50th anniversary of the 14th October 1968 Mw 6.5 (Ms 6.8) Meckering earthquake

Australian Earthquake Engineering Society Pre-conference Field Trip, Meckering, 15 November 2018.

D.Clark and M. Edwards.
50\textsuperscript{th} anniversary of the 14\textsuperscript{th} October 1968 $M_w$ 6.5 ($M_s$ 6.8) Meckering earthquake

Australian Earthquake Engineering Society Pre-conference Field Trip, Meckering, 15 November 2018.

GEO SCIENCE AUSTRALIA
RECORD 2018/39

D.Clark and M. Edwards
## Contents

<table>
<thead>
<tr>
<th>Section</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>Itinerary</td>
<td>1</td>
</tr>
<tr>
<td>Introduction: The 14th October 1968 Mw6.5 Meckering earthquake</td>
<td>3</td>
</tr>
<tr>
<td>Geology and Geography of Southwest Western Australia</td>
<td>3</td>
</tr>
<tr>
<td>Regional Seismicity and Tectonic Setting</td>
<td>5</td>
</tr>
<tr>
<td>The 1968 Meckering Earthquake and Surface Rupture</td>
<td>5</td>
</tr>
<tr>
<td>Intensity, Damage to the Built Environment and Social impact</td>
<td>8</td>
</tr>
<tr>
<td>Stop 1: Meckering (new) town site</td>
<td>12</td>
</tr>
<tr>
<td>Heritage Park</td>
<td>12</td>
</tr>
<tr>
<td>Meckering Town Hall</td>
<td>14</td>
</tr>
<tr>
<td>Meckering earthquake Heritage Walk</td>
<td>15</td>
</tr>
<tr>
<td>Stop 2: Salisbury Ruin</td>
<td>17</td>
</tr>
<tr>
<td>Mortlock River floodplain liquefaction study (2003)</td>
<td>17</td>
</tr>
<tr>
<td>Salisbury Ruin</td>
<td>19</td>
</tr>
<tr>
<td>Stop 3: North paleoseismic trench location (2005)</td>
<td>21</td>
</tr>
<tr>
<td>Stop 4: Fault scarp reserve</td>
<td>25</td>
</tr>
<tr>
<td>Intersection of the scarp with the Mortlock River</td>
<td>25</td>
</tr>
<tr>
<td>Fault reserve</td>
<td>28</td>
</tr>
<tr>
<td>Stop 5: York town site</td>
<td>30</td>
</tr>
<tr>
<td>What have we learned about cratonic fault behaviour in the 50 years since the 1968 Meckering earthquake?</td>
<td>34</td>
</tr>
<tr>
<td>Summary</td>
<td>37</td>
</tr>
<tr>
<td>Acknowledgements</td>
<td>38</td>
</tr>
<tr>
<td>References</td>
<td>39</td>
</tr>
</tbody>
</table>
This report describes stops and presents background information for a pre-conference field excursion from Perth to Meckering, associated with the 2018 Australian Earthquake Engineering Society Conference. Some of the following site descriptions lend from publications created for the Meckering Earthquake 50th anniversary commemorative event. Meckering residents Rebekah Burges and Alice Snooke are warmly thanked for their interest and input.

Table 1 Field excursion provisional itinerary. The rough location of stops are shown on Figure 1.

<table>
<thead>
<tr>
<th>Location</th>
<th>Start Time</th>
<th>Duration</th>
<th>End Time</th>
<th>Comment</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aloft Motel Perth</td>
<td>7:30</td>
<td>0:30</td>
<td>8:00</td>
<td>Meet at 7.30am for an 8.00am departure</td>
</tr>
<tr>
<td>Drive to Stop1</td>
<td>8:00</td>
<td>1:30</td>
<td>9:30</td>
<td><a href="https://goo.gl/maps/aH8a13mE6Co">https://goo.gl/maps/aH8a13mE6Co</a></td>
</tr>
<tr>
<td>Meckering heritage park</td>
<td>9:30</td>
<td>0:20</td>
<td>10:00</td>
<td>Introduction to the Meckering earthquake (Dan Clark and Alice Snooke)</td>
</tr>
<tr>
<td>Meckering Town Hall</td>
<td>10:00</td>
<td>0:30</td>
<td>10:30</td>
<td>photo and document collection (Rebekah Burges)</td>
</tr>
<tr>
<td>Meckering heritage walk</td>
<td>10:30</td>
<td>0:40</td>
<td>11:00</td>
<td>Starts at the park, ends near the Sporting Club</td>
</tr>
<tr>
<td>Drive to Stop 2</td>
<td>11:00</td>
<td>0:15</td>
<td>11:15</td>
<td><a href="https://goo.gl/maps/zN7e7TTLEvL2">https://goo.gl/maps/zN7e7TTLEvL2</a></td>
</tr>
<tr>
<td>Salisbury House</td>
<td>11:15</td>
<td>0:20</td>
<td>11:35</td>
<td>Alice Snooke</td>
</tr>
<tr>
<td>Drive to Stop 3</td>
<td>11:35</td>
<td>0:15</td>
<td>11:50</td>
<td><a href="https://goo.gl/maps/mWDc6XQcbun">https://goo.gl/maps/mWDc6XQcbun</a></td>
</tr>
<tr>
<td>2005 Trench site</td>
<td>11:50</td>
<td>1:00</td>
<td>12:50</td>
<td>~ 1.3 km round trip walk</td>
</tr>
<tr>
<td>Drive to Stop 4</td>
<td>12:50</td>
<td>0:15</td>
<td>13:05</td>
<td><a href="https://goo.gl/maps/BRe47Jckhvo">https://goo.gl/maps/BRe47Jckhvo</a></td>
</tr>
<tr>
<td>Fault scarp reserve</td>
<td>13:05</td>
<td>1:00</td>
<td>14:05</td>
<td>pre-packed lunch</td>
</tr>
<tr>
<td>Drive to Stop 5</td>
<td>14:05</td>
<td>0:30</td>
<td>14:35</td>
<td><a href="https://goo.gl/maps/sTQyRPRaBKw">https://goo.gl/maps/sTQyRPRaBKw</a></td>
</tr>
<tr>
<td>York</td>
<td>14:35</td>
<td>2:00</td>
<td>16:35</td>
<td>Catholic Church, walking tour, afternoon tea</td>
</tr>
<tr>
<td>Drive to Perth</td>
<td>16:35</td>
<td>1:20</td>
<td>17:55</td>
<td><a href="https://goo.gl/maps/JAoE41yW9W12">https://goo.gl/maps/JAoE41yW9W12</a></td>
</tr>
<tr>
<td>Feral Brewery</td>
<td>17:55</td>
<td>2:00</td>
<td>19:55</td>
<td>dinner</td>
</tr>
<tr>
<td>Return to accommodation</td>
<td>19:55</td>
<td>0:45</td>
<td>20:40</td>
<td><a href="https://goo.gl/maps/phLnZcCmvw82">https://goo.gl/maps/phLnZcCmvw82</a></td>
</tr>
<tr>
<td>Aloft Motel Perth</td>
<td>20:40</td>
<td></td>
<td>20:40</td>
<td>Perth</td>
</tr>
</tbody>
</table>
Figure 1 Map of the 1968 Meckering earthquake fault scarp (after Gordon and Lewis, 1980). The scarp is 37 km long and is up to 2 – 2.5 m high. Red star marks the revised epicentre location (Somerville et al., 2010). Excursion stop locations marked with blue dots. Blue dashes show locations where trenches were excavated to investigate how often large earthquakes occur on this fault. Blue-green shading highlights the Mortlock River Valley. Inset shows published focal mechanisms for the main shock (after Dentith et al., 2009); (a)Fitch et al. (1973), (b) Vogfjörd and Langston (1987), (c) Fredrich et al. (1988).
Introduction: The 14th October 1968 $M_W$6.5 Meckering earthquake

At 10.59 am on 14 October 1968, the town of Meckering, approximately 110 km ENE of Perth, was destroyed by an $M_W$ 6.5 earthquake. Approximately twenty people were injured, but incredibly, no one was killed (Gordon and Lewis, 1980). The Meckering earthquake is the second largest recorded onshore earthquake in Australia (Storchak et al., 2015), and remains one of the most significant in Australian history in terms of the damage to infrastructure and the subsequent cultural upheaval. The earthquake occurred in a well-documented zone of enhanced seismicity known as the Southwest Seismic Zone (Doyle, 1971), and was associated with a surface faulting that extended for 37 km and locally reached up to 2-3 m high (Figure 1). The 1968 Meckering earthquake was the first of nine historic earthquakes in Australia documented to have produced a surface scarp. All nine have occurred in the ancient cratonic rocks of central and western Australia, and none show evidence to suggest a prior event in the geologically recent past (Clark and Allen, 2018). This raises the question of whether the interplate models commonly used in seismic hazard analyses to describe earthquake recurrence in intraplate cratonic regions are appropriate.

