TEMPORAL CLUSTERING OF SURFACE RUPTURES ON STABLE CONTINENTAL REGION FAULTS: A CASE STUDY FROM THE CADELL FAULT SCARP, SOUTH EASTERN AUSTRALIA.

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1. INTRODUCTION

A characteristic of Australian stable continental region (SCR) faults appears to be the temporal clustering of large earthquakes. With the possible exception of active faults in the Flinders/Mt Lofty Ranges region of South Australia, active periods of earthquake activity comprising a finite number of large events are separated by much longer periods of seismic quiescence. This behaviour poses particular problems for seismic hazard assessment in that it implies that recurrence of large earthquake events is not random (Poisson) as is implicitly assumed in most seismic hazard assessment methods. The relationship is well illustrated by the Cadell Fault, which is the most prominent example of a multiple-event Quaternary fault scarp in southeast Australia. We present the results of a multidisciplinary study of the scarp involving seismic reflection profiles, examination of a 1 m resolution digital elevation model (DEM), field survey and optically stimulated luminescence (OSL) dating of fault-related surfaces and sediments. The data are used to construct a conceptual model through which the behaviour , and hazard, of intraplate faults might better be understood.

2. LOCATION AND CONTEXT

The Cadell Fault scarp is situated in the Riverine Plain, a broad, topographically subdued region of the Murray-Darling Basin, southeast Australia (**Fig. 1**). West-up displacements across the 80 km long fault have uplifted Quaternary sediments by as much as 20 m, diverting the course of Australia's largest river, the Murray River. The scarp has been extensively modified by fluvial processes – both footwall and hanging wall preserve a multitude of geomorphic surfaces that can be used to constrain the timing, size and number of faulting events.

3. SURFACE EXPRESSION AND RECORD OF FAULTING

OSL ages obtained on faulted (70±10 ka) and unfaulted (65±5 ka) sediments exposed in a trench excavation south of Mathoura bracket the earliest recognised deformation event in the most recent active period between ca. 60-80 ka. This is consistent with an OSL age of 72.5±5 ka [1] obtained on the basal section of the Barmah Fan, which is interpreted to have formed as the Murray River bed aggraded consequent of faulting. The 3-4 m height of a tectonic terrace riser bordering the channel of the palaeo-Murray River in Green Gully, now an airgap, is consistent with entire scarp-length rupture (~M_w 7.2-7.3). The Murray and Goulburn Rivers continued to occupy their pre-faulting channels until ca. 45 ka when they were simultaneously abandoned (45±3 ka and 42±2 ka respectively), presumably as the result of a seismic uplift event at ca. 40-45 ka. Aggradation of the Barmah Fan ceased at the time the Murray River was diverted (46.5±3 ka, [1]). Barmah Fan deposits reached a thickness exceeding 6 m, implying at least 10 m uplift prior to ca. 45 ka (including the 3-4 m terrace riser height on the hangingwall).

