Proceedings of the Tenth Pacific Conference on Earthquake Engineering
Building an Earthquake-Resilient Pacific
6-8 November 2015, Sydney, Australia

Recognising intraplate seismogenic faults and associated seismic hazard: examples from Western Australia

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ABSTRACT: The location of past earthquake activity is a parameter required in assessments of seismic hazard. In intraplate regions such as Western Australia (WA), establishing the characteristics and location of past seismicity is difficult due to: (i) the long recurrence intervals between large events (ii) the subtle nature of the earthquake activity surface expression and (iii) the potential occurrence of earthquakes over vast areas (with unclear tectonic mechanisms).

In recent years, various tools have been used to improve the understanding of past earthquake activity in WA, placing emphasis on recognising and characterising potentially seismogenic faults. These tools include:

- analysis of digital elevation models (DEMs) to recognise fault scarp morphology
- analysis of tectonic geomorphology associated with potential fault scarps
- drainage analysis to infer tectonic deformation
- use of shallow geophysical surveys such as GPR and magnetic surveys to confirm faulting and geological context

The above, relatively inexpensive, tools are used to recognise potentially seismogenic faults before carrying out paleoseismologial studies, which are expensive and time consuming.

Applying these tools resulted in the recognition of tens of potentially seismogenic scarps across WA. Here we describe work on two fault scarps that have been analysed in this fashion: the Lort River Fault and the newly recognised Dumbleyung Fault. The evidence exposed by trenching of these structures during the paleoseismological investigations confirmed their association with faulting and revealed their recent earthquake history. Both structures show recurrent earthquakes, separated by thousands of years, with magnitudes up to 7.0.

1 INTRODUCTION

The southwest of Western Australia (WA) is an intraplate region located thousands of kilometres away from plate tectonic boundaries where most earthquake activity takes place. The characteristics, occurrence and mechanisms of earthquake activity in intraplate regions are not fully understood and their low frequency commonly leads to a low perception of risk, which is reflected in building codes. However, even moderate size intraplate events can potentially be destructive (e.g. the 1989 Newcastle earthquake).

One of Australia's most seismically active zones, the Southwest Seismic Zone (SWSZ) occurs in the southwest of WA (Figure 1). Recent strong earthquakes have occurred in the SWSZ, including Meckering (1968) and Cadoux, (1979) with magnitudes M_L 6.9 and 6.2, respectively (Gordon and Lewis, 1980; Lewis et al., 1981). The existence of the SWSZ and the recent strong earthquakes not only demonstrate the potential seismic hazard of the southwest of WA but also highlight the need for its comprehensive assessment.

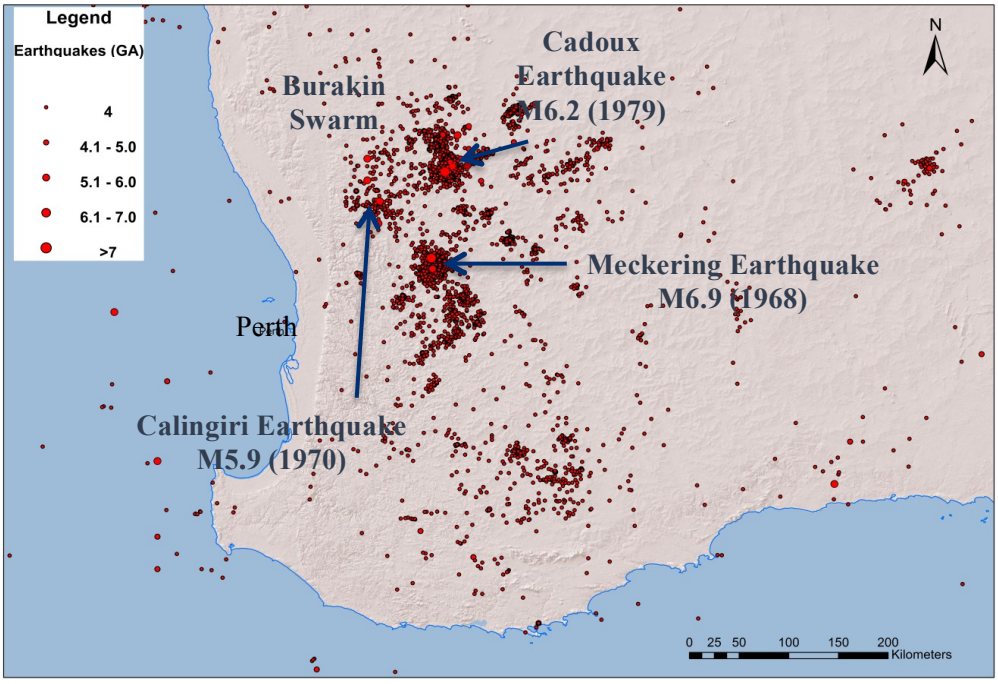

Figure 1. Location of the SWSZ and recent strong earthquakes (earthquake activity from the Geoscience Australia earthquake database).