Geology and Geography of Southwest Western Australia

The bus departs from the relatively flat landscape of the Perth Coastal Plain and quickly climbs up onto the Darling Range (Perth Hills) towards Mundaring. The western margin of the Darling Range is bound by one of the more prominent geological boundaries in Australia, the ~1000 km long, steeply west-dipping Darling Fault (Dentith et al., 1994; Middleton et al., 1995) (Figure 2). On the western side, the Precambrian Pinjarra Orogen (e.g. Fitzsimons, 2003; Janssen et al., 2003) floors late Palaeozoic and Mesozoic rocks of the Perth Basin. The basin sequence was deposited in response to the breakup of Australia with Greater India and reaches a maximum thickness of approximately 10 km (e.g. Veever, 1972; Dentith et al., 1994; Mory et al., 2005). Phanerozoic rocks are overlain by a thin sequence of sands, limestones, silts, clays, and gravels of marine, estuarine, and eolian origin, which interfinger with colluvial material proximal to the foot of the Darling Ranges (Gozzard, 2007).

East of the Darling Fault are the Archaean rocks of the Yilgarn Craton. The majority of the Yilgarn Craton comprises granitoid-greenstone rocks which range in age from 3.0 and 2.6 Ga (Wilde et al., 1996). Proximal to Meckering bedrock comprises Achaean granitoids, high-grade metamorphic rocks (the Jimperding Metamorphic Belt) and Proterozoic dykes. The local terrain is subdued and outcrop is exceptionally poor. The most detailed description of the geology of the Meckering area is that of Lewis (1969). Exposed bedrock consists of poorly-exposed mafic (quartz dolerite) dykes that intrude various types of granitoid.

Cratonization was complete by 2.6 Ga, since which time deformation has largely been localized to marginal mobile belts (e.g. the Pinjarra Orogen to the west and Albany-Fraser Orogen to the south, Figure 2). Post cratonisation mafic dykes, comprising a number of swarms with different orientations and ages, are common in the Yilgarn Craton (Hallberg, 1987). The dykes near Meckering have a variety of orientations. The dominant trend is northeast–southwest. The dykes vary in width from tens of centimetres to around 30 m (Dentith et al., 2009). Superficial deposits consist of massive ferricrete,
iron-rich pisolitic gravel and aeolian sand and alluvium. Lines of drainage along valley floors typically overlie buried inset valleys that can contain Tertiary fluvial sedimentary fill (de Broeckert and Sandiford, 2005). What information is available suggests the cover thickness is a few metres, increasing to tens of metres in drainage channel areas (e.g. Anand and Pain, 2002; De Silva and Smith, 2010; Bell et al., 2012).

The river morphology developed on the Yilgarn Craton transitions between stagnant drainage to the east of Meckering (broad, infilled paleo-valleys and salt pans with sluggish and intermittent drainage), and the rejuvenated drainage to the west (relatively narrow-floored and steep-sided with higher gradients). This geomorphic transition occurs along a NNW-trending trend which is called the Meckering line (Jutson, 1934; Figure 2), which roughly corresponds with a gravity feature called the Cape Riche – Yandanooka lineament (Everingham, 1965; Doyle, 1971). The Meckering line also parallels isohyetal lines (http://www.bom.gov.au/jsp/ncc/climate_averages/rainfall/index.jsp), and the continent-scale axis of tilt proposed by Sandiford (2007). Initiation of uplift of the southwest margin of Australia across this tilt axis is thought to have occurred in the Neogene, largely after ca. 15 Ma (Sandiford, 2007; Czarnota et al., 2014), and well explains the rejuvenation of drainage (e.g. Jakica et al., 2010).

Figure 2 Fault scarps and earthquakes (1885 – 2010) in the Southwest Seismic Zone (modified after Clark, 2010). The scarps were discovered using a combination of the 10 m resolution DLI Landmonitor digital elevation model, and the 90 m Shuttle Radar Tomography Mission digital elevation model. The even distribution of scarps is consistent with very little strain accumulation (i.e. recurrence) occurring on individual faults. Thin grey lines show major geological boundaries (Shaw et al., 1996). Grey shaded regions to the west and south of the Yilgarn Craton are the Pinjarra and Albany-Fraser Orogens, respectively. The solid black line separating the Pinjarra Orogen and the Yilgarn Craton is the Darling Fault. Heavy dashed black line is the Meckering line (after Anand and Butt, 2010).
Regional Seismicity and Tectonic Setting

The distribution of historic earthquake epicentres in the southwest of Western Australia is heterogeneous, with a generally low level of seismicity being characteristic of much of the area (Figure 2). A relatively high level of seismicity is characteristic of a broad band crossing the SW corner. This band is known as the Southwest Seismic Zone (SWSZ, Doyle, 1971). The SWSZ is one of the most seismically active regions in Australia (e.g. Leonard, 2008; Allen et al., 2018b). Earthquake activity appears to have increased significantly since the 1940s (Leonard, 2008), and it has generated five of the nine known Australian historic surface ruptures; 1968 Meckering, 1970 Calingiri, 1979 Cadoux, 2007 Katanning and 2018 Lake Muir (e.g. Gordon and Lewis, 1980; Lewis et al., 1981; Dawson et al., 2008). In addition to large events and scattered smaller events, the SWSZ has produced several dozen earthquake swarms in the last 40 years, including the Burakin swarm of 2001 which resulted in the recording of 18,000 events in a period of only a few months (Leonard, 2002; Dent, 2016). While most swarm centres occur within the SWSZ, they have a broader distribution across the southwest of Western Australia, similar to fault scarps relating to pre-historic events (Figure 2).

The uniform distribution of northerly trending reverse fault scarps is consistent with scarp formation under conditions imposed by the contemporary E-W oriented compressive crustal stress regime (e.g. Rajabi et al., 2017), and suggests that strain is uniformly distributed over the Yilgarn Craton over the timescale recorded in the land surface (ca. 100 kyr or more) (Leonard and Clark, 2011). These observations, when combined with the above evidence, are consistent with a seismicity/crustal strain model whereby the ductile part of the lithosphere deforms uniformly in response to an imposed easterly trending contractional strain, and the upper (seismogenic) layer accommodates this large-scale flow by localized, transient brittle deformation along lines of pre-existing crustal weakness (cf. Braun et al., 2009). Generally low bedrock erosion rates (Belton et al., 2004), combined with an absence of well-defined ranges bound by faults (Clark, 2010), provide an upper bound on relief generation on individual faults of ~ 5 m /Myr (and hence limits the potential for recurrence of large events).

