The Cadell Fault: a record of long-term fault behaviour in south-eastern Australia

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Introduction

Australia is classified as a Stable Continental Region (SCR) in terms of its plate tectonic setting and seismicity (Johnston *et al.* 1994). While such settings produce only approximately 0.2% of the world's seismic moment release, large and potentially damaging earthquakes are not uncommon (e.g. Crone *et al.* 1997). In the last four decades five locations in Australia are documented as having experienced surface rupturing earthquakes (Figure 1).

Despite only a small number of large historical earthquakes, Australia boasts arguably the richest Late Neogene to Quaternary faulting record in all of the world's SCR crust (cf. Figure 1) (Quigley *et al.* 2010; Clark *et al.* 2011). This record of large, surface-rupturing (morphogenic) earthquakes, spanning tens of thousands of years or more, owes its existence to the preservation of neotectonic features, such as fault scarps, in a landscape characterised by low erosion rates and negligible glacial influences.

A common characteristic of such large earthquake occurrence in Australia appears to be temporal clustering. The available evidence for the 'Neotectonic Era', that is, since the establishment of the current Australian crustal stress regime some 5-10 Ma B.P. (Dickinson *et al.* 2002; Sandiford *et al.* 2004; Hillis *et al.* 2008) supports this. Periods of earthquake activity comprising a finite number of large events are separated by much longer periods of seismic quiescence, at both the scale of a single fault and of proximal faults. What is not clear from the limited palaeoseismological data available is whether successive active periods are comparable in terms of slip, number of events, magnitude of events, etc. In any case, this apparent bimodal recurrence behaviour poses challenges for probabilistic seismic hazard assessment in that it implies that large earthquake recurrence for long return periods is not random, as is often assumed in such models.

Presently, long-term fault behaviour and characteristics for most areas of the Australian continent are largely based upon inference from geomorphic features (mainly fault scarps), fault parameters inferred from the physical characteristics of these features (such as fault length relationship to magnitude, e.g. Leonard 2010), and sparse palaeoseismic data. However, the palaeo-earthquake record occasionally affords the opportunity to examine the behaviour of SCR faults over multiple seismic cycles, providing rare insight into recurrence behaviour. In this paper we use both new and existing data to characterise morphogenic earthquake recurrence on the Cadell Fault, located within the Murray Basin in south-eastern Australia (Figure 2a).

The Cadell Fault

The Cadell Fault is the most prominent example of a multiple-event Quaternary fault scarp in southeast Australia. A multi-disciplinary study of the scarp involving seismic reflection profiles, analysis of high-resolution digital elevation model (DEM) data, field survey, and optically stimulated luminescence (OSL) dating of fault-related surfaces and sediments has permitted a reconstruction of the displacement history of the fault over the Neotectonic Era (i.e. the last 5-10 Ma). As such, this study represents an important advance in our knowledge of long-term fault behaviour in the SCR setting.

Geologic context

The Cadell Fault scarp is situated on the Riverine Plain, a broad, topographically subdued region of the Murray Basin, southeast Australia (Figure 2a) (Harris 1939; Hills 1960; Bowler & Harford 1966; Pels 1966; Bowler 1978; Brown & Stephenson 1991). The Murray-Darling Basin developed during the Cenozoic following the break-up of Antarctica and southern Australia in the Late Mesozoic (Brown & Stephenson 1991). Cenozoic sequences within the basin onlap a composite collage of Proterozoic-Palaeozoic tectonostratigraphic basement terranes and Upper Palaeozoic-Mesozoic infra-basins. The basin history is characterised by slow tectonic subsidence rates, minimal compaction rates, and low rates of sediment supply and/or preservation (Brown & Stephenson 1991). The stratigraphic architecture of the basin is strongly influenced by interactions between superimposed mild tectonics, eustasy, and palaeoclimate. Deposition of laterally extensive sequences of intercalated fluvio-deltaic, paralic and shallow-marine sediments correlates with major periods of high global sea-level, whereas periods of erosion or lack of sediment preservation correlate with major sea-level lows (e.g. Paine *et al.* 2004; Wallace *et al.* 2005).