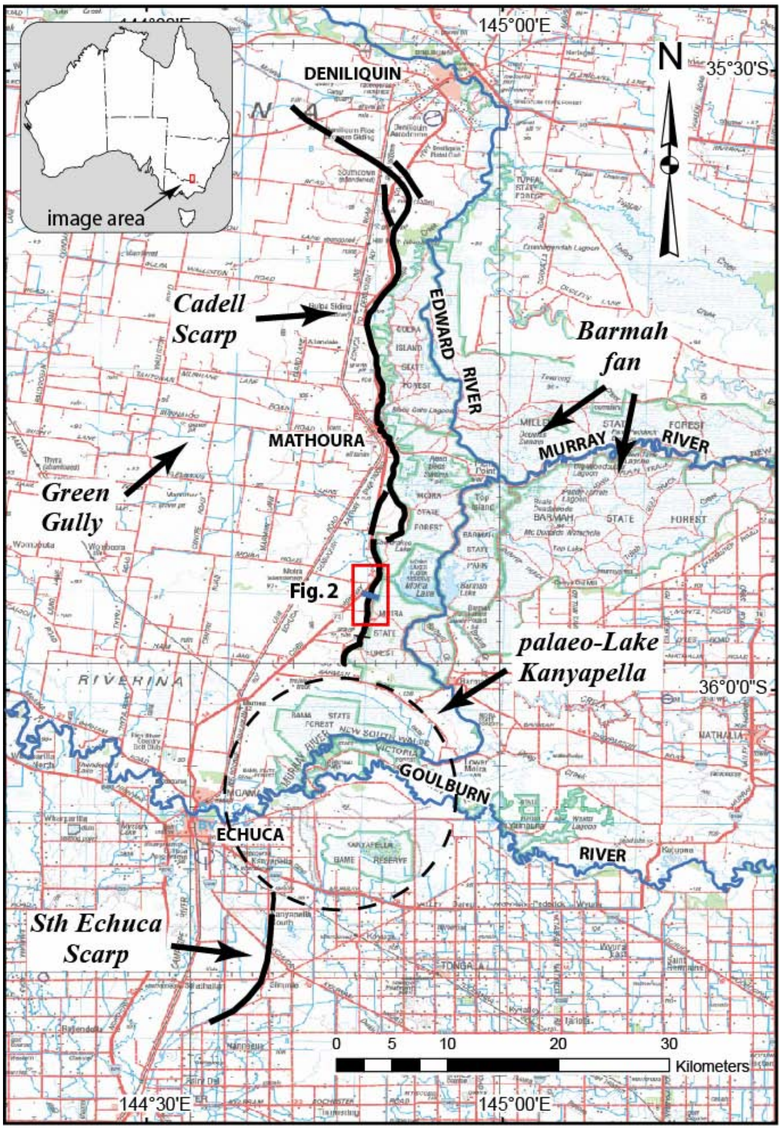

Figure 1 (inset) Location of the Cadell Fault in the Murray Darling Basin and (main) detailed scarp location map showing the current configuration of the major rivers. Prior to uplift of the western side of the Cadell Scarp the Murray River flowed westward across the scarp at Mathoura. After initial diversion, the Murray is thought to have occupied the course of the Edward River. Perhaps as little as 500 years ago the course changed to its current location, probably as the result of non-seismic avulsion [1].

The lower (inset) terrace within Green Gully is elevated approximately 10 m above the current floodplain level. At least two large seismic events subsequent to the ca. 45 ka event which resulted in the abandonment of the Murray palaeochannel are required to explain this relief. Evidence constraining the timing of these events is provided by the undeformed bed of palaeo-Lake Kanyapella, which is located between the northern and southern scarp sections (**Fig. 1**).

Ages from OSL samples taken from silts deposited in Lake Kanyapella indicate that the lake formed ca. 34±3 ka, potentially as the result of a seismic event, and held water until at least 25±1 ka [1]. A sand lunette (relating to Little Kanyapella) formed in the southeast corner of the dry lake bed at 19±1 ka [1]. This record requires that fault activity had certainly subsided by ca. 19 ka, and probably by ca. 25 ka.

Table 1 Results of luminescence dating of the sandy sediment samples from Cadell

Sample	Depth (m)	Water[a] (%)	Radionuclide concentrations[b] K (%)	Th (ppm)	U (ppm)	α radiation[c] (Gy ka^{-1})	β radiation[d] (Gy ka^{-1})	γ radiation[e] (Gy ka^{-1})	Cosmic-ray radiation[f]	Total dose rate (Gy ka^{-1})	Equivalent dose[g]	Optical age (ka)
CF12B	1.8	5 ± 2	3.76 ± 0.17	16.79 ± 0.69	5.82 ± 0.26	0.03 ± 0.01	3.72 ± 0.19	1.67 ± 0.13	0.13 ± 0.02	5.55 ± 0.27	251 ± 12	**45 ± 3**
CF13	2.0	5 ± 2	2.24 ± 0.10	15.41 ± 0.63	3.09 ± 0.15	0.03 ± 0.01	2.30 ± 0.12	1.44 ± 0.11	0.15 ± 0.02	3.91 ± 0.17	166 ± 6	**42 ± 2**
DT01	2.7	10 ± 2	1.96 ± 0.07	5.56 ± 0.19	1.68 ± 0.06	0.03 ± 0.01	1.60 ± 0.08	0.80 ± 0.06	0.13 ± 0.02	2.55 ± 0.11	180 ± 23	**70 ± 10**
DT02	1.4	10 ± 2	2.13 ± 0.07	5.38 ± 0.19	0.98 ± 0.04	0.03 ± 0.01	1.62 ± 0.08	0.69 ± 0.05	0.16 ± 0.02	2.50 ± 0.11	161 ± 11	**65 ± 5**

[a] estimated time-averaged moisture contents, based on measured field water values (% dry weight)
[b] obtained by INAA (Becquerel Laboratories, Menai)
[c] assumed internal alpha dose rate
[d] derived from INAA radionuclide concentration measurements, corrected for attenuation by water and beta attenuation
[e] derived from field gamma spectrometry for EF03-EF12, INAA radionuclide concentration measurements for EF14-EF17, corrected for attenuation by water
[f] calculated using the equation of Prescott and Hutton (1994), based on sediment density, time-averaged depth and site latitude, longitude and altitude
[g] including a ± 2 % systematic uncertainty associated with calibration of the laboratory beta-source.