The 1968 Meckering Earthquake and Surface Rupture

The Meckering earthquake produced a 37 km long arcuate surface rupture that locally reached up to ~2-3 m in height (Figure 1). The characteristics of the rupture are described in considerable detail by Gordon and Lewis (1980); their study includes detailed maps of the distribution of faults and associated structures and determination of displacement at the surface. Broadly, the rupture comprised a northeast trending northern part characterised by dextral reverse motion, a central northerly trending part characterised by thrust motion with a minor dextral component, and a southern southeast trending part characterised by dominant reverse motion. The dip of the rupture plane, measured on the surface, varies between 35° and 52° towards the concave side (east) of the arc. The maximum displacements occurred on the central northerly trending segment, as would be expected in the extant E-W trending compressive stress field (cf. Rajabi et al., 2017) (Figure 3). A sinistral component to motion that might be expected on the southern section (e.g. Dentith et al., 2009) was not observed, potentially as the result of local rotation of the stress field (cf. Faulkner et al., 2006).
Figure 3 Section of the 1968 Meckering surface rupture between the Eastern Highway and the railway line, looking northeast. This section of scarp will be examined at Stop 3. Note the difference between the 1968 landscape, and the current landscape (Figure 16 upper panel). Photo taken by Ian Everingham (BMR).

At the time that Gordon and Lewis (1980) wrote their seminal volume, sparse outcrop prevented the relationship between surface faulting and bedrock geology from being fully understood. New aeromagnetic data have defined anomalies of structural and lithological origin that allow bedrock geology to be mapped with considerably more confidence (Dentith et al., 2009). The pattern of surface faulting is shown to be controlled by combinations of northwest–southeast trending, northeast–southwest trending, and linking northerly trending structures in the basement (Figure 4a). Dentith et al. (2009) interpret the northeast trending structures to be faults and dykes, and the northwest structures to exploit lithological contacts within the Jimperding Metamorphic Belt.

The marked pre-1968 excursion of the westerly course of the Mortlock River, to parallel the 1968 scarp over a distance of ~10 km (e.g. Gordon and Lewis, 1980) (Figure 4b), does not appear to have occurred in response to prior neotectonic events. The present Mortlock River course follows a Tertiary paleovalley (e.g. de Broeckert and Sandiford, 2005; Bell et al., 2012) that is entrenched into the very slowly eroding landscape (Belton et al., 2004). There is no evidence in the landscape for an abandoned channel continuing to the west across the scarp, implying that the current course of the river is ancient. A topographic profile constructed up the Mortlock River Valley (Figure 4b) is consistent with this interpretation, comprising three elements: (1) an upstream section with an average fall of ~0.5 m/km relating to the stagnant drainage regime east of the Meckering line, (2) a downstream section with a steeper gradient of ~1.1 m/km relating to the rejuvenated drainage regime west of the Meckering Line, and (3) a small perturbation on the larger exponential curve of the rejuvenated drainage section relating to the 1968 Meckering scarp. The rejuvenated drainage section relates to the farthest upstream penetration of knickpoints that originated at the coast in the last ca. 15 Ma (Sandiford, 2007; Czarnota et al., 2014). It would therefore be bold to interpret the location of the Meckering surface rupture straddling this boundary as being other than coincidental. That being said, kilometre-scale eastward tilting of the uplifted side of the 1968 Meckering rupture has resulted in increased stagnation and salinization of the Mortlock River floodplain east of Meckering.
Figure 4 Surface rupture relating to the 1968 Meckering earthquake. Blue line shows the location of the Mortlock River, and the pink dot shows the physical location of the Meckering Line in the Mortlock River bed. (a) Total Magnetic Intensity greyscale image – 2015 – from the Meckering area. Interpretation of NE-trending lineaments as faults and dykes, and NW-trending lineaments as being lithological trends relating to the Jimperding metamorphic belt from Dentith et al. (2009). (b) ALOS 30 m DEM data. Note that the southerly bend in the Mortlock River follows the line of an ancient paleo-valley. There is no topographic evidence to support the concept that the river has been recently deflected to the south consequent of prior events on the faults underlying the 1968 Meckering scarp. More plausible is that the river follows ancient bedrock structures, as imaged in the aeromagnetic data. (c) topographic profile down the Mortlock River Valley obtained using ALOS 30 m DEM data. Note that the 1968 Meckering scarp is a small perturbation on the larger pattern of headward retreat of a knickpoint (originating at the coast) eroding to the east into the region of stagnant drainage east of the Meckering Line.

Consistent with the complex pattern of surface rupture, the Meckering earthquake itself was found to be seismologically complex (Fitch et al., 1973; Vogfjörd and Langston, 1987; Fredrich et al., 1988). There is general agreement that the Meckering event involved predominantly compressional failure (see focal mechanisms on Figure 1), that the hypocentre was at a depth of ~ 3 km (e.g. Langston, 1987), and that approximately 3.5 seconds prior to the main shock there was a precursor event, although the type of failure involved is not known. Somerville et al. (2010) derived a finite rupture model for the earthquake by jointly inverting both geodetic data (surface offset and levelling) and teleseismic body waves. Three planar fault segments were used to account for the curved surface
fault traces relating to the event (Figure 5). The dip of each segment of the rupture plane was constrained to 37° towards the concave side (east) of the arc. The derived rupture model shows that the Meckering event first nucleated in the middle of the fault and propagated in a southerly direction, generating large deep slip in the southern-most segment (1-3 seconds after rupture initiation). It also generated significant shallow slip in the northern segment of the fault towards the end of the rupture sequence (>4 seconds) (Somerville et al., 2010). This slip is verified by large vertical offsets in this region.

Intensity, Damage to the Built Environment and Social impact

Four hundred and twenty intensity questionnaire forms were distributed to about five observers in the region of each township in a network selected to cover the State south of latitude 22°S, whilst a further eighty were distributed to residents of Perth, Fremantle and suburban areas (Everingham and Gregson, 1970). Approximately eighty percent of questionnaires were answered. Each town or centre was allotted an intensity rating, which is shown on Figure 6. Field visits were made in the region of Meckering in order to assess the higher intensities near the earthquake epicentre. Intensities in the range VII to IX were observed within roughly 14 kilometres of the earthquake fault zone, and the isoseismals were about parallel to the fault. Because of the sparse population and the rapid decrease of intensity away from the fault, the isoseismals were thought by Everingham and Gregson (1970) to be relatively inaccurate.

Figure 5 Rupture model estimated by inverting both geodetic (surface offset and levelling data) and teleseismic data jointly. Large deep slip in the southern segment is supported by the teleseismic data while large near surface slip is required by both surface offset and levelling (Somerville et al., 2010). The majority of energy release occurs in the first 5 seconds.
Gordon (1968) noted that houses were rendered useless up to 19 km east of the fault and 5 km west of the fault and that severe damage occurred in northerly and southerly directions along the fault trend to a distance of 30 km from Meckering. Gordon's first observation indicates that the energy sufficient
to cause say MM VIII intensities was propagated better towards the east than towards the west (Everingham and Gregson, 1970).

Gordon and Lewis (1980) reported comprehensively on damage to buildings in Meckering town. Below is an excerpt of their appraisal.

Prior to 14th October 1968, Meckering town contained 51 occupied dwellings, 12 private business premises and 15 buildings devoted to government, public or sporting uses. The ANZ Bank and the Railway Hotel were the only two-storied buildings, the remainder being single storied. There were no new public or commercial buildings. Many of the private houses were built from mud bricks manufactured on the site, and had been completed or embellished in a variety of materials. A few substantial brick houses reflected a recent tendency for local farmers to retire to the town to be near social and sporting amenities.

The following types of structure had been used: (1) timber frame, with wooden, asbestos, or brick-veneer cladding; (2) steel frame with corrugated iron, asbestos, or aluminium cladding; (3) reinforced concrete; (4) double brick, with some reinforcing; (5) double brick; (6) concrete block; (7) granite block or masonry; (8) sundried brick (mud batt); and (9) various combinations.

Buildings which survived the earthquake and were still usable came from construction types 1 to 4, and consisted of 16 houses and 3 business premises. An analysis of the performance of various types of construction is given in Table 2 which is a slightly modified version of a table presented by Smith (1969) from an architectural appraisal of damaged buildings in Meckering.

Extensive damage was also reported to public utilities and communications, including the Goldfields water supply pipeline, the Perth to Kalgoorlie Railway Line, and to the Great Eastern Highway.

### Table 2 Damage to buildings, Meckering Townsite (reproduced from Gordon and Lewis (1980) courtesy of the Geoscience and Resource Strategy Division, Department of Mines, Industry Regulation and Safety. © State of Western Australia 2018).

