UNDERSTANDING THE MECKERING EARTHQUAKE:

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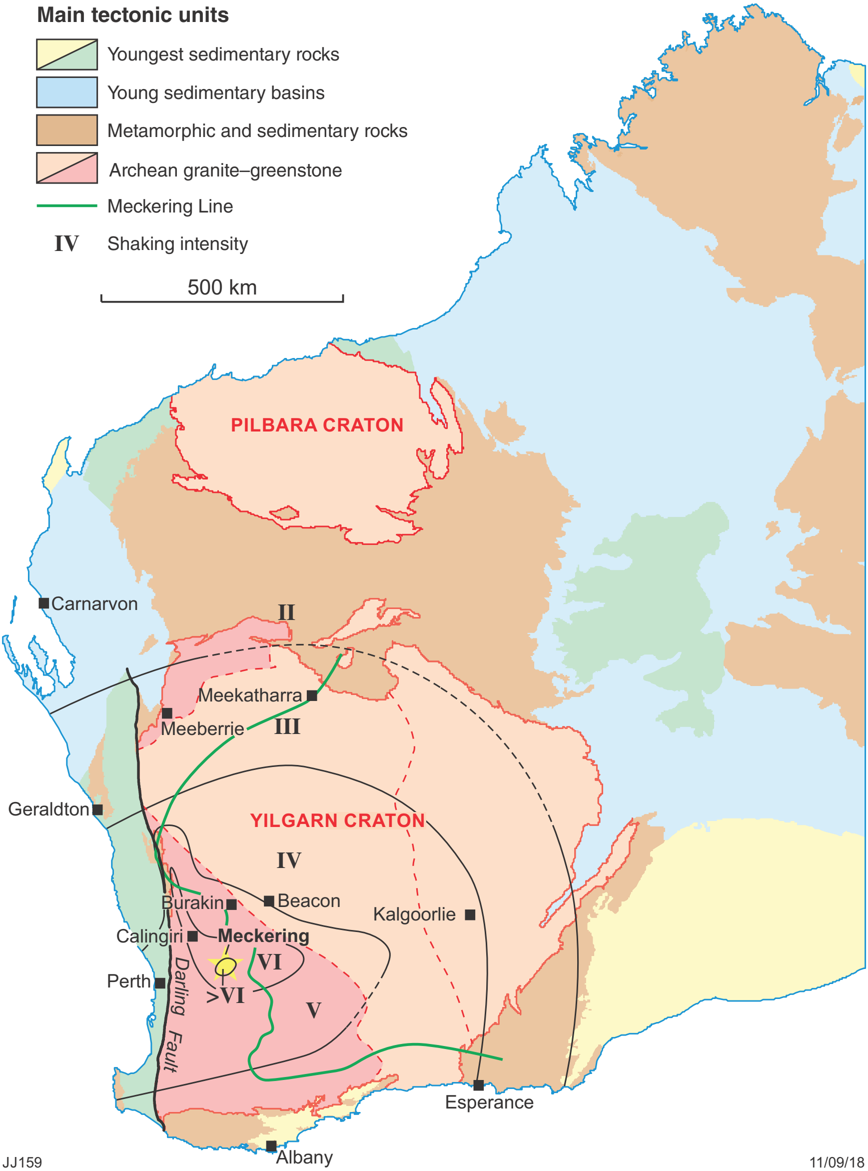

Map of main tectonic units of Western Australia, locating Meckering and showing zones of shaking intensity caused by the Meckering earthquake. See text and Table 1 for an explanation

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Government of **Western Australia**
Department of **Mines, Industry Regulation and Safety**

Geological Survey of Western Australia

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Cover image: Early morning light casts long shadows that highlight a complex section of the newly formed scarp of the Meckering Fault, October 1968. View is northeast along Wilson Street towards the intersection with Carter Road, northwest of Meckering township (photo courtesy West Australian Newspapers)

Understanding the Meckering earthquake:

Western Australia, 14 October 1968

Forty seconds that changed lives

For the people of Meckering in the Wheatbelt region of Western Australia, the public holiday on 14 October 1968 probably started like any other. But at 10.59 am, a devastating earthquake measuring 6.9 on the Richter scale took only 40 seconds to smash buildings to the ground and reduce the main street to rubble. Now, 50 years on, the people of Meckering reflect on that event: the shocks before, the earthquake itself, and the aftershocks — in more ways than one. This book looks at some of the geological reasons for the event that still haunts the town.