Borehole data suggest that the Cadell Fault deforms an approximately 200-250 m thick section of Eocene to Late Pleistocene sediments (Tickell 1978; Tickell & Humphrys 1987) overlying granitic basement rocks between Deniliquin and Echuca, and Ordovician and Devonian sedimentary rocks south of Echuca (Cayley *et al.*, 2002, 2011). The scarp relating to the Cadell Fault is mapped in two segments separated by the floor of a palaeo-lake known as Lake Kanyapella (Figure 2b). The 12-15 m high and up to 55 km long northern segment of the scarp is developed between Deniliquin and Echuca, and the 3-4 m high and 13 km long southern segment, known as the Echuca South Scarp (Bowler 1978), extends south of Echuca to Rochester. Together the scarps extend for almost 80 km along a northerly trend approximately collinear with the Mount William Fault Zone to the south (Cayley *et al.* 2002). Uplift at the scarp face tails off over 15-20 km to the west, forming what is known as the Cadell Tilt Block (Harris 1939; Pels 1966; Bowler 1978).

Geomorphic record of surface faulting

Recent uplift across the Cadell Fault is indicated by the stranding of former fluvial channels associated with the Quaternary Shepparton Formation on the Cadell Tilt Block (Brown & Stephenson 1991). The uplift had a dramatic effect on the drainage of the Riverine Plain, and in particular on the Murray, Goulburn and Campaspe Rivers. Between Echuca and Deniliquin the ancient courses of the Murray and Goulburn Rivers were defeated by uplift across the Cadell Fault, leaving two incised channels known respectively as Green Gully and the Goulburn Tributary (Figure 2b) (Bowler 1978). On the Murray River system, the combination of backwater effect and changes in slope triggered a shift from an incised meandering system to a vertically aggrading anastomosing channel system, both upstream and downstream of the fault (Rutherfurd 1994; Rutherfurd & Kenyon 2005). As a result three large alluvial fans formed; the Barmah, Wakool and Gunbower fans. The apex of the Barmah fan occurs 60 km upstream of the fault (Rutherfurd & Kenyon 2005). The fan attains a maximum thickness of 6-7 m approximately 15 km east of the scarp (Figure 2b) (Stone 2006b).

The Green Gully channel (Figure 2b) is incised into the uplifted block, where the presence of paired terraces suggests several phases of movement on the fault prior to abandonment (Bowler 1978). Three inset terrace levels of varying continuity and development are recognised, each associated with a unique channel plan form (Figure 3). Highest in the landscape are remnants of a highly sinuous and relatively narrow channel form ('ch1' - Figure 3a). The second channel form ('ch2' - Figure 3a) is represented by a large meander with a relatively wide channel similar to pre-diversion forms seen on the palaeo-Murray scroll plain east of the fault. The terrace tread relating to this channel form (T2 - Figure 3b) is inset below the level of T1 surface by approximately 1 m. Two to three fragmentary terrace levels between the T1 and T2 levels may reflect rapid downcutting in conjunction with lateral migration. This form is overprinted by the most recent channel form (prior to abandonment; 'ch3' - Figure 3a), which is significantly less sinuous, and has a highly developed and continuous paired terrace associated with it (T3 - Figure 3b). This third level is inset just over a metre below the T2 level.

Ultimately, the Murray River could not keep pace with the uplift, and the river was diverted to the north, where it found a way around the northern end of the scarp (Pels 1966). Subsequent to the defeat of the Murray River, the abandoned Green Gully plain (T3 - Figure 3b) was uplifted 10 metres above the current floodplain level. The profile of the last occupied channel of the Murray is notably warped proximal to the scarp face (Figure 3b), suggesting that uplift involved a strong folding component in the hanging wall sediments.

Geochronological constraint on the uplift history

Collection of samples for optically stimulated luminescence (OSL) dating from several of the geomorphic surfaces mentioned above, and several machine excavated pits, allows for a chronology of faulting to be pieced together. A wealth of complimentary OSL data, which is referred to herein, is contained in the unpublished Ph.D. thesis of Tim Stone (Stone 2006b).

Stone (2006b) obtained ages of 72.5 ± 4.6 ka and 63.5 ± 3.9 ka from Bullatale Creek, both of which are located on the down-thrown side (east) of the fault (MP1 and Bulla1 - Figure 4), and contends that these dates mark the onset of aggradation of the Barmah Fan. This timing is consistent with that obtained for a minor faulting event exposed in a trench excavated south of Mathoura by the present authors (DT01: 70 ± 10 ka and DT02: 65 ± 5 ka - Figure 4). Channel sands dated on the uplifted block adjacent to the trench, 15 m above the floodplain level, yielded slightly younger ages of (CD01: 54 ± 4 and CD02: 60 ± 6 ka - Figure 4). Stone (2006b) obtained an OSL age of 46.5 ± 3.6 ka from near the surface of the Barmah fan where it is thickest (Bulla2 - Figure 4). This age was interpreted to date the termination of aggradation on the Barmah Fan, and the abandonment by the Murray River of its Green Gully channel. Ages of 52 ± 7 ka and 45 ± 3 ka (CF12A&B - Figure 4) for the uppermost channel sands in the last abandoned channel at the mouth of Green Gully, and the lowermost sediments of the post-abandonment clay plug, respectively, corroborate Stone's interpretation. Green Gully therefore appears to have been abandoned by the Murray River at *ca*. 45 ka, potentially as the result of an uplift event.