A requirement to assess seismic hazard is the determination of the location of past earthquake activity by identification and characterisation of seismogenic faults. However, establishing the location of past seismicity is difficult in the southwest of WA, and in intraplate regions in general, due to:

- the usually very long recurrence between earthquakes (thousands, hundred of thousand years or more)
- the subtle nature of the earthquake surface expression due to erosion of associated geomorphological evidence
- the potential occurrence of earthquakes over vast areas (with unclear association with evident tectonic mechanisms)

Consequently, the evidence of seismogenic faults associated with past earthquake activity in WA may be very subtle, hidden by vegetation or deposition or destroyed by erosion.

In this paper we will summarise the methods and tools used to recognise intraplate seismogenic faults in the southwest of WA. We will describe these methods by using specific examples from their application on two structures: the newly recognised Dumbleyung Fault Scarp and the Lort River Fault scarp. The methods described here were systematically used to assess the seismogenic nature of the Dumbleyung and Lort River scarps before undertaking specific paleoseismological investigations.

2 CHARACTERISTICS OF THE SOUTHWEST OF WESTERN AUSTRALIA

The southwest of WA has very subdued topography and is formed on ancient geology (Figure 2). The main geological entity in the region is the Archaean Yilgarn Craton, which is bounded to the south by the Proterozoic Albany-Fraser Orogen and to the west by the Pinjarra orogeny (Wilde et al., 1996; Myers, 1985, 1990a, 1990b). Phanerozoic basins such as the Eucla and Bremer Basins to the south, and the Perth Basin to the west, overlay the rocks of the Albany-Fraser and the Pinjarra Orogens, respectively (Cockbain, 1990; Hocking, 1990).

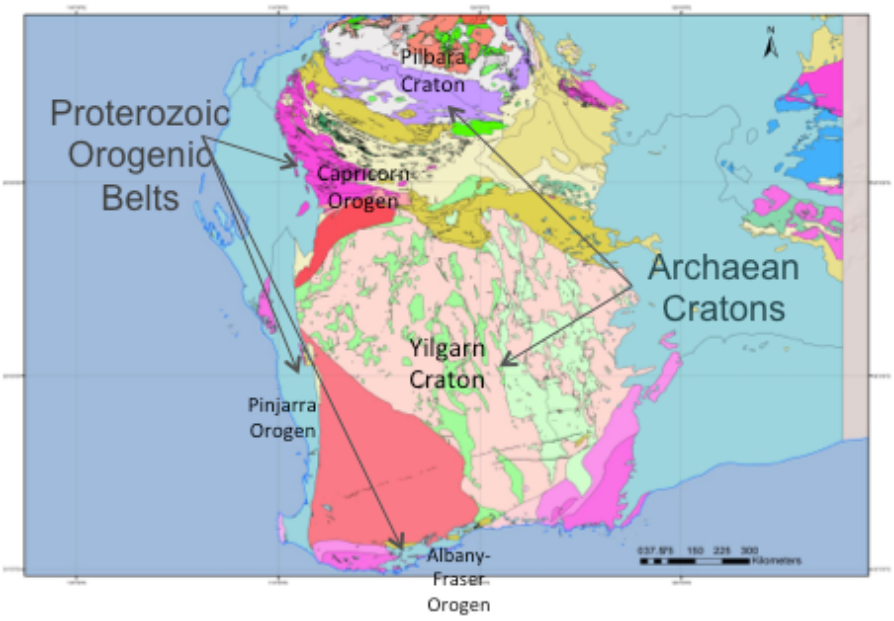

Figure 2. Geology of WA.

2.1 The South West Seismic Zone and surface rupturing earthquakes

The SWSZ is a north-northwest trending belt of seismic activity that cuts across the southwest corner of WA (Figure 1). It occurs about 150 km east of Perth and has been one of the most seismically active areas in Australia over the past 45 years (Leonard, 2008; Geoscience Australia earthquake database – GAED). Thousands of earthquakes have been recorded in the SWSZ including the surface rupturing and destroying events of Meckering (1968), Calingiri (1970), and Cadoux (1979). Many swarm events have also taken place; the most notable close to Burakin, which has been active since 2000 (Figure 1; Leonard, 2008).