<table>
<thead>
<tr>
<th>Wall material</th>
<th>Buildings surveyed</th>
<th>Demolished</th>
<th>Minor damage</th>
<th>Negligible damage</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Number</td>
<td>Per cent of total</td>
<td>Number</td>
<td>Per cent of those surveyed</td>
</tr>
<tr>
<td>Timber</td>
<td>27</td>
<td>30.7</td>
<td>2</td>
<td>7.4</td>
</tr>
<tr>
<td>Steel frame</td>
<td>2</td>
<td>2.3</td>
<td></td>
<td></td>
</tr>
<tr>
<td>In situ concrete</td>
<td>1</td>
<td>1.1</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Brick veneer</td>
<td>1</td>
<td>1.1</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Brick or brick &amp; stone</td>
<td>32</td>
<td>36.4</td>
<td>31</td>
<td>97</td>
</tr>
<tr>
<td>Concrete block</td>
<td>4</td>
<td>4.5</td>
<td>4</td>
<td>100</td>
</tr>
<tr>
<td>Mud &amp; concrete block or bricks</td>
<td>16</td>
<td>18.2</td>
<td>16</td>
<td>100</td>
</tr>
<tr>
<td>Timber &amp; brick, stone or concrete blocks</td>
<td>5</td>
<td>5.7</td>
<td>4</td>
<td>80</td>
</tr>
<tr>
<td>Totals</td>
<td>88</td>
<td>100.0</td>
<td>57</td>
<td>64.8</td>
</tr>
</tbody>
</table>

Per cent of Total 100.0 64.8 22.7 12.5
In October 1968 the population of Meckering numbered around 230 with a further 300 living on farms in the vicinity (Gordon and Lewis, 1980). Seventeen people from the Meckering area and three from York were admitted to hospital with injuries ranging from broken limbs to concussion, cuts, bruises, and shock. The time of day and date of occurrence were undoubtedly the main reasons for the low casualty rate. October 14th was a public holiday which meant that shops were shut, and school buildings unoccupied. In addition, many farmers were working in iron framed sheds, preparing machinery for the coming harvest.

The loss of a town, homes and to some a lifetimes’ work, was a severe blow to everyone in the community. In the days following the earthquake, the town’s population halved, as 45 families left Meckering never to return (Snooke, 2010). An immediate problem following the earthquake was to accommodate the homeless and organise food. The showground was made the emergency centre by the Civil Defence Emergency Service. Tents were erected on the showground by the day after the earthquake and a catering committee was organised. The showground pavilion was able to close after 21 days as farmers had power restored and sheds organised for home living. Power, water and the narrow gauge railway line were in use within 24 hrs of the earthquake, and shops and businesses opened in temporary buildings in the days following. After much discussion a new town site was chosen 500 m south of the original town site. Rebuilding was co-ordinated and funded by all of local, state and federal governments, and was largely complete by 1970.
Stop 1: Meckering (new) town site

Heritage Park

At the time of the Meckering earthquake, water for the Eastern Goldfields and many small wheatbelt towns, was carried from Mundaring to Kalgoorlie via twin 76 cm concrete-lined steel conduits. The earthquake broke the pipeline in several places. Perhaps most notable was approximately 4 km to the southwest of Meckering, where the pipeline crossed the Meckering fault (Figure 7). At this location the Meckering fault takes the form of a series of en echelon scarps 3 m apart and stepping to the right (Gordon and Lewis, 1980) (see also Figure 16). Tectonic shortening was approximately 2.11 m, with both pipelines being telescoped by ~1.32 m, and arched upwards off their reinforced concrete supports (Figure 7). A section of this part of the pipeline has been preserved in the Meckering Heritage Park.

Figure 7 The Mundaring to Kalgoorlie pipeline was severely damaged where it crossed the main 1968 Meckering scarp. (A) damaged pipeline in the days following the earthquake, (B) preserved section in the Meckering Heritage Park.
The standard and narrow gauge rail lines ran together and parallel to the Goldfields water supply pipeline where they crossed the Meckering Fault. This is the site of the famous ‘buckled railway line’ photographs (e.g. Figure 8). The rail lines were subject to the same 2.11 m of shortening as the pipelines, and the eastern side was uplifted 1.52 m. This resulted in spectacular patterns of surplus track in the form of a double reverse ‘S’ on the standard gauge line and a reverse S on the narrow gauge (Gordon and Lewis, 1980). The crest of the scarp was locally up to 3 m high as the result of compression of plastic residual clay. Levelling showed that the standard gauge line had been uplifted for a distance of >10 km east of the fault (Wellman and Tracey, 1987).

Figure 8 (upper panel) photograph looking east of the buckling of the standard and narrow gauge railway lines (photo Ian Everingham, BMR). (lower panel) Section of the buckled Perth to Kalgoorlie railway line preserved in Meckering Heritage Park.
Meckering Town Hall

As part of the 50th anniversary commemorative event, Rebekah Burges has collected media articles, photos and previously “sealed” council documents to put on display in the Meckering Town Hall. Rebekah has kindly agreed to keep this display in place for our field excursion, and supplied the words below.

“The first Meckering Public Hall was built in 1896. A new hall was built adjoining it in 1906 but was badly damaged by fire in 1927. It was rebuilt in 1929 using existing walls. Clinic Rooms were added in 1949 (Figure 9). The Public Hall could accommodate up to 400 people and housed both a piano and organ. Attached to the hall entrance on the left wing was a library.

In the early 1900’s the Public Hall was an important meeting place for the Meckering community. It was used for the business of the local branch of the Liberal League, the Meckering Farmers and Settlers Association, the Meckering Health Board and the Meckering Road Board. Prior to establishing their own churches, Catholic and Methodist services were held each Sunday in the Public Hall. In the 1940’s films were shown in the hall on a weekly basis. In the 1950’s weekly films were screened on a Monday night. Film screenings ceased in the early 1960’s prior to the earthquake destroying the building.

When the town was rebuilt southwest of the original town site, a new Meckering Hall was constructed and was opened in 13 November 1970. This is the hall that stands today.”

Figure 9 A) Meckering Public Hall prior to the earthquake (image provided by Rebekah Burges). B) Damaged façade of the Meckering Public Hall prior to demolition (image by Ian Everingham, BMR).
Meckering earthquake Heritage Walk

Prior to the earthquake the Meckering town contained 51 occupied dwellings, 12 private business premises and 15 buildings devoted to government, public or sporting uses. Only 16 houses and 3 business premises survived the earthquake (Figure 10). The town’s population plummeted by half, as 45 families left Meckering never to return.

Following the earthquake, the town site became subject to seasonal waterlogging in the winter time, presumably as the result of gradient changes along the Mortlock River valley. In the years following the earthquake, a new, much diminished town centre was constructed several hundred metres south of the old town site. The Meckering Earthquake Historic Walk Trail takes you on a journey through the old town centre. This walk is a stark reminder of the enormity of this natural disaster to a once thriving community.

Figure 10 Meckering township 2 days after the earthquake, looking southwest (image courtesy of Rebekah Burges).

The map overleaf shows the layout of the old town (Figure 11). Each site has an interpretive sign explaining the building that once stood on that spot.

The bus will pick us up from the intersection of Dempster and Johnston Streets, near the sporting club. It is a distance of 1 km from the town hall and we have until 11 am (~40 mins) to complete the walk. This may necessitate choosing your favourite stops ahead of time.
Figure 11 Meckering historic walk trail map (courtesy of Rebekah Burges)
Stop 2: Salisbury Ruin

From the old Meckering town site the bus takes us to the north, over the Mortlock River floodplain. The river morphology at this location is transitional between stagnant drainage to the east (broad, infilled paleo-valleys and salt pans with sluggish and intermittent drainage – stippled area of Figure 1), and the rejuvenated drainage to the west (relatively narrow-floored and steep-sided with higher gradients). Ray Gordon from the Geological Survey of Western Australia noted evidence for limited liquefaction in the Mortlock River floodplain, west of the town, and near to the former site of Nicol and Wiley’s Garage (Stop 24 on Figure 11). More than twenty sand mounds up to 15 cm high were observed, often associated with linear cracks and scarps trending 345-360°. Water flowed from the central crater of the mounds for several hours after the earthquake (Gordon and Lewis, 1980).