An age of 42 ± 2 ka from the Goulburn Tributary near the scarp in what appeared to be the basal sediments of the post-abandonment clay plug (CF13 - Figure 4), is consistent with the simultaneous abandonment of the pre-faulting courses of the Goulburn and Murray Rivers. This is an unexpected result given the lack of evidence for incision and terracing associated with the Goulburn palaeo-channel. The last occupied channel of the Goulburn Tributary has been uplifted to 7-7.5 m above the current floodplain.

To the south, textural variation from lake floor to dune, and the presence of coarse sandy beach deposits preserved within the Barmah Sandhills, demonstrate that aeolian deflation of wave-nourished beaches has led to the formation of the lunette on the eastern margin of the tectonically formed Lake Kanyapella (Bowler 1978) (Figure 4). An age for the formation of the lake is provided by a date of 32.4 ± 2.2 ka on the basal sediments of the lunette from Fitt's Quarry (BS4 - Figure 4) (Stone 2006b). The drying of the lake is constrained by the depositional age of the upper Kanyapella lacustrine silts at 24.7 ± 1.5 ka (KS1 - Figure 4) (Stone 2006b), and the formation of a lunette relating to a smaller lake named Little Kanyapella (Bowler 1978) on the dry Kanyapella lake floor at 18.9 ± 1.1 ka (IKDB - Figure 4) (Stone 2006b). There is no evidence for seismic deformation of the dry lake floor.

Sub-surface structure

Two seismic reflection profiles were acquired in order to investigate the displacement history of the fault prior to the most recent active period (70-20 ka), and image the bedrock-offset across the fault (Collins 2004). Seismic refraction data were co-acquired in order to provide velocity control.

The data suggest that the Cadell Scarp overlies a reverse fault dipping at ~50° to the west (Figure 5). A 75-80 m vertical offset is evident across Palaeozoic bedrock (~100 m slip). Abundant evidence for onlapping strata in this lower section suggests that the relief generation occurred at a time of sea level high of Eocene to Miocene Renmark Group sediments (Olney Formation - Brown & Stephenson 1991). The section above the level of bedrock in the hanging wall is characterised by parallel strata until the base of the Calivil Formation is reached, suggesting a time of tectonic quiescence during the Mid- to Late Tertiary. Strong reflectors immediately beneath the base of the Calivil Formation, perhaps relating to Eocene to Mid-Oligocene (and perhaps as young as mid-Miocene - Martin 1977) coal measures within the Renmark Group (Holdgate & Gallagher 2003), are folded into an east-facing monocline, but not obviously faulted.

The interpreted contact between the Renmark Formation and Calivil Formation is undulating and disconformable. At the resolution of the seismic data, very little section appears to have been lost to erosion across the disconformity, indicating that little if any of the 40 m of relief across the fault (~52 m slip) in underlying Mid-Tertiary strata existed significantly before the transgression in the Late Miocene that saw the backfilling of topography with fluviatile sand and gravel of the Calivil Formation. However, onlap onto the disconformity surface is consistent with relief building during the Late Miocene to Pliocene deposition of the Calivil Formation.

The base of the Pliocene to Quaternary Shepparton Formation is vertically displaced by approximately 20 m (~26 m slip). Parallel folding of strata in the lower half of the Shepparton Formation suggests that this deformation occurred in the time interval represented by the upper part of the section. Higher resolution seismic reflection data collected 450 m to the north of the Mini-Vibe line reveal folded strata spatially coincident with the monocline at greater depth, and consistent with the folding seen in the Green Gully stream bed close to the scarp (cf. Figure 3b). The amplitude of the fold in the upper 30 m of section is approximately 15 m, which is consistent with the surface topography. At the location of the seismic lines, no lake sediments bury the toe of the scarp, so the 15 m height is likely to be an accurate representation of the uplift during the most recent active period. The implication is that only ~5 m of the ~20 m of Quaternary uplift across the fault precedes the most recent active period *ca*. 70 - 20 ka.

Sparse borehole data provide a consistent story, showing ~40 m of vertical displacement across the base of the Calivil Formation, with a suggestion of ≤10 m of thickening of the Calivil Formation across the fault (Tickell 1978; Tickell & Humphrys 1979).