Seismicity in the SWSZ is typically shallow, occurring at depths less than 20 km. Most of the recent significant earthquakes have been reported at depths of less than 10 km (Gordon and Lewis, 1980; Lewis et al., 1981, Leonard, 2008; GAED). Interestingly, the location of the current earthquake activity of the SWSZ is not associated with places of higher relief as is usually the case in interplate regions.

The causative faults associated with the recent destructive earthquakes of Meckering, Calingiri and Cadoux reached and ruptured the surface (Figure 3; Gordon and Lewis, 1980; Lewis et al., 1981). The M_L 6.9 Meckering earthquake was associated with a main fault scarp of 37 km of length and 3.5 m of maximum total displacement (Gordon and Lewis, 1980). The M_L 5.9 Calingiri earthquake was associated with a 3.24 km long fault scarp (Gordon and Lewis, 1980), whilst the M_L 6.2 Cadoux earthquake resulted on a complex set of faults and fractures formed in a north-south trending zone approximately 15 km long and 3 km wide (Lewis et al., 1981).

3 METHODS AND TOOLS TO RECOGNISE INTRAPLATE SEISMOGENIC FAULTS

The association between the Meckering, Calingiri and Cadoux earthquakes with surface rupturing faults and fault scarps prompted Geoscience Australia (Clark, 2004 and 2010) to conduct an investigation to search for morphologically similar features that could relate to pre-historic earthquake events. High-resolution digital elevation models, DEMs, (10m Landgate DEMs) were used to identify scarps potentially associated with pre-historic surface-rupturing earthquakes.

The DEM analysis resulted in the identification of more than 80 scarps-like features (Figure 3). A detail of a DEM showing one of these scarps (Dumbleyung Scarp) is shown in Figure 4. The recognised scarps are not confined to places of enhanced current seismicity such as the SWSZ. Instead, they are widely distributed across the low-relief cratonic rock of southwest WA.

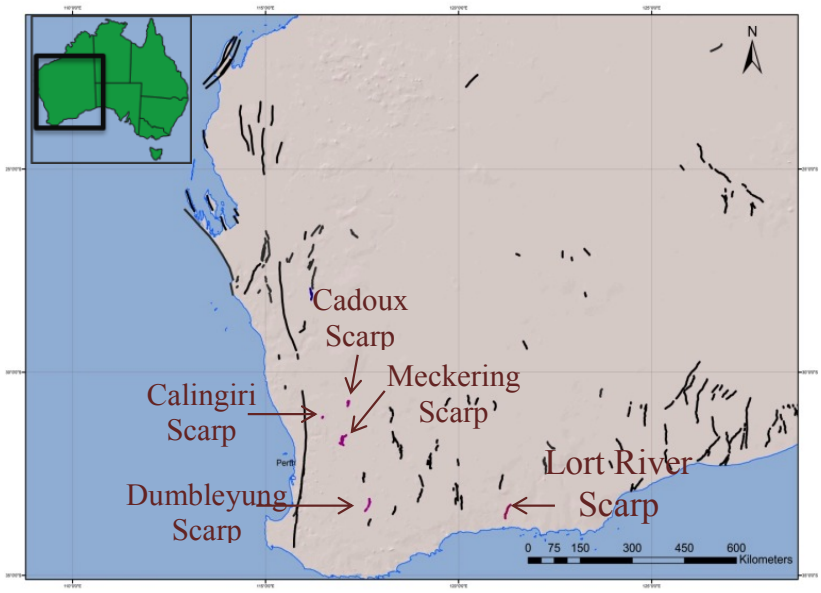

Figure 3. Scarps recognised by Clark (2004) in WA using DEMs. The scarps referred herein are highlighted.