Mortlock River floodplain liquefaction study (2003)

Trenches were excavated in the Mortlock River floodplain at a site near the former Nicol and Wiley’s Garage, where Gordon and Lewis (1980) reported that liquefaction had occurred during the 1968 Meckering earthquake. These failed to find unequivocal evidence for liquefaction produced as the result of the 1968 earthquake, but did find structures that may reflect prior strong ground shaking events (Tuttle, 2003) (Figure 12). Two generations of sand-filled features that superficially resemble root casts but share properties in common with liquefaction-induced sand dykes (e.g. fining of grainsize away from the “vent”, and silt accumulations at “vent” margins) were present in the trenches. Optically Stimulated Luminescence (OSL) dating of soil samples collected in the trenches constrains the older sand sheet and “vent” to the interval ca. 17-20 ka, and the younger to ca. 0.15-17 ka (Olley, 2004). Further research is required to prove an earthquake origin for these features.

If these features do relate to prior liquefaction events, the events are not associated with the faults that ruptured in 1968 (see paleoseismic trenches in Stop 3). Relationships developed between earthquake magnitude and the radius of the area affected by liquefaction (e.g. Maurer et al., 2015 and references therein) indicate that for maximum credible earthquakes in the Yilgarn Craton (Mw 7.25±0.1, Leonard and Clark, 2011), liquefaction in susceptible sediments might not be expected beyond ~70 – 100 km. An earthquake the size of 1968 Meckering (Mw 6.5) is unlikely to have liquefied susceptible sediments beyond ~ 50 km radius, and a Lake Muir sized earthquake (Mw 5.3) ~10 km.

Liquefaction was very limited in extent following the 1968 Meckering earthquake, presumably because of low susceptibility of the generally salt-cemented floodplain sediments. It is likely that these sediments, and floodplain sediments elsewhere in southwest Western Australia, were significantly less cemented prior to clearing for agriculture, and the consequent raising of saline water tables. Hence, floodplain soils in the southwest of Western Australia may have once been significantly more susceptible to liquefaction, particularly in the wet winter season. Paleoliquefaction studies (cf. Tuttle et al., 2002) might therefore hold potential for assessing the frequency of strong ground shaking at locations of interest.
Figure 12 Trenches excavated in the Mortlock River floodplain at a site where Gordon and Lewis (1980) reported that liquefaction occurred during the 1968 Meckering earthquake (modified from Tuttle 2003). Parts A and B from Trench 1. Parts C and D from Trench 3. Trench locations are on the Mortlock River floodplain between Stops 1 and 2 on Figure 1.
Salisbury Ruin

Most other damaged roads and buildings in and around Meckering were demolished and removed after the quake, but the Salisbury homestead (built in 1904) remains preserved in its ruined state (Figures 13 and 14). The site of the house is only ~ 600 m from the primary surface rupture, on the upthrown eastern (hanging wall) side. A splay, parallel to the main rupture, was mapped within 100 m of the homestead (Gordon and Lewis, 1980). Over the years since the quake, the owners Alice and Graham Snooke have recounted their experience many times. Below are a couple.

“Alice Snooke was a young 24-year-old mother of one when the earthquake hit. After hanging the washing on the line Alice was returning to the house when it fell down in front of her, trapping her 17-month-old daughter inside. Heavily pregnant, Alice ran around the house, climbing through a window and sorting through the rubble to find her daughter. Amazingly Alice’s daughter was found with no more than a few scratches on her back”.

ABC MidWest & Wheatbelt, The Day Meckering Moved, 15 October, 2008, Grady Winfield.

“Dashing in from the paddocks, Graham [Snooke] couldn’t get his tractor and towing gear across the 37 km-long fault line where the earth rose higher than two metres. So he unhitched the gear and found a spot where he could just ease the tractor over the scarred earth”


Figure 13 Interpretive sign outside the ruin of Alice and Graham Snooke’s homestead ‘Salisbury’.
‘Salisbury’ was an unreinforced masonry single storey residential building. The walls were stone – broken ashlar with brick quoins, and the roof material was metal sheet. This is one of the more vulnerable building types encountered in Australia. The vulnerability curve for this type of building is of the form shown in Figure 15 below. The steep tail is informed by buildings from Meckering – there was almost complete loss of this type of building at Modified Mercali intensity (MMI) IX (Everingham and Gregson, 1970).

![Figure 14: The ruin of Alice and Graham Snooke’s homestead ‘Salisbury’.](image)

![Figure 15: Vulnerability curve for unreinforced masonry buildings constructed prior to 1945 (Martin Wehner pers comm, 2018). Refer to Figure 6 for the isoseismal map constructed for the 1968 Meckering earthquake, and an explanation of the Modified Mercali intensity scale.](image)
Stop 3: North paleoseismic trench location (2005)

The bus will stop on a railway access track and let us out immediately south of where the Goldfields water supply pipeline and Perth-Kalgoorlie railway line were damaged. The restored pipeline has been placed underground, and the alignment is marked by a series of inspection points.

Walking to the south, the Meckering fault takes the form of a series of *en echelon* scarp ~1.5 m high, ~30 m apart and stepping to the right (Gordon and Lewis, 1980) (*Figure 16*). The scarp dammed an east-flowing tributary of the Mortlock River between the Great Eastern Highway and the Perth – Kalgoorlie railway line. A saline marsh formed on the western side of the scarp, where productive farmland existed prior to the earthquake. Shortly after the event, a channel was cut through the fault barrier with a bulldozer in order to restore the flow of the creek. As can be seen in the upper panel of *Figure 16*, this was only partly successful.

In 2005, a team from the University of Western Australia (Prof. Mike Dentith) and Geoscience Australia (Dr. Dan Clark) excavated two trenches across the 1968 earthquake rupture to find out how often large earthquakes occur on the fault (*Figures 17 and 18*). The northern-most of the two trenches straddles the scarp between the Great Eastern Highway and the Perth – Kalgoorlie Railway, where it is almost 1.5 m high (*Figure 16*).

The trench wall showed sandy stream sediments had been warped into a broad fold, and faulted by ~1.3 m across a shallowly east-dipping fault plane (*Figure 17*). Given that sediments at ~1 m depth in the paleo-liquefaction trenches are several tens of thousands of years old, the sediments in the bottom of the trench are likely to be older. Only the displacement from the 1968 earthquake is evident (i.e. the oldest sediments at the base of the trench are displaced across the fault by the same amount as sediment near the top).

The second trench, 1200 m to the south, was excavated on a hillside location into a ferruginous duricrust developed in granite bedrock (*Figure 18*). This landscape setting is very similar to that which we will see in the fault scarp reserve at Stop 3. The ferruginous duricrust has not been dated at this location. However, similar rocks to the east on the crest of the Darling Ranges have been dated at ~5 Myr old (Pidgeon *et al.*, 2004). A step in the saprolite layer within the hanging wall is associated with an ancient fault zone. Shear bands developed in the overlying duricrust may have formed in the 1968 event. However, no surface expression was found relating to them, suggesting that they may alternatively relate to a prior event. The erosion rate of ferruginous duricrusts in similar environments are less than 5 m/Myr, implying that any penultimate event must have occurred hundreds of thousands of years prior to the most recent event.