4. SUB-SURFACE STRUCTURE

A 1.6 km seismic reflection line (10 m geophone spacing) was acquired with a Mini-Vibe where the scarp height is greatest (**Figs. 1, 2**). Interpretation of the data suggests that the Cadell scarp overlies a reverse fault dipping at ~50° to the west (**Fig. 2**). A 75 m vertical offset (~98 m total displacement assuming dip-slip and a 50° fault) of the base of late Tertiary Renmark Group sediments was imaged at 175 m depth. The base of the Pliocene to Quaternary Shepparton formation is vertically displaced, though not obviously faulted, by approximately 40 m (~50 m slip). A simple sequence stratigraphic analysis of the seismic data shows two distinct growth sequences separated by a thick section where no fault growth occurred.

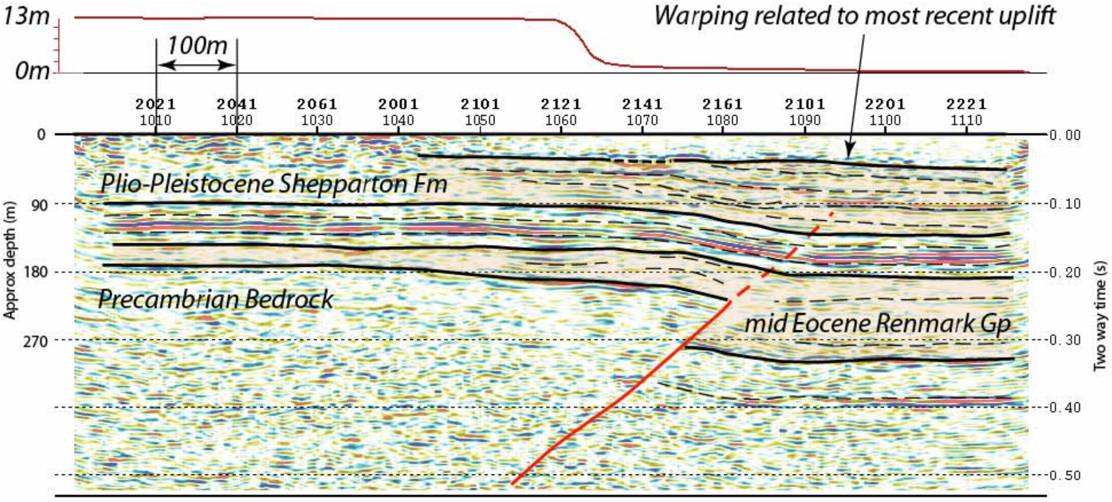

Figure 2 East-west seismic reflection profile with 10 m geophone spacing. Note that scarp has retreated ~400m from the projection of the intersection of the fault tip with the surface due to fluvial erosion. Expression in the upper section is of a fault propagation fold. Two distinct growth sequences are present (shaded areas).

5. CADELL FAULT RUPTURE BEHAVIOUR

At least four earthquakes of between M_w 7.0-7.3 are required to produce the observed 14-15 m relief across the Cadell Fault Scarp. Perhaps a further two events are required to account for the 6 m aggradation of the Barmah Fan. These events occurred over a *ca.* 60 ka time interval between 80-20 ka, and involved a total slip in the order of 25 m, suggesting an average slip rate of ~0.4 mm/yr. The seismic reflection data indicate ~100 m total displacement across of the base of the Eocene (<56 Ma) Renmark Group. Approximately 50 m of this is required to account for the displacement of the base of the Pliocene to Quaternary Shepparton Formation (<5 Ma). The post-mid Eocene slip rate is therefore in the order of 0.003 mm/yr, and the post-Miocene slip rate is ~0.010 mm/yr. Hence, the slip rate calculated for the most recent period of activity is one to two orders of magnitude greater than the long term slip rate. The simple sequence stratigraphic analysis of the seismic reflection data confirms the indication of temporally clustered rupture behaviour, with two distinct growth sequences of strata alternating with thick sections of no apparent fault growth.