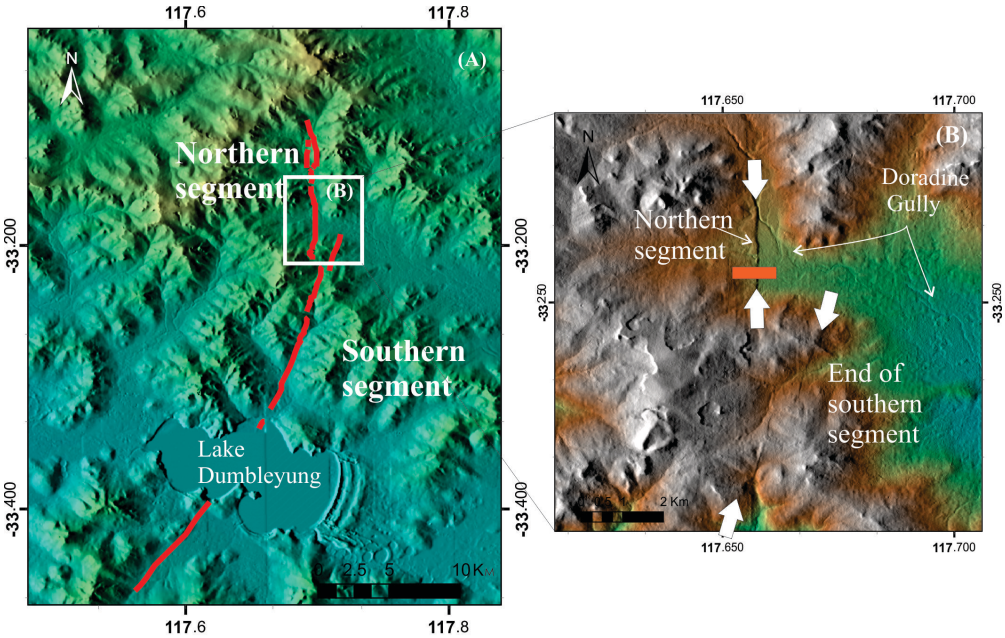

Figure 4. Identification of the Dumbleyung Scarp from DEMs. The scarp location is shown in Figure 3. (A) DEM showing the scarp's northern and southern segments, (B) detail of the northern and southern segments (shown by the white arrows). The location a subsequent paleoseismological trench across the scarp is shown by the orange rectangle.

Confirmation that the scarps identified by Clark are in fact associated with past earthquakes may significantly affect the perception of seismic hazard in WA

Ideally, trenches for detailed paleoseismological investigations excavated across the scarps could confirm or deny their earthquake genesis. However, paleoseismological investigations are time consuming and expensive, so other methods and tools have been used to recognise the potential seismogenic nature of the scarps before undertaking detailed investigations. The application of these tools aims to narrow the number of scarps selected for paleoseismological trenches to maximise resources and increase the probability of success in recognition of seismogenic faults.

Following the recognition of scarps on DEMs, the tools and methods used to recognise potentially seismogenic scarps in the southwest of WA include:

1. analysis of tectonic geomorphology of the recognised scarps
2. examination of nearby drainage to infer tectonic deformation
3. use of shallow geophysical surveys such as ground penetration radar (GPR) and magnetic surveys to confirm faulting associated with the scarps and geological context

The following sections illustrate the use of the above tools by using specific examples of their systematic application on two fault scarps from the southwest of WA. The majority of the examples are related to the Dumbleyung Scarp, a feature originally discovered by the DEM analysis undertaken by Clark (2004 and 2010), and to a lesser extent to the Lort River Scarp which has been previously confirmed as associated with faulting (Thom, 1972; Crone et al., 1997). The tools were used prior to the selection of these scarps for detailed paleoseismological studies.

The Dumbleyung Scarp is a 36 km long feature identified approximately 6 km to the west of the town of Dumbleyung and approximately 230 km southeast of Perth (Figures 3 and 4). DEM and aerial photo interpretation showed the scarp as a prominent and well preserved northeast trending feature.

Similarly, the Lort River Scarp is a 40 km long north-south trending feature located approximately 540 km southeast of Perth, and approximately 75 km northwest of Esperance (Figure 3). The Lort River Scarp is relatively sharp and continuous over most of its 40 km length. The scarp was initially described by Thom (1972) and has been the subject of previous paleoseismological investigations (Crone et al., 1997).

3.1 Tectonic geomorphology and drainage analysis

After the initial recognition of the scarp-like features on DEMs, detailed analysis of both the scarp morphology and the characteristics of the nearby drainage is undertaken to identify the scarp's potential association with earthquake deformation. The analysis of tectonic geomorphology may include but is not limited to:

- field reconnaissance
- topographic surveys
- scarp modelling
- analysis of drainage

The aim of the field reconnaissance is to rank scarps according to geomorphological expression. We look for prominent, well preserved and continuous features that may be morphologically different and/or apparently unrelated to their geomorphological context. Following the field reconnaissance, the scarps with the most youthful geomorphological expression are selected for topographic surveys and drainage analysis.

Figure 5 shows an example of the results from the topographic surveys on the Dumbleyung Scarp. In this case, topographic profiling using a Total Station was required as the best resolution DEM available (the 10m Landgate DEMs) has a vertical resolution in the order of 1-1.5 m. The scarp shows significant differences in height and form between its northern and southern segments. These differences may be used to model scarp segmentation and the characteristics of the underlying fault.