To the west of Meckering, the marked excursion of the westerly course of the Mortlock River valley, to parallel the 1968 scarp over a distance of ~ 5 km (e.g. Gordon and Lewis 1980), certainly predates this potential penultimate event given the very low bedrock erosion rates in Western Australia (Belton *et al.*, 2004), and the likely Late Tertiary timing of paleo-valley formation (de Broeckert and Sandiford, 2005). However, subtle pre-1968 changes in river channel profile and plan-form as the river crosses elements of the Meckering Scarp, as noted by Gordon and Lewis (1980), may reflect tilting consequent of a prior morphogenic seismic event. The UAV topographic survey described at Stop 3 was flown to test for evidence of a prior event where the Meckering scarp crosses the Mortlock River.
Figure 16.4 Aerial orthomosaic (upper) and digital elevation model (lower) of the 1968 Meckering scarp between the Great Eastern Highway and the Perth – Kalgoorlie Railway (acquired August 2018). The blue lines are scarp elements, and the red lines show the pre-earthquake course of a formerly east-flowing tributary of the Mortlock River. Both sets of lines were taken from aerial photos collected two days after the earthquake.
Figure 17 Northern trench excavated across the 1968 fault scarp in 2005 by researchers from the University of Western Australia and Geoscience Australia. Orange, green and blue layers represent sandy sediments deposited by the stream over thousands of years. The dark green layer is the 1968 soil layer. The purple layer is material that has eroded off the scarp since 1968. The fault line that slipped during the Meckering earthquake occurred on is shown by the red lines – note that sedimentary layers are faulted with east side up. See Figure 1 and Figure 16 for trench location.
Figure 18 Southern trench excavated across the 1968 fault scarp in 2005 by researchers from the University of Western Australia and Geoscience Australia. Pale orange and pink layers represent a deep weathering profile developed in granite bedrock. The green layer is the 1968 soil layer. The purple layer is material that has eroded off the scarp since 1968. The fault line that slipped during the Meckering earthquake occurred on is shown by the red lines – note that layers are faulted with east side up. See Figure 1 for trench location.
Stop 4: Fault scarp reserve

Gordon and Lewis (1980) considered that "one of the most striking features of the Mortlock River is the arcuate swing from a westerly to a southerly direction around Meckering. For about 12 km the river is parallel to, and about 1.5 km east of, the Meckering fault scarp. Not until about 9 km south of the town does the river resume its westerly course and cross the fault scarp". The authors considered one potential cause of the arcuate course to be that the river has eroded along the trace of an older fault. Aeromagnetic data shows that the river deviation follows well-imaged lineaments, which Dentith et al. (2009) interpret to be faults and dykes (Figure 4). A pertinent question is do these lineaments reflect basement faults that have been the focus of recurrent large earthquake ruptures, are they basement faults that rupture infrequently, or did they rupture for the first time in the neotectonic era in 1968? At this stop we continue our examination of the evidence for or against a history of recurrent large earthquakes on the faults that failed during the 1968 Meckering earthquake.

Intersection of the scarp with the Mortlock River

The channel of the Mortlock River was not intercepted by the fault until the river turned to the southwest, about 10 km southwest of Meckering (Figures 1 and 4). The river bed was disrupted by an uplift of about 1.5 m, but because the scarp and river channel are sub-parallel the grade of the river was only reduced from 0.91 m/km to 0.76 m/km in the section between the Great Eastern Highway and the fault (Gordon and Lewis, 1980). However, prior to the earthquake Meckering town site was already prone to flooding and salt intrusion as a consequence of clearing the native vegetation for agriculture. As the river gradient change had the effect of raising the flood level at Meckering by 12 cm (Green, 1969), the Public Works Department decided to clear and improve the main river channel for 16 km upstream of the scarp. The main scarp was cut through (Figure 20), as were several dammed east-flowing tributaries (e.g. at Stop 3, Figure 16). The modification works at the scarp crossing consisted of the grading of the sharp relief relating to the scarp in the main channel, and the construction of a cut-off channel through a low point in the scarp where it jogs 100 m to the left (Figure 19). The general form of the 1968 uplift is still clearly visible in the channel profile of the river (Figure 20, profile inset).

Despite the post-1968 modifications to the river, the landscape may still be assessed in terms of whether there is evidence for prior neotectonic uplift events across the faults involved in the 1968 ruptures. Alluvial rivers are extremely sensitive to changes in the gradient of their channels caused by tectonic tilting (Holbrook and Schumm, 1999). They may respond to uplift or subsidence by changes in plan form (i.e. increased or decreased channel sinuosity), or by vertical changes in longitudinal profile (i.e. aggradation or incision of channels).

Immediately north of where the 1968 rupture crosses the Mortlock River is a reach that parallels the scarp over a distance of ~ 300 m (Figures 19 and 20). The orientation of this reach predates 1968, and implies bedrock structural control on the river. However, the general character of the geomorphology where the 1968 scarp crosses the Mortlock River, as revealed in ALOS and UAV DEMs (Figures 4 and 20), is inconsistent with recurrent large events having affected the river morphology. Specifically:

1. ALOS DEM data (Figure 4) shows no evidence for constriction of the Mortlock River valley north of the intersection, as might be expected to be the consequence of recurrent uplift. A
profile through the ALOS DEM shows that the 1968 uplift is a small perturbation on the larger disequilibrium profile relating to a progressive lowering of base level as the Australian continent tilts northwards (e.g. Sandiford, 2007).

2. The UAV DEM (Figure 20) shows that river flats and terraces upstream and downstream of the fault are similar in character, with the exception that these features have been relatively uplifted by ~ 1.5 m on the eastern side of the fault. Additional flights of terraces on the uplifted block, resulting from incision into the uplifted block as the river adjusted its gradient, might be expected if recurrent uplift had occurred.

3. The sinuosity of the river does not change across the position of the scarp, suggesting no ‘recent’ tectonic perturbations have affected the river gradient prior to the 1968 event.

Figure 19 Oblique aerial photos of the Meckering fault scarp immediately north of where it crosses the Mortlock River, taken by Ian Everingham (BMR) in the days following the earthquake. (A) looking to the north at a prominent 100 m wide left step in the fault scarp. The linking scarp knicked the Mortlock River in the far right of the photo. (B) looking at the same step-over as part (A), but from the north. Note that the area south of the step-over is crop land. To alleviate flooding, the Department of Public Works cut a channel from where the linking scarp knicked the Mortlock River, south along the scarp face, to link to the main channel again 400 m to the south. This channel is clearly evident in the UAV DEM in Figure 20. The former cropland is now scrub.
Figure 20 UAV DEM where the Meckering scarp crosses the Mortlock River. Red lines denote scarp segments. Black dashed line relates to the profile inset. Blue profile line is along the river between the red arrows. Note that the river profile shows a 1.5 m high displacement relating to the earthquake, despite engineering works to alleviate flooding levels. The green arrow also marks the step-over shown in Figure 19, through which the major engineering works at this location were completed (i.e. the cut through channel).
Fault reserve

Following the earthquake, farmers were facing the difficult problem of harvesting crops along the fault line (Snooke, 2010). Harvesting became a precarious operation as care had to be taken not to hit the fault line with the header comb. Crop unable to be harvested was left for sheep feed. Looking to the field to the north from this stop, it may be difficult to see the fault scarp. The scarp here was bulldozed by the Public Works Department to allow farming to continue, as it was over much of its 37 km length. Thanks to the foresight of the landowner, the late Merv Reynolds, a kilometre-long segment of the Meckering Fault scarp has been preserved to the south (Figure 21).

Figure 21 Images of a section of the 1968 Meckering scarp, looking south. a) Captured in 1970 by Ian Everingham (BMR), and b) captured in May 2002. Scarp preservation has been assisted by the durable ferricrete and weathered bedrock layer exposed in the hanging wall. Note the rolling topography of farmland in the background.
The geological setting and surface expression of the scarp at this location is very similar to that encountered at the southern 2005 trench location (see Figure 18). The scarp is developed in weathered and ferruginised granite bedrock with a thin pisolithic soil mantle over the top. The competency of these materials has resulted in the preservation of a free hanging face at several locations. As you look down the moderately east dipping (54°) fault plane, consider that this plane extends for 10 km into the earth (Somerville et al., 2010)! Topographic profiles across the scarp within the fault reserve (e.g. Figure 22) show no evidence to suggest fault-related surface expression pre-1968. Very low erosion rates within this material suggest that it might take a million years to remove the relief from the 1968 event. This requires that at least a similar period of time must have elapsed since any prior similar sized event.