Rupture Behaviour on the Cadell Fault

During the Neotectonic era (i.e. the last 5-10 Ma) the Cadell fault has undergone two periods of displacement, each involving ~15-20 m of uplift. The earlier active period is postulated, on the basis of seismic reflection evidence, to have occurred during the deposition of the Late Miocene to Pliocene Calivil Formation. This timing for reactivation of the fault is consistent with evidence for a widespread pulse of activity on Australian faults that coincides with the establishment of the current stress regime (Dickinson *et al.* 2002; Sandiford *et al.* 2004; Hillis *et al.* 2008).

Following a prolonged period of relative tectonic quiescence spanning almost the entire Quaternary and involving 5 m or less of uplift, the Cadell Fault entered a new phase of activity. At approximately 70 ka the Murray River system started aggrading in response to renewed uplift across the Cadell Fault. The oldest recognised rupture event occurred between 70 ± 10 ka and 65 ± 5 ka. Approximately 8-9 m of uplift occurred prior to the abandonment of the former channel of the Murray River at Green Gully *ca*. 45 ka, involving roughly equal portions of incision into the uplifting block and aggradation at the scarp toe. The record of terracing from within Green Gully is consistent with three large morphogenic seismic events. Relationships between seismic moment and fault area (e.g. Somerville 2001; Leonard 2010; Somerville *et al.* 2010) suggest that in order to produce 3 m of uplift across a 50° dipping reverse fault, the entire 80 km length between Deniliquin and Rochester (i.e. including the Echuca South Scarp) is likely to have ruptured in each event. The magnitude of each event was potentially in the range of Mw 7.3-7.5. The three complete seismic cycles in this interval are associated with an average recurrence of 8.3 ka and a vertical slip rate of 0.36 mm/a (equivalent to slip along the fault of 0.47 mm/a).

Including the *ca*. 45 ka event that ultimately defeated the Murray and probably Goulburn Rivers, a further ~10 m of uplift occurred in the interval between *ca*. 45 ka and the drying of Lakes Kanyapella and Old Barmah (*ca*. 25-20 ka - Stone 2006a,b). We speculate that three full scarp-length rupture events are responsible for this uplift. The formation of Lake Kanyapella (*ca*. 32 ka - Stone 2006b) is likely to have resulted from one of these events. Evidence for the timing of the third event in the sequence was not observed in the geomorphology. The average uplift rate for the interval 45-20 ka is 0.4 mm/a (0.52 mm/a fault slip).

The slip rate on the fault, averaged over perhaps as many as five complete seismic cycles in the period 70-20 ka B.P., is ~0.50 mm/a, as compared to an averaged rate of 0.05 mm/a over the entire Neotectonic Era. If full length rupture is assumed, the average recurrence for Mw 7.3-7.5 events on the Cadell Fault is approximately 8 ka. More than two average seismic cycles have lapsed since the last seismic event on the fault. It might therefore be speculated that this fault has expended its stored strain and has relapsed into a quiescent period (cf. McCalpin 2009). Accordingly, the Cadell Fault provides a record of bimodal rupture behaviour on an SCR fault extending beyond the most recent active period. Such examples are difficult to find, and have rarely been documented in Australia, but provide useful models for conceptualising rupture behaviour on other Australian SCR faults, and SCR faults in general.