Figure 6 illustrates an example of scarp modelling based on a topographic section across the Dumbleyung Scarp by using Trishear modelling (Erslev, 1991; Allmendinger, 1998; Allmendinger and Shaw, 2000). In this particular case, the scarp morphology was modelled as the result of movement along a blind trust fault dipping 30 degrees to the west. The scarp morphology is associated with a propagation fold developed at the tip of a blind fault. The modelling result is consistent with the style and orientation of deformation predicted from the compressive east-west oriented regional stress in the southwest of WA.

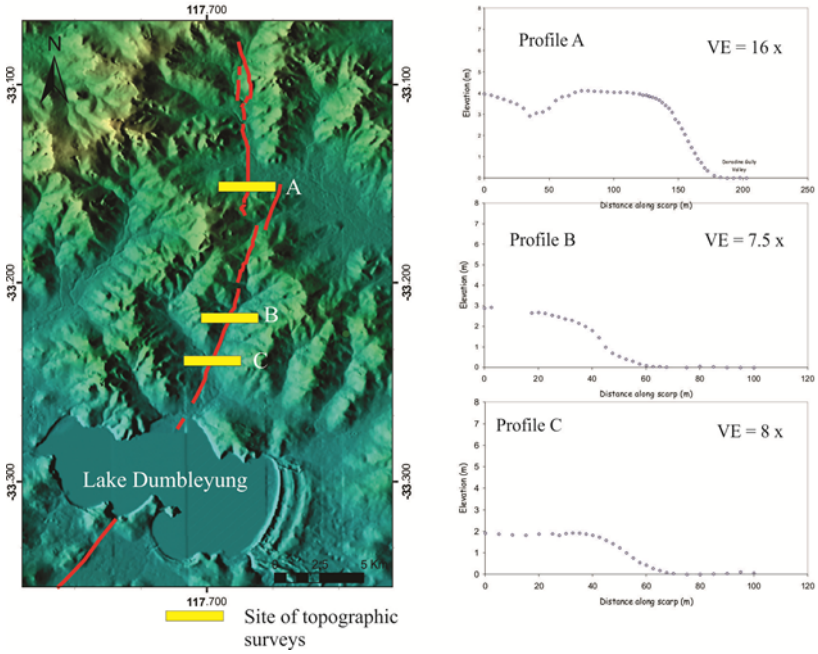

Figure 5. Example of surveyed profiles across the Dumbleyung Scarp showing differences in scarp morphology and height.

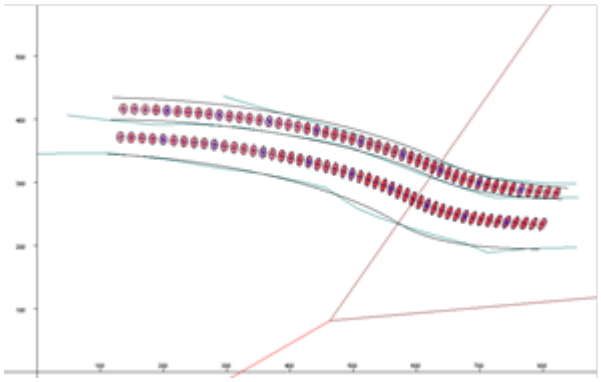

Figure 6. Modelling of the Dumbleyung Scarp (Trishear model) indicating that the scarp morphology may result from movement on a blind thrust fault (fault tip 3 m below surface) dipping 30 degrees to the west.

The drainage nearby the scarp is also assessed. Rivers can be very useful indicators of earthquake deformation because of their sensitivity to subtle changes along their channel (Schumm et al., 2000; Snyder et al., 2000; Mather and Hartley, 2006, Wobus et al., 2006, Burbank and Anderson, 2011).

Effects of earthquake movement on nearby drainage may include:

- changes in the longitudinal river profile (i.e. deviation from an expected concave equilibrium profile; Hack, 1973; Burbank and Anderson, 2011)
- changes in river channel direction
- damming and development of ponds
- changes in sinuosity and/or channel bed incision
- occurrence of river aggradation or degradation

Figure 7 shows how the Dumbleyung Scarp appears to affect the nearby Meinmuggin and Washpool gullies by changing their course. The presence of abandoned channels (inside the ellipse in Figure 7) suggests that the Meinmuggin and Wash Pool gullies appeared to have once flowed as a single channel. Current drainage characteristics suggest that the scarp has forced these gullies to separate, resulting in the Meinmuggin and Washpool gullies currently paralleling both sides of the scarp. The characteristics of the drainage therefore, further support that earthquake deformation hast taken place along the scarp.