Figure 22 UAV DSM superposed onto ESRI World Imagery at the Quellington Road Fault Reserve.
Stop 5: York town site

York is the oldest inland town in Western Australia and is situated approximately 100 km by road east of Perth in the Avon Valley. The town was established in 1835, just six years after Perth was settled in 1829, and boomed during the gold rush as it was one of the last railway stops before the long walk to the goldfields. This prosperity contributed to the construction of many significant masonry buildings, the most notable being the Town Hall. When the railway line was extended to Kalgoorlie it went through Northam, not York, transferring the focus of new development to Northam and leaving York remarkably preserved. The town has many notable heritage buildings that today attract tourists to York, thereby indirectly making a major contribution to the local economy. Recent survey activity in York has identified some 307 unreinforced masonry (URM) buildings of pre-1914 age. Figure 23 shows the extent of survey work undertaken from February to April 2018 in York.

Figure 23 York Survey extent and building stock use.
The presence of valued older masonry structures in York is ‘two edged’ in that it has also given the town an inherent vulnerability to earthquake ground shaking. The 1968 Meckering Earthquake not only devastated the town of Meckering, but also caused widespread damage to York as it is located only 38 km from the epicentre. The township of York is sited mainly on hard rocks found at depths of a few meters, including gneiss and granite (Wilde and Low, 1978). However, soft alluvial deposits exist along the Avon River, which runs through the centre of town (McPherson, 2017). These sediments reach thicknesses of 10 m or more and serve to amplify earthquake ground motions. Felt intensities of MMI VI were experienced during the Meckering Earthquake causing significant damage to older buildings in the town (see Figure 6). Some 245 insurance claims were reported (Gordon, 1972) and three York residents were admitted to hospital with injuries that included broken limbs to concussion, cuts, bruises, and shock (Gordon and Lewis, 1980). The two-storey Crown Hotel on Avon Terrace was so severely damaged that the owners decided to demolish it rather than undertake extensive repairs.

The Meckering earthquake subsequently prompted a range of local efforts in York to make buildings structures more resilient to future earthquakes. The vulnerability of York to future credible earthquakes is of concern to several stakeholders; the York Shire would be greatly impacted locally, the WA Department of Fire and Emergency Services (DFES) would need to respond following an event, and the WA Department of Planning, Lands and Heritage seeks in general to preserve these valuable structures. The interests of local stakeholders have prompted a research utilisation project under an overarching earthquake mitigation focussed project that is part of the current Bushfire and Natural Hazards Collaborative Research Centre (BNHCRC). Under Project A9 entitled Cost Effective Mitigation Strategy For Building-Related Earthquake Risk (bnhcrc.com.au/research/understanding-mitigating-hazards/244), a mitigation project led by the University of Adelaide and partnered with Geoscience Australia is developing earthquake mitigation strategies for masonry buildings in York. These will be “virtually” applied to the town to assess the most cost-effective approaches for making common building types in York more resilient to future earthquakes.

This field trip will introduce you to the project, the project aims and the importance placed on it by the local stakeholders. At the start of the visit brief presentations will be made by the BNHCRC project team, the Shire of York and the WA DFES on the project and the significance of the information it is developing. The progress made to date will be described along with future activities. These include translating the retrofit information into more generic forms that will enable the research outcomes to be applied to other low-growth regional towns in Australia with similar vulnerable building stock. Most importantly, the visit will introduce you to the town itself. As part of this visit a walking tour of the town (Figure 24) will include the following structures:

1) The York Town Hall, 81 Avon Terrace, built in 1911. The building is well maintained but has not been the subject of any seismic retrofit (Figure 25a).

2) The Masonic Lodge, 3 Joaquina St, York, built in 1887 which has been the subject of several strengthening measures (Figure 25b).

3) St Patricks Parish Catholic Church, dedicated in 1860, which was the subject of novel retrofit measures to strengthen the church steeple following the Meckering Earthquake (Figure 25c).

4) The old York Fire Station. 151 Avon Terrace, built in 1897. The building is now used as a book shop. Retrofit measures were undertaken to tie the masonry elements together (Figure 25d).
Figure 24 York walking tour route.

Figure 25 York building stock. (a) York Town Hall as seen from Avon Terrace, (b) side elevation of the Masonic Lodge, York, with floor tie-back measures visible, (c) St Patricks Catholic Church as seen from South St, (d) the old York Fire Station, as seen from Avon Terrace.
5) The York Post Office, 131 Avon Terrace, built in 1893, with its distinctive entranceway arch and dormer clock at roof level (Figure 26a).

6) The Magistrates Court, 132 Avon Terrace, built in 1895 to replace an existing courthouse complex (Figure 26b).

7) The Castle Hotel, 95-97 Avon Terrace, built in 1873. Measures were implemented to tie back the street frontage parapets of the hotel following the Meckering Earthquake (Figure 26c).

8) The Mill, 10 Henrietta St, constructed from 1892 (if time permits). The main building is a four storey load bearing brick and timber structure which is one of the tallest masonry structures in the town. Retrofit measures to add earthquake resilience to this structure can be seen (Figure 26d).

Where possible, structural measures applied following the Meckering Earthquake to retrofit the buildings will be examined on the tour. If time permits after refreshments, the visit will include short bus journey to the old flour mill before departing for Perth.

Figure 26 York building stock. (a) the York Post Office, of stone and brick masonry construction, as seen from Avon Terrace, (b) The Magistrates Court, as seen from Avon Terrace, (c) The Castle Hotel, as viewed from cnr of Avon Terrace and South St, (d) Retrofit measures applied to the wheat mill to tie-back perimeter walls to floor diaphragms.
What have we learned about cratonic fault behaviour in the 50 years since the 1968 Meckering earthquake?

The Meckering earthquake was the first known to have ruptured the ground surface in Australia, and prompted the production of Australia's first earthquake building code, AS 2121 in 1979 (cf. Woodside and McCue, 2017). The seismic hazard assessments underpinning this code, and its successors AS1170.4 (1993, 2007), have increased in sophistication with time as the science of earthquake analysis evolved and earthquake catalogues accrued new data. Knowledge of the recurrence characteristics of Australian intraplate seismogenic faults, such as those which ruptured during the Meckering earthquake, has progressed at a slower rate. Several fault scarps associated with physiography consistent with the 1968 rupture were identified in the course of routine geological mapping in the years after Meckering (e.g. Thom, 1972; Chin et al., 1984; Chin, 1985; Chin and Brakel, 1986; McCue, 1990). However, it was only in the early to mid-1990s that the first paleoseismic data were obtained (Crone et al., 1997; Crone et al., 2003; McCue et al., 2003), and the process of characterising the recurrence behaviour of Australian intraplate faults began.

Across Australia nine earthquakes are known to have broken the Earth’s surface in historic times, producing a scarp (Figure 27, Table 3). These ruptures are located exclusively in the Precambrian Stable Continental Region (SCR, Johnston et al., 1994) rocks of central and western Australia (Clark et al., 2014a), and are associated with magnitudes in the range from $M_W$ 4.73 - 6.76 (Clark et al., 2014b). None of the eight historic surface ruptures could have been identified and mapped using topographic signature prior to the historic event (Table 3). For example, Crone et al. (1997) excavated trenches across the 1986 Marryat Creek and 1988 Tennant Creek ruptures and found that while each rupture in part exploited pre-existing bedrock faults, there was no unequivocal geomorphic, stratigraphic or structural evidence to suggest a penultimate event in the preceding 50,000 to 100,000 years or more.