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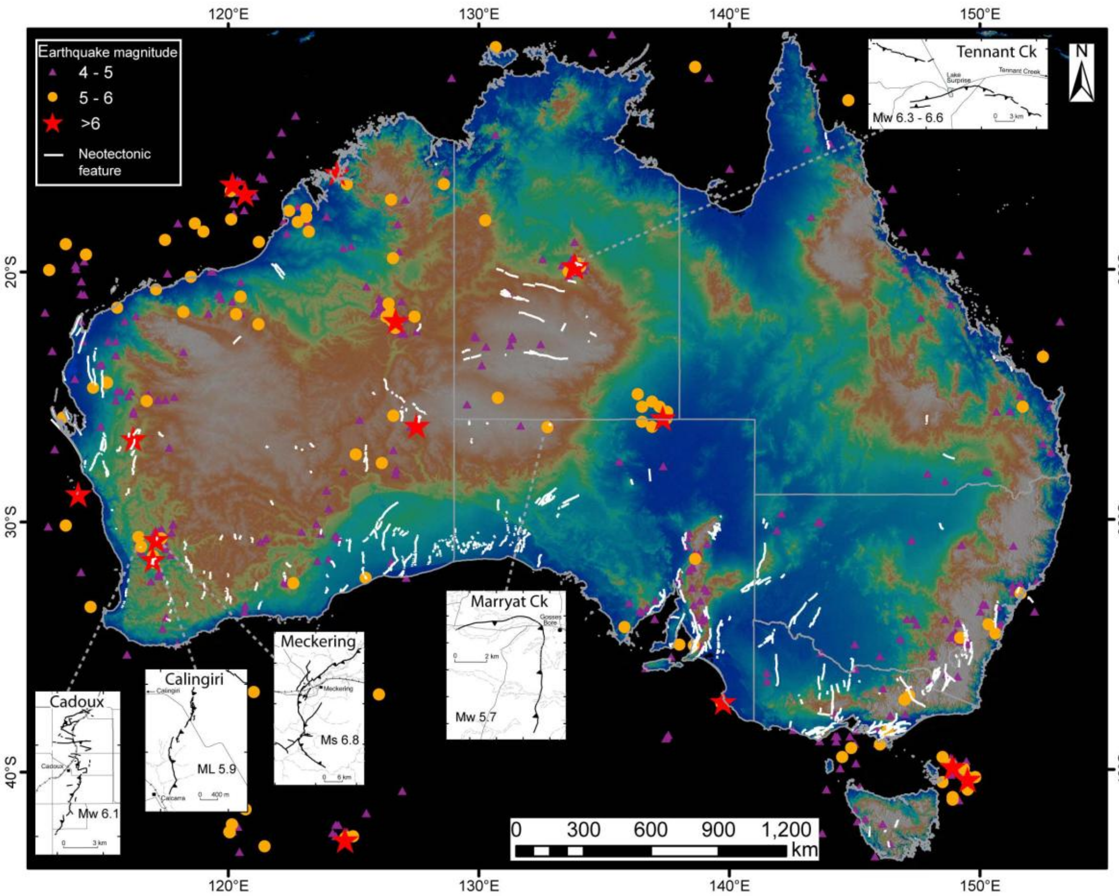

Figure 1: Digital elevation image (SRTM 90 m) of Australia showing locations and magnitudes of historic seismicity (M>4), traces for the five historic surface ruptures (Gordon & Lewis 1980; Lewis *et al*. 1981; Bowman *et al*. 1990; Machette *et al.* 1991, 1993; Crone *et al*. 1992, 1997), and locations of known and suspected neotectonic features (Geoscience Australia, unpublished data). Note: Tennant Creek involved a series of three consecutive surface rupturing events within one day.