6. A MODEL FOR LARGE SCR EARTHQUAKE OCCURRENCE BASED UPON THE CADELL FAULT

While the suite of active fault behaviours may vary across Australia, one individual fault characteristic appears to be common to most Australian intraplate faults studied (e.g. [2-4]). Active periods comprising a finite number of events are separated by typically much longer periods of quiescence (**Fig. 3a**). The sparse dataset available (e.g. [2-4]) suggests that an active period might constitute less than a half-dozen events, and perhaps as few as 2-3 in Western Australia. The slip rate in an active period might be several orders of magnitude greater than in the long term. Consequently, our expectation of a future rupture (say within the following several tens of thousands of years) subsequent to the first surface rupture in a new active period might be greatly elevated (**Fig. 3b**). This expectation will decay with successive ruptures until eventually reaching the “background” level again.

An implication of this model is that the faults most likely to be discovered are those that have recently finished an active period, as Cadell appears to have, or are currently within an active period. Published data on faults in the west of Australia suggest that the interseismic intervals between large events in an active period might be in the order of 20 - 40 ka [2-3]. Our data on the Cadell Fault indicate more frequent rupture; three times in the interval ca. 70 – 45 ka, and 3 times in the interval ca. 45 – 25 ka. The fact that three uplift events on the Cadell Fault had occurred prior to the diversion of the Murray and Goulburn Rivers suggests that these events are likely to have been spaced thousands of years apart. This contrasts to the New Madrid Seismic Zone in the intraplate central Unites States where a semi-regular recurrence of ~500 years has pertained for at least the last 3 seismic cycles in the current active period (e.g.[5]).

The model presented in Figure 3 helps to conceptualise the points critical to understanding the hazard posed by intraplate faults, and modelling this hazard probabilistically: 1) is the SCR fault in question about to enter and active period, in the midst of an active period, or in (or just entered) a quiescent period. Related to this it becomes important to know how many previous ruptures the fault has generated in its current active period (should it be in one, e.g. **Fig. 3b**), and 2) if a fault is in an active period, what is the “average” recurrence interval and what is the variability around this average. This “average” could be incorporated statistically into probabilistic seismic hazard assessments.

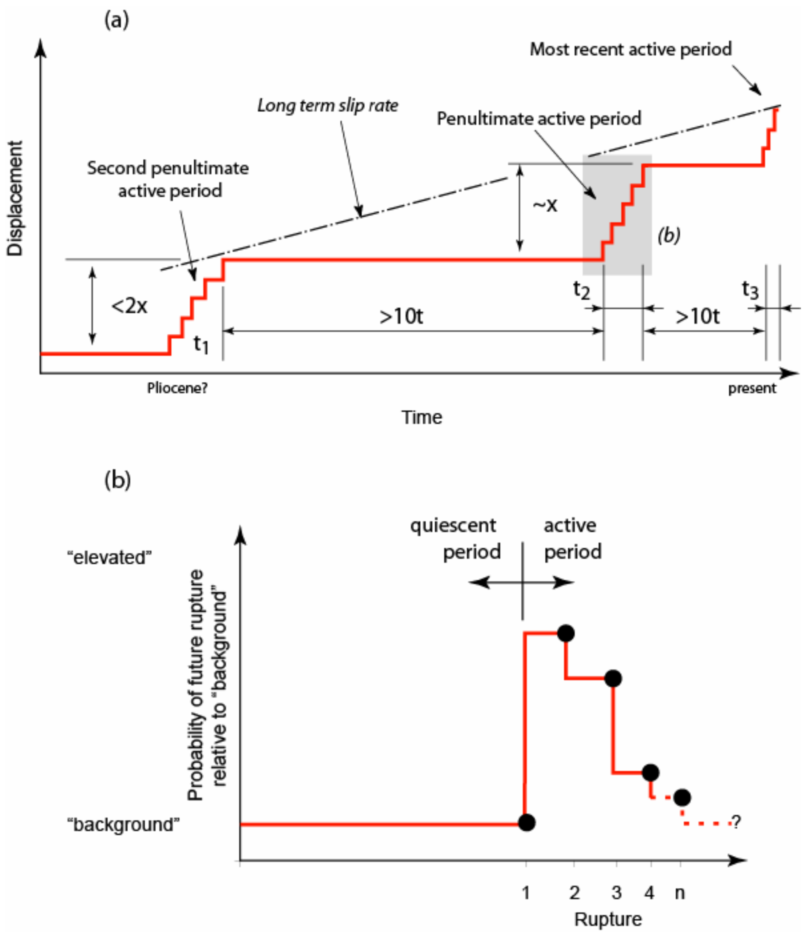

Figure 3 (a) Generalised slip diagram for an active Australian intraplate fault modelled on the Cadell Fault. t=time d=displacement; (b) generalised expectance of a near-future event derived from the penultimate active period in (a).

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