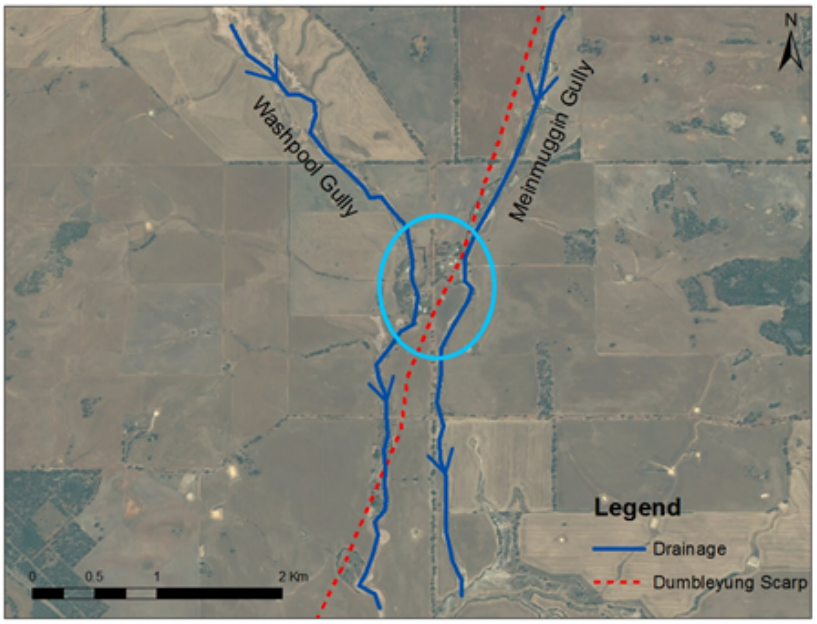

Figure 7. Effects of the Dumbleyung Scarp on the drainage. The scarp is represented by the red dashed line between the two blue solid lines representing the Washpool and the Meinmuggin gullies. The ellipse shows the location where the gullies were apparently joined before being forced to separate by deformation on the scarp. The location of this Figure coincides with the location of the topographic profile C shown in Figure 5.

3.2 Geophysical surveys

In shallow soil, weathered bedrock dominated environments, geophysical methods such as ground penetrating radar (GPR) and aeromagnetic surveys may be used to confirm the presence of faults associated with the scarps and determine their geological context (Dentith et al., 2009 and 2010). In alluvial environments, these techniques might be augmented by electrical resistivity imaging (ERI) and/or seismic reflection to define the relationship between faulting and sedimentary/lithological layering below the level that a trench might reach (Dentith et al., 2009).

Aeromagnetic surveys and GPR have been used to assist in the identification and characterisation of seismogenic faults in WA. Figure 8 shows an aeromagnetic survey over the Lort River Scarp. This survey showed the extent of the fault scarp and its association with a lithological contact in the Precambrian basement rocks.

Figure 9 shows GPR data across the Dumbleyung Scarp. In this particular case, and in contrast with the methods described above, the GPR survey was carried out after a paleoseismological trench was excavated across the scarp. The GPR profile was located along the trench illustrated in Figure 4 (orange rectangle).

The Dumbleyung GPR data shows folding of the stratigraphy on the fault zone although none of the individual stratigraphic units can be recognised with confidence. Some evidence for faulting is associated with the disruption of basement responses and the apparent increase in frequency of the GPR responses. The GPR data mostly depicts folding, consistent with propagation folding associated with a blind fault observed during trenching (Figure 10). Therefore, the Dumbleyung GPR survey demonstrates the ability for GPR to be a useful screening tool prior to conducting more expensive trenching studies.