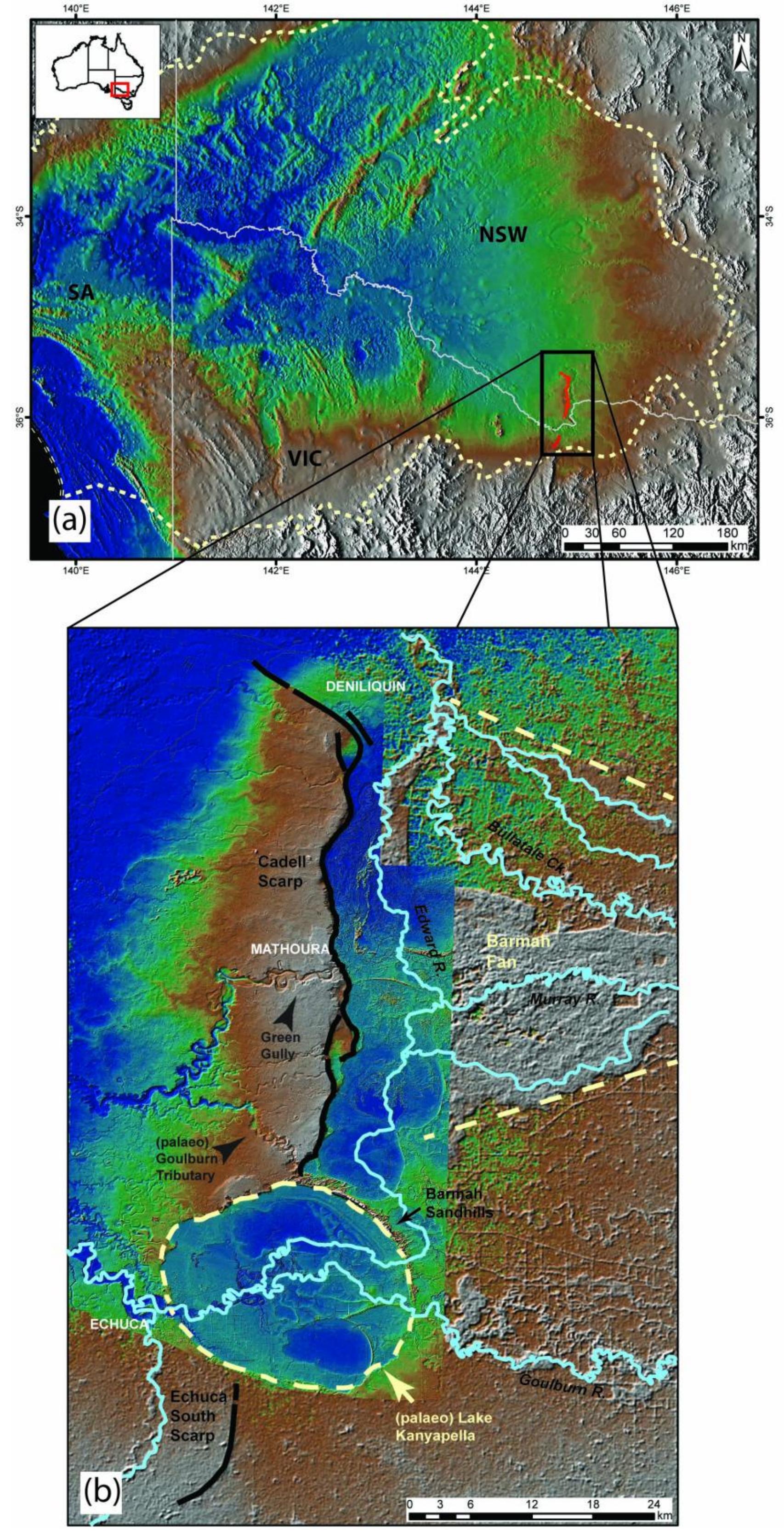

Figure 2: (a) Digital elevation image (90 m SRTM) of southeastern Australia, showing the regional setting of the Cadell and Echuca South scarps within the eastern Murray Basin (basin margin indicated by dashed yellow line). **(b)** Inset showing the local setting of the Cadell Fault scarp, and other localities and geomorphic features mentioned in text. Note that change in image between east and west marks the boundary between 90 m SRTM and 10 m LiDaR data respectively.