Paleoseismic investigations of several faults in the same Precambrian SCR tectonic setting provide evidence for limited recurrence of large earthquakes, with up to four events documented on an individual fault within the last ca. 100 kyr (Crone et al., 2003; Clark et al., 2008; Estrada, 2009). These scarps, the Roopena, Hyden, Lort River and Dumbleyung (see the Australian Neotectonic Features database for location), all overlie simple through-going faults imaged in aeromagnetic data (https://researchdata.ands.org.au/total-magnetic-intensity-vrtp-greyscale/1256158). The two to five Quaternary events documented on the Hyden (Clark et al., 2008) and Lort River (Estrada, 2009) scarps are all that are evident across Tertiary duricrust. While shallow trenches across the 2 – 5 m high Roopena scarp exposed Precambrian bedrock on both sides of the fault (Crone et al., 2003), nearby scarps are associated with an extended Tertiary to recent history of movement (Miles, 1952; McCormack, 2006; Weatherman, 2006). For example, the Randell and Poynton Faults on the northeastern Eyre Peninsula are associated with 30-70 m of Pliocene and younger vertical displacement (McCormack, 2006). Scarpas developed in the ca. 15 Ma surface of the Nullarbor Plain, which overlies Neoproterozoic mobile belt basement, are associated with up to 15 – 30 m of vertical surface displacement (Hillis et al., 2008; Clark et al., 2012), implying the recurrence a dozen or so events at most. In general, scarps developed within Archaean and Paleoproterozoic crust tend to be more modest in height, less well connected (e.g. spatially isolated), and more complex in plan than...
scars in Mesoproterozoic and Neoproterozoic crust (neotectonic Domain 1 cf. Domain 3 of Clark et al., 2012) (Figure 27).

![Figure 27 Neotectonic features (red lines) from the Australian Neotectonic Features database (updated from Clark et al., 2012). Historic surface ruptures shown as red dots annotated with the year of the event. Base map are neotectonic superdomains (after Leonard et al., 2014). Note all historic surface ruptures have occurred in Precambrian SCR crust.](image)

**Table 3** Historic events known to have produced surface rupture in Australia (expanded after Clark et al., 2014b).

<table>
<thead>
<tr>
<th>Earthquake</th>
<th>Year</th>
<th>Magnitude (MW)</th>
<th>SRL (km)</th>
<th>v.d. (max: m)</th>
<th>Pre-existing fault?</th>
<th>Pre-existing topography?</th>
</tr>
</thead>
<tbody>
<tr>
<td>Meckering</td>
<td>1968</td>
<td>6.58</td>
<td>37</td>
<td>2.5</td>
<td>part</td>
<td>no</td>
</tr>
<tr>
<td>Calingiri</td>
<td>1970</td>
<td>5.46</td>
<td>3.3</td>
<td>0.4</td>
<td>no</td>
<td>no</td>
</tr>
<tr>
<td>Cadoux</td>
<td>1979</td>
<td>6.13</td>
<td>14</td>
<td>1.4</td>
<td>part?</td>
<td>no</td>
</tr>
<tr>
<td>Marryat Creek</td>
<td>1986</td>
<td>5.74</td>
<td>13</td>
<td>0.9</td>
<td>part</td>
<td>no</td>
</tr>
<tr>
<td>Tennant Creek*</td>
<td>1988</td>
<td>6.76</td>
<td>36</td>
<td>1.8</td>
<td>yes</td>
<td>part?</td>
</tr>
<tr>
<td>Katanning</td>
<td>2007</td>
<td>4.73</td>
<td>1.26 (0.2?)</td>
<td>0.1</td>
<td>no</td>
<td>no</td>
</tr>
<tr>
<td>Ernabella</td>
<td>2012</td>
<td>5.37</td>
<td>1.5</td>
<td>0.5</td>
<td>no</td>
<td>no</td>
</tr>
<tr>
<td>Petermann Ranges</td>
<td>2016</td>
<td>6.10</td>
<td>20</td>
<td>1.0</td>
<td>part?</td>
<td>no</td>
</tr>
</tbody>
</table>

* The Tennant Creek surface rupture was produced by three events in a 24 hr period

Knowledge of the characteristics of Australian seismogenic faults has advanced in the last two decades (Sandiford, 2003; Quigley et al., 2010; Clark et al., 2012; Clark et al., 2014a; Clark et al., 2015) to the stage where faults are now more commonly being explicitly included in probabilistic seismic hazard assessments, at scales from site–specific to national (e.g. Somerville et al., 2008; Clark et al., 2016; Griffin et al., 2016). Despite the advances, most faults in Australia remain poorly...
characterised in terms of their paleoseismology, and in many cases, their geometry. Hence, hazard modellers face significant uncertainty in assigning magnitude, rupture geometry, segmentation behaviours, and recurrence behaviours. The 2018 revision of the Australian National Seismic Hazard Assessment (NSHA18), for the first time, includes intraplate fault sources (Clark et al., 2016; Griffin et al., 2016; Allen et al., 2018a). Epistemic uncertainty in the fault source model is captured in the NSHA18 through a weighted logic tree framework (Clark et al., 2016; Griffin et al., 2018). In terms of recurrence behavior the model described a seismogenic fault as either; slipping at the long term average rate, in a period of heightened activity – slipping at a rate ten times the average rate, or in an inactive period – slipping at one tenth of the long term average rate (cf. Stirling et al., 2011). By virtue of the scarcity of data with which to validate such a model, the underpinning assumption that a ‘long-term slip rate’ is a meaningful concept in an intraplate setting, as per the prevailing plate margin paradigm, remains to be fully tested. Indications are that the concept may be useful in the Phanerozoic stable continental region (SCR) crust of eastern Australia (Figure 28), where faults with up to a couple of hundreds of metres of slip occur (cf. Clark et al., 2015; Clark et al., 2017). However, it is not so certain whether assigning a long-term slip rate is meaningful for Precambrian SCR crust (e.g. Calais et al., 2016). Based on our current understanding of earthquake recurrence on neotectonic faults in the Precambrian SCR crust, there appears to be limited advantage to including these features in seismotectonic source models for national-scale PSHAs. Low implied slip rates, and thus low rates of earthquake recurrence, have little effect on overall PSHA calculations at return periods of engineering interest (Clark and Allen, 2018).

Figure 28 Mean total displacement for neotectonic features (black lines) from the Australian Neotectonic Features database (updated from Clark et al., 2012; Clark et al., 2014a). For instances where robust displacement information is not available in the database, estimates have been made using offset landscape features imaged in SRTM 90 m and ALOS 30 m resolution DEMs. Interpolation generated using ARCGIS Point Statistics routine with 0.5 degree output cell dimension and 1.5 degree search radius. Color ramp is stretched using histogram equalize (i.e. is not linear), and saturates at the upper end at 100 m displacement. Reverse ruptures are assumed to be exclusively dip slip (which may underestimate displacement in the Otway and Gippsland basins), and features on the northwest shelf are assumed to be exclusively strike-slip. See Figure 27 for explanation of base map shading.
Summary

The 1968 Meckering earthquake is the second largest recorded onshore earthquake in Australia (Storchak et al., 2015), and remains one of the most significant in Australian history in terms of the damage to infrastructure and the subsequent cultural upheaval. The event stimulated Australia’s nascent intraplate-specific earthquake research program and prompted the production of Australia’s first earthquake building code (cf. Woodside and McCue, 2017). Herein, we have provided a guide to the geological and societal effects of the 1968 earthquake, the knowledge gained as the result of the focused research effort following the event, and the practical steps York Shire is taking to mitigate the effects of a future similar event. We conclude in the previous section with a reflection on how the accumulated knowledge might be applied to seismic hazard assessments in Australia’s cratonic regions into the future (cf. Clark and Allen, 2018).
Acknowledgements

Thanks to Colin Pearse for allowing access to his property for the trenching investigation, and for the field excursion. Thanks also to Alice and Graham Snooke for allowing access to their property for the paleoliquefaction investigation, and for providing first-hand accounts for this guide, and on the excursion. Rebekah Burgess is warmly thanked for providing material for this guide, and for retaining the display in the Meckering town hall for the excursion participants to see. Mike Griffiths and Paul Martin are thanked for welcoming the field trip participants to York and leading the York walking tour.
References


Estrada, B. (2009). Neotectonic and palaeoseismological studies in the southwest of Western Australia, School of Earth and Environment. Perth, The University of Western Australia. PhD.