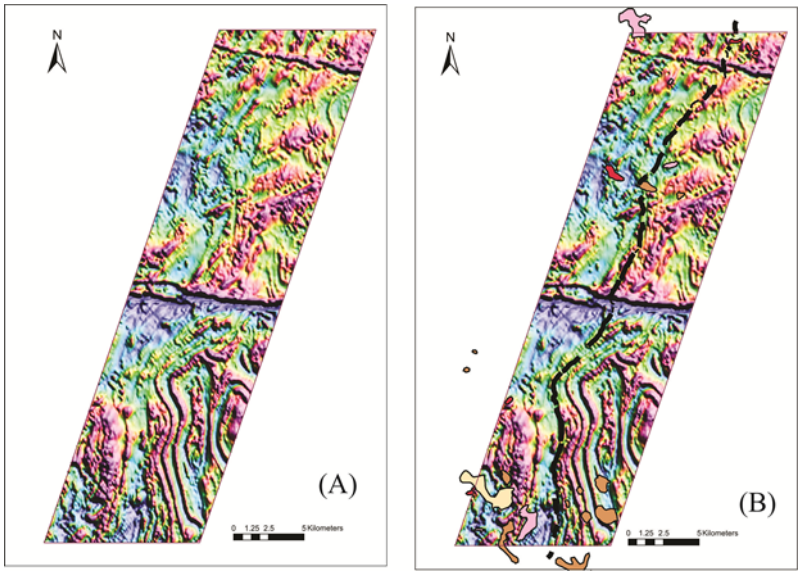

Figure 8. Total field magnetic data from the Lort River Scarp. (A) Field magnetic data. (B) Field magnetic data with the location of the Lort River Scarp superimposed (thick black line). Modified from Estrada, 2009.

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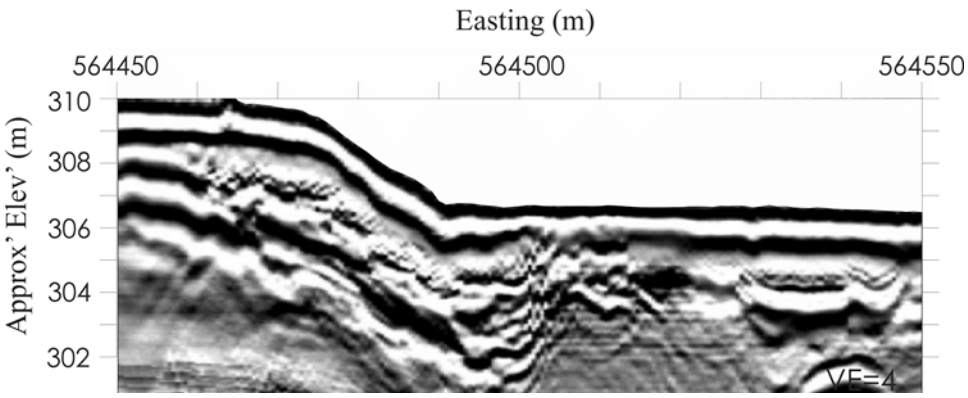

Figure 9. GPR data across the Dumbleyung Scarp (modified from Dentith et al., 2010) showing fault propagation folding.

4 APPLICATION

The Dumbleyung and Lort River scarps were selected for detailed paleoseismological studies after the evaluation of their scarp geomorphology, the characteristic of their nearby drainage and the geophysical data.

The paleoseismological trenches across the Dumbleyung and Lort River Scarps confirmed their association with seismogenic faults and revealed their recent earthquake history. The methods and tools briefly discussed above were effective not only in identifying scarps associated with earthquake deformation in the south west of WA but also in assisting in the selection of appropriate location for paleoseismological trenches.

Figure 10 and 11 show two of the paleoseismological trenches excavated across the Dumbleyung and the Lort River Scarps, respectively. The paleoseismological investigations on both scarps confirmed their association with recurrent large pre-historic earthquake events with magnitudes reaching up to M_w 7.0.

The detailed results from the paleoseismological investigations are not published here due to space constrains but further information can be found in previous publications (i.e. Estrada, 2009).