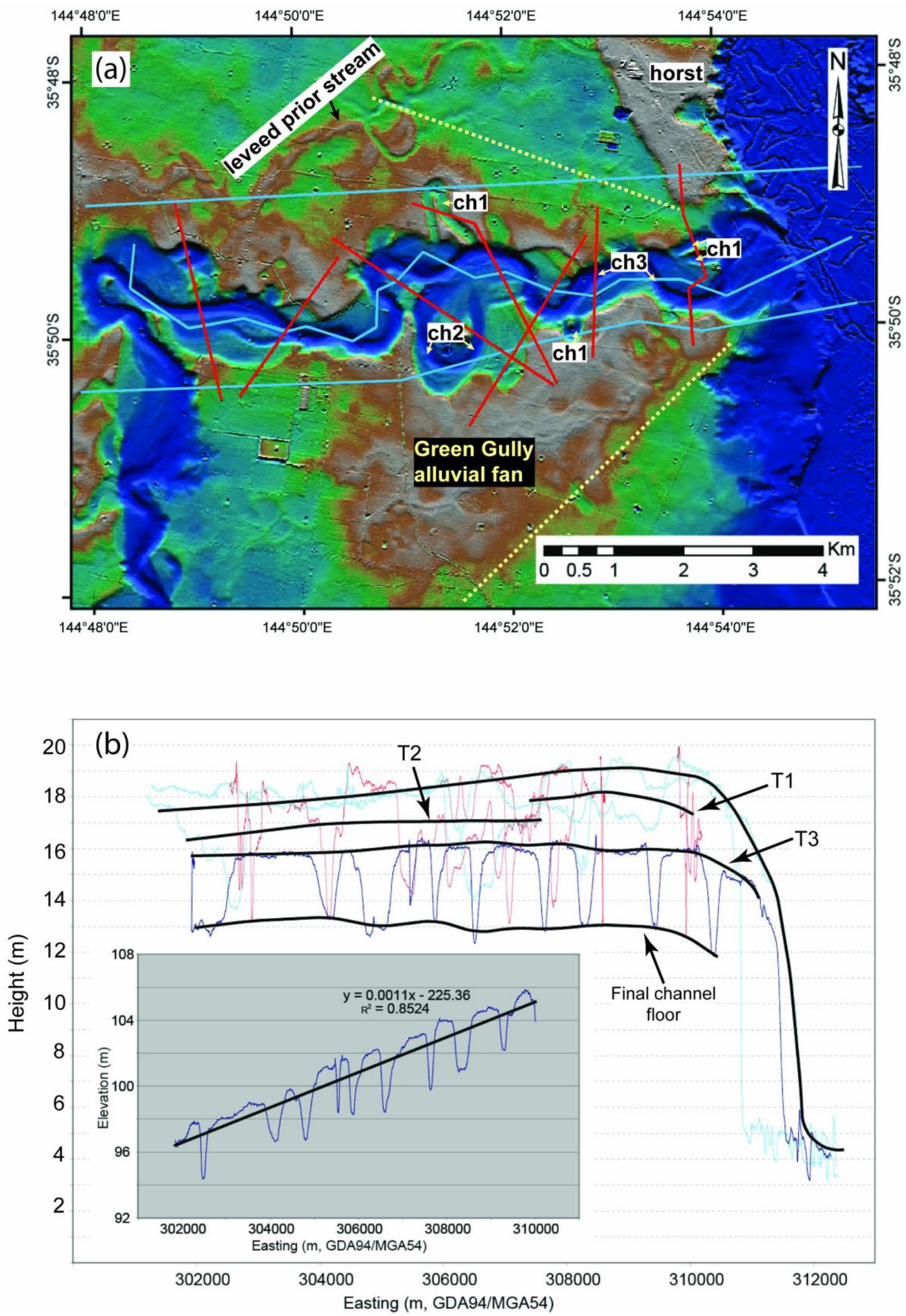

Figure 3: (a) Digital elevation image (10 m LiDaR) showing identified palaeochannel systems (ch1-ch3) within Green Gully on the upthrown western side of the Cadell Fault. Data has been corrected for the E-W tilt of the Cadell Tilt Block (see inset in (b)). Light blue and red lines mark elevation traverses, and correspond to the same coloured lines in (b). **(b)** Cross-section of elevation data from traverses marked in (a) showing displacements across the three terrace levels (T1-T3) related to uplift on the Cadell Fault. Dark blue line at lowest elevation represents last period of incision prior to abandonment, with lowest height values corresponding to the base of the youngest channel ((ch1). Inset shows correction applied to elevation data to account for tilt. Note the stronger influence of folding related to younger deformation, as suggested by T1 and the current land surface.

