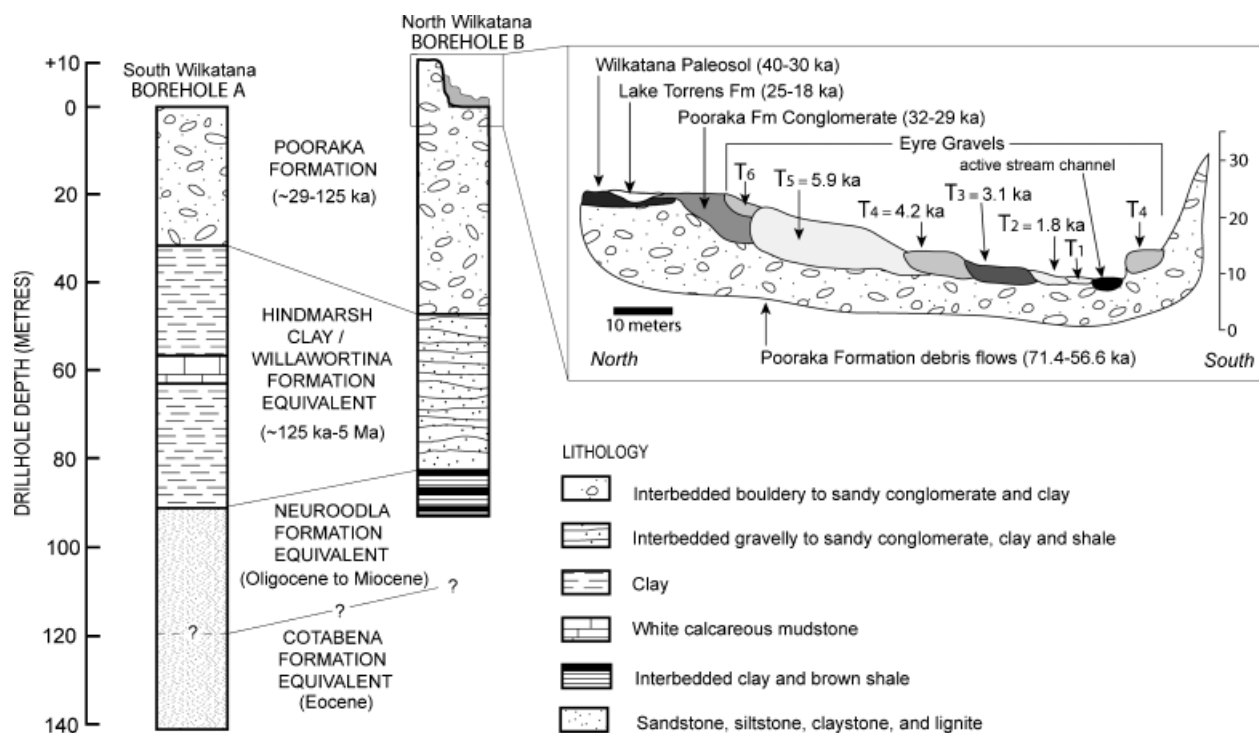
Fig. 6. Borehole stratigraphy and cross-section of the Eyre Gravel terraces identified in the incised apex of the North Wilkatana Fan. Location of boreholes shown in Fig. 2. Borehole chronology derived by comparing comparing borehole stratigraphy with descriptions of Cenozoic stratigraphy from the Lake Torrens Basin (Johns, 1968; Alley & Benbow, 1995); the Santos Wilkatana 1 and 2 boreholes southwest of the study area (Harris, 1970), and the Pooraka Formation from the Mount Lofty (Bourman *et al.*, 1997) and Barrier Ranges regions (Quigley *et al.*, 2006). Compiled OSL and ^{14}C chronology shown with respective terrace unit on cross section. Lake Torrens Fm deposits projected onto section from exposures of this unit to the west of this section.

measured in the field using a portable spectrometer and converted to dry values by oven-drying sediment from the sample location. Internal α dose rates were also assumed to be $0.03 \pm 0.01 \, Gy \, ka^{-1}$ 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 β and γ rays by water (Aitken, 1998).

Results

Optical ages of 18 ± 1 and 25 ± 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 T_4 terrace sample yielded an optical age of 4.2 ± 0.5 ka (Table 2, Fig. 6). This age is within error of the calibrated ^{14}C age of 3.7 ± 0.1 cal kyr BP obtained by Williams (1973). The age of the T_4 terrace is therefore interpreted as 4.2 ± 0.6 ka, consistent with the interpretations that the higher elevation T_5 terrace is older and the lower elevation T_2 and T_3 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 T_6 terrace sometime before *ca.* 6 ka until the formation of the T_1 terrace sometime after *ca.* 2 ka. Punctuated depositional events occurred at 5.9 ± 0.1 ka (T_5), 4.2 ± 0.6 ka (T_4), 3.1 ± 0.2 ka (T_3) and 1.8 ± 0.4 ka (T_2) (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