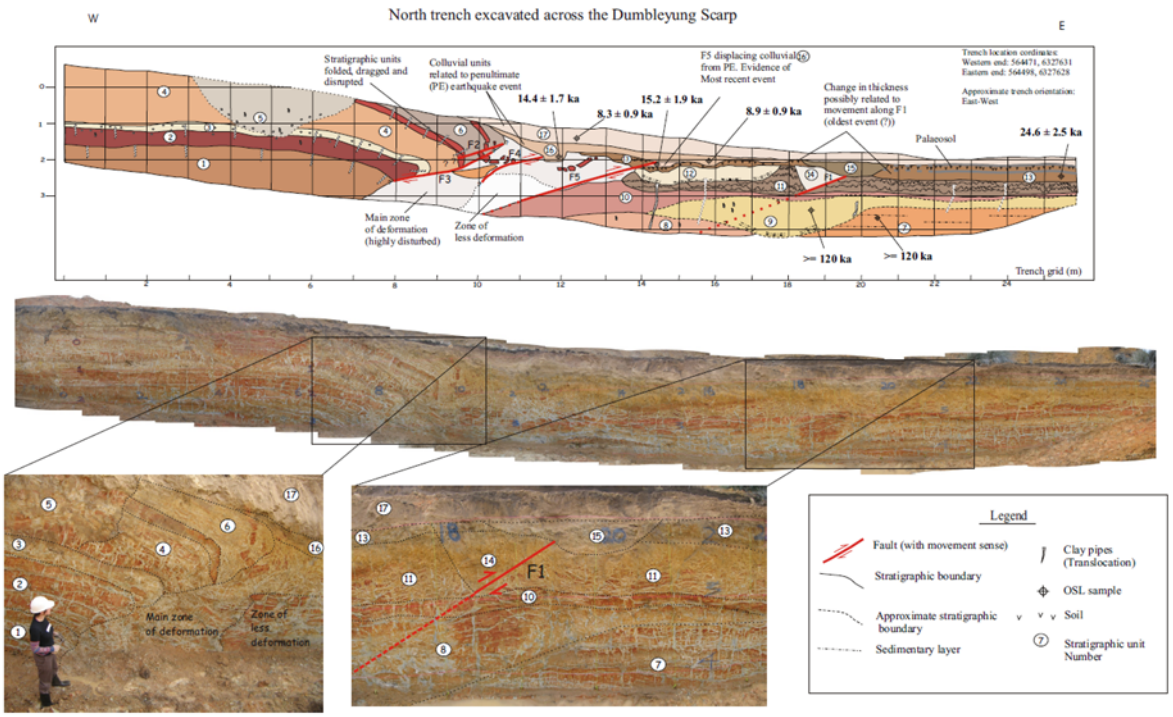

Figure 10. Paleoseismological investigation across the Dumbleyung Scarp confirming that the scarp is associated with a seismogenic fault. The fault is interpreted as capable of generating long recurrence interval earthquakes with magnitudes reaching up to M_w 7.0 (From Estrada, 2009).

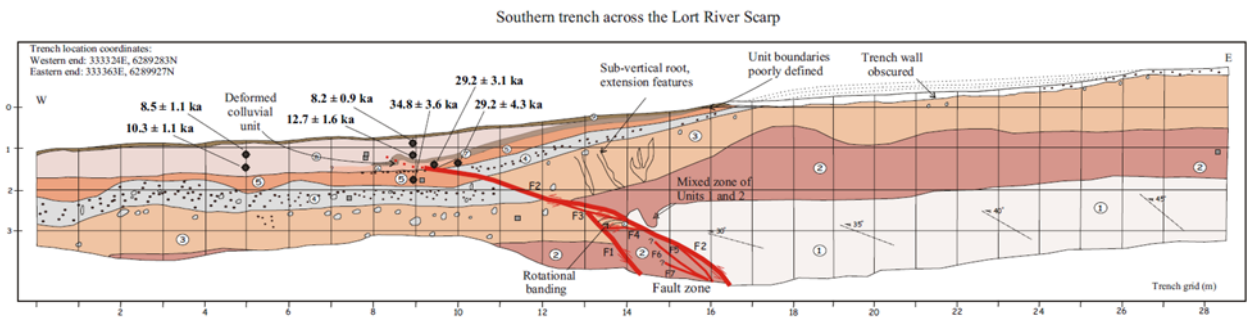

Figure 11. Trench interpretation of the Lort River Scarp showing faulted stratigraphy (From Estrada, 2009).

5 CONCLUSIONS

Detailed analysis of high resolution DEMs in the southwest of WA resulted in the identification of tens of scarp-like features potentially associated with strong earthquake activity. The confirmation of the seismogenesis of these features will have a strong impact in the assessment of the seismic hazard in the region.

Due to the large number of identified scarps, it is not viable to undertake detailed paleoseismological studies on each of the identified features. Consequently, different tools and methods are employed to recognise the scarps with the highest potential of being the result of recent earthquake activity.

The used tools include:

1. analysis of tectonic geomorphology

2. drainage analysis to infer tectonic deformation
3. shallow geophysical surveys such as ground penetration radar (GPR) and magnetic surveys to confirm faulting and geological context

The application of the above relatively inexpensive tools has proven to be effective in ranking scarps to concentrate on those more likely to be associated with earthquake deformation.

Subsequent trenching for paleoseismological investigations across two scarps, the Dumbleyung and Lort River Scarps, analysed using these tools confirmed their association with faulting and revealed their recent earthquake history. Both structures show recurrent earthquakes, separated by thousands of years, with magnitudes up to 7.0. The application of the methods and tools briefly discussed here not only aid in the identification of seismogenic fault scarps but also assist in the selection of the best locations for paleoseismological investigations.

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