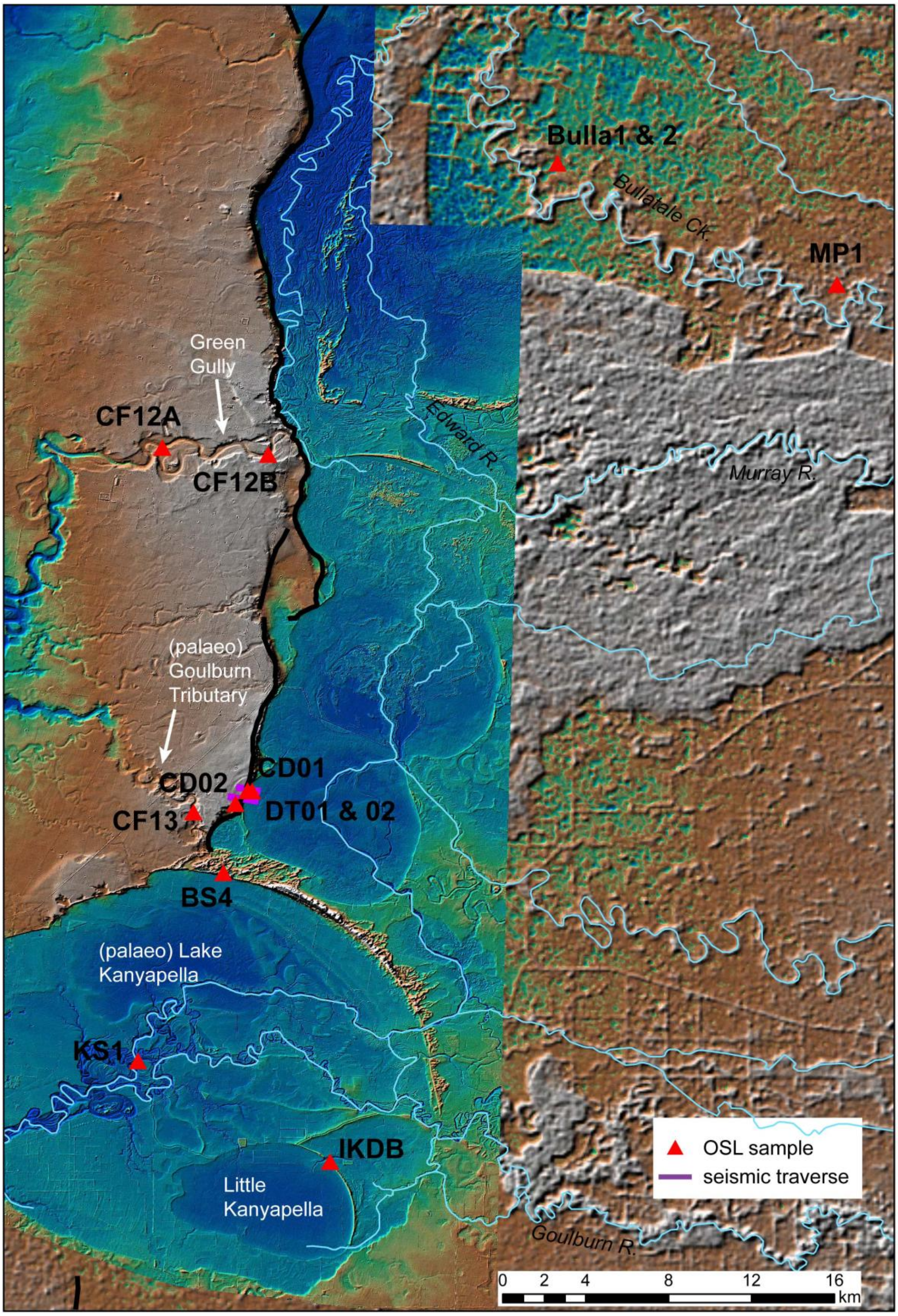

Figure 4: Digital elevation image labelled with locations of optically stimulated luminescence (OSL) sample sites and seismic traverses referred to in text. Note that change in image between east and west marks the boundary between 90 m SRTM and 10 m LiDaR data. Major features and locations referred to in text are labelled.

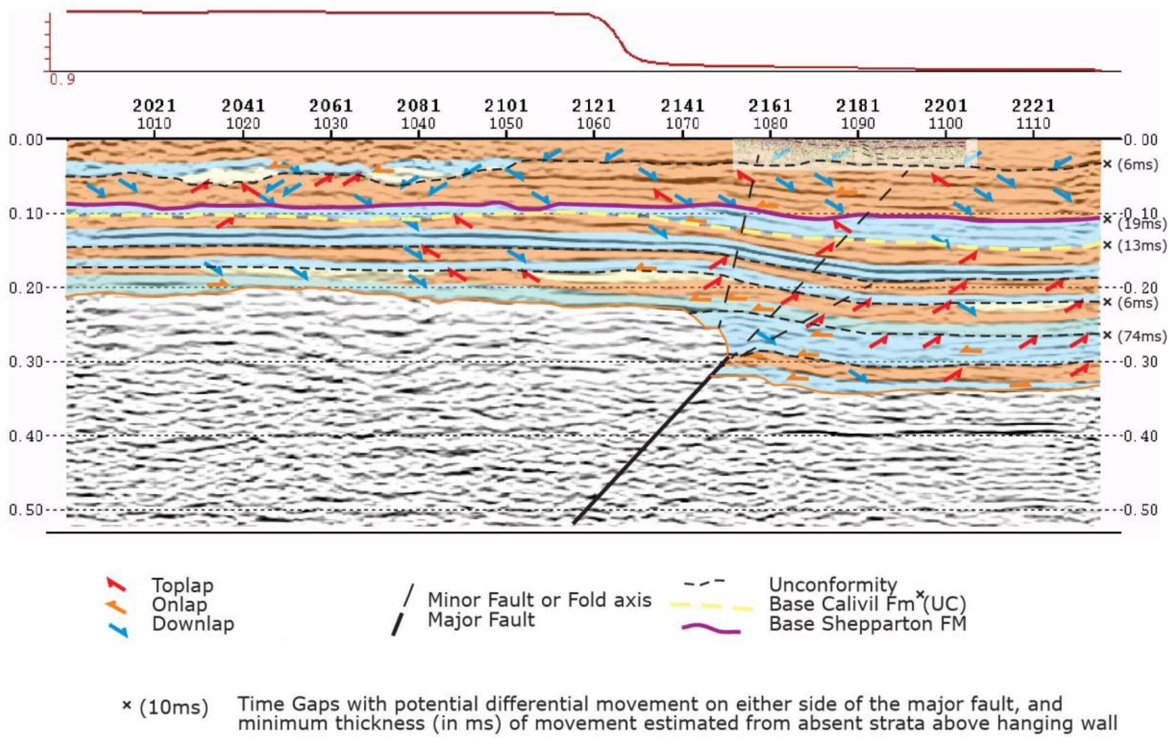

Figure 5: Interpreted seismic section showing deformation in basement and across Calivil and Shepparton Formations.