Laboratory number	Stratigraphic unit	Locality	Depth (m)	Water* (%)	Radionuclide concentrations† K (%)	Th (ppm)	U (ppm)	α-radiation‡ (Gy ka⁻¹)	β-radiation§ (Gy ka⁻¹)	γ-radiation¶ (Gy ka⁻¹)	Cosmic-ray radiation‖ (Gy ka⁻¹)	Total dose rate (Gy ka⁻¹)	Equivalent dose** (Gy)	Optical age (ka)
WF02	Eyre Gravel	North Wilkatana	2.5	2 ± 1	2.13 ± 0.04	7.56 ± 0.06	0.84 ± 0.09	0.03 ± 0.01	1.81 ± 0.07	0.86 ± 0.06	0.15 ± 0.02	2.85 ± 0.09	12.1 ± 1.3	**4.2 ± 0.5**
WF09	Lake Torrens Formation	South Wilkatana	0.5	5 ± 1	1.46 ± 0.02	7.15 ± 0.06	1.37 ± 0.03	0.03 ± 0.01	1.35 ± 0.05	0.75 ± 0.06	0.18 ± 0.02	2.30 ± 0.07	41 ± 3	**18 ± 1**
WF10	Lake Torrens Formation	South Wilkatana	1.7	5 ± 1	2.01 ± 0.02	8.09 ± 0.07	1.47 ± 0.03	0.03 ± 0.01	1.76 ± 0.06	0.82 ± 0.06	0.16 ± 0.02	2.77 ± 0.08	69 ± 5	**25 ± 2**

Bold equivalent to sediment deposition age.
*Estimated time-averaged moisture contents, based on measured field water values (% dry weight).
†Obtained by INAA (Becquerel Laboratories, Menai).
‡Assumed internal α dose rate.
§Derived from INAA radionuclide concentration measurements using the conversion factors of Adamiec and Aitken (1998), corrected for attenuation by water and beta attenuation.
¶Derived from field γ spectrometry measurements using the conversion factors of Adamiec 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 β-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 suggest 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 conglomeritic 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 C_4 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 conglomeritic alluvial facies (Pooraka Conlgomerate) 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 conglomeritic 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 flood events in the mid to late Holocene. This indicates a large flood-recurrence interval of one flood per 1370 ± 300 years between deposition of the T_5 and T_2 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 (Cèlérier 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-
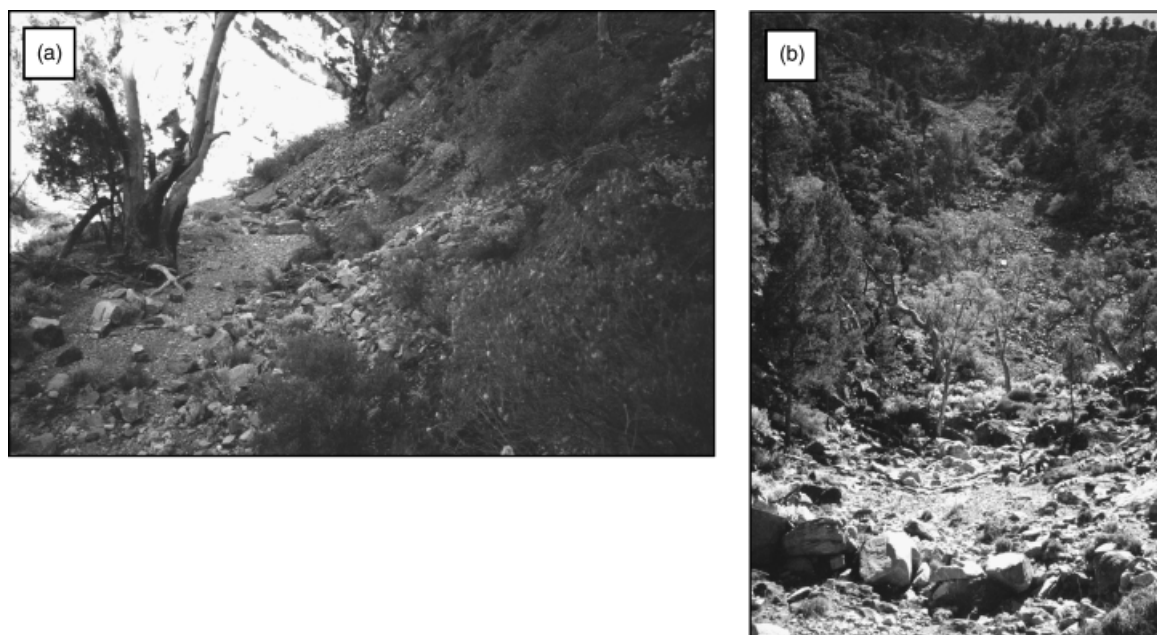

Fig. 7. Field photographs of catchment geomorphology in the North Wilkatana Catchment (a) Talus slope debris encroaching onto the modern stream bed. (b) Large talus slope and coarse alluvial material.

ders – Mt Lofty Ranges, with the Murray Basin uplifted and the Torrens Basin lowered, are interpreted to reflect spatial variability in the mode of tectonic deformation superimposed on a large wavelength, SW-side-up tilting of the Australian continent (Sandiford, 2007). We suggest that the Murray Basin has uplifted in response to broad lithospheric buckling (e.g. Cèlérier *et al.*, 2005) whereas the Torrens Basin – Spencer Gulf region has been depressed in response to range front thrust faulting and flexural loading. These regional patterns of tectonism have governed both the distribution and morphology of alluvial sedimentation and the distribution of marine sedimentation in south-central Australia.

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 gradients 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-synch 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 > *ca*. 71 to < *ca*. 55 ka, as indicated by aggraded debris flow deposits. Progressive regolith erosion culminated with the transition to a bedrock landscape by *ca*. 32 ka, as indicated by the deposition of conglomeritic 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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