A devastated town and its people

In 1968, Meckering, 130 km east of Perth in the Wheatbelt of Western Australia, was a thriving agricultural township of 230 people. Banks, businesses and government offices lined the main street. An additional 300 people lived in the surrounding district. Then, in less than a minute on 14 October, the town was reduced to ruins. When the dust settled, fifty-nine buildings had been destroyed or rendered uninhabitable (Fig. 1), leaving the residents dazed and shaken. An earthquake measuring 6.9 on the Richter scale (later revised to M_W 6.5) had decimated Meckering and left a scar across the landscape (Figs 2a and 4; see boxes *What is an earthquake?* and *How we measure earthquakes*).

Figure 1. Meckering township immediately after the earthquake on 14 October. Buildings in the foreground and town centre have collapsed and the main street is littered with fallen masonry

Despite the damage to buildings there were no deaths, although about 20 people were injured. However, the iconic Eastern Goldfields Water Supply pipeline taking water from Mundaring to Kalgoorlie was concertinaed and ruptured. Three vital communications links to the rest of the continent that pass through Meckering were also seriously disrupted: the transcontinental railway to Adelaide and beyond was buckled and fractured; telephone lines were cut; and the main highway from Perth to Adelaide became impassable when the road surface rose and buckled in front of cars (Fig. 2a,b).

Figure 2. Photos of the disruption caused by the earthquake: a) the newly formed Meckering Fault scarp snaking across the countryside; b) a car 'parked' on the fault scarp where it crossed a road gives an idea of the scale of the damage

What is an earthquake?

An earthquake is a seismic release of energy that occurs when rock under stress suddenly ruptures or slips rapidly along a plane of weakness, termed a **fault**. The place where the earthquake originated is the focus, and the point on the ground surface directly above the focus is the **epicentre** (see Fig. 5). The energy released radiates out from the focus as **primary (P)** and **secondary (S)** elastic waves (which are essentially sound waves), travelling at several kilometres per second through the solid rock (YouTube videos graphically show this). Where the waves reach the surface, they generate **surface waves** that are most strongly felt by observers, and do most of the damage because the ground movement distorts buildings or other infrastructure.

The Meckering earthquake was captured in a **seismogram** (Fig. 3) recorded at Mundaring Observatory. The P-waves and S-waves, which travel fastest and would normally arrive before the surface waves (Fig. 3 inset), are difficult to pick in the seismogram and may have been overwhelmed by the strong surface waves.

b)

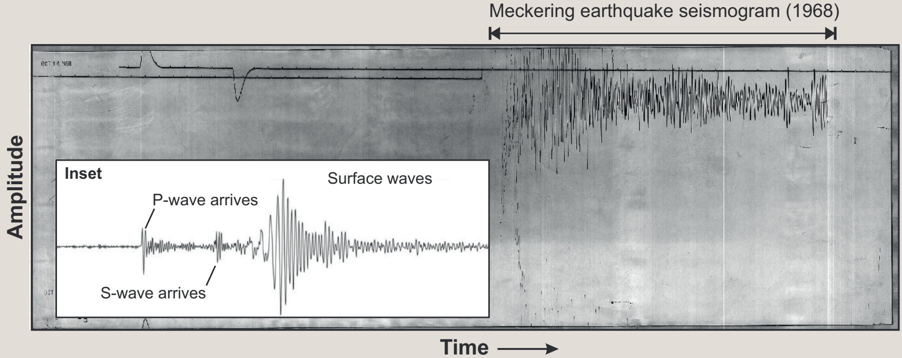


Figure 3. Seismogram of the Meckering earthquake recorded at Mundaring Observatory on 14 October 1968. The strong signal exceeded the limits of the instrument and was cut off at the top of the paper. The inset shows an ideal earthquake seismogram in which the P-waves and S-waves clearly arrive before the surface waves. This sequence is not so evident in the Meckering signal

“Earthquakes are happening all the time — several million of them each year around the planet — but most are tiny, they are not felt, do no damage, or are deep under the oceans”

Geoscience Australia (GA), Australia’s national geoscience organization, reported that this was one of the largest Australian earthquakes at the time (see *Ten largest earthquakes in Australia* inside back cover). All observers in the vicinity of Meckering agreed that the initial strong motion was a near vertical blow, followed by two episodes of east–west shaking — all accompanied by an explosive or thundering noise. Their experiences were confirmed by geoscientist FR (Ray) Gordon from the Geological Survey of Western Australia (GSWA), who co-wrote a detailed bulletin on the earthquake and its aftermath. He was impressed by the reliability of the observers, who talked about two or three distinct pulses of shaking, followed by groundwaves rolling across the town’s main street (see box *Their stories*).

The earthquake was felt over an area with a radius of about 700 km from Meckering, affecting almost the entire southern half of Western Australia (see map inside front cover). Buildings in York, Northam, and the Perth metropolitan area were damaged, some severely. However, there were some positive outcomes. Australia’s first Earthquake Code AS 2121 was published in 1979 as a direct result of the Meckering earthquake, and updated building codes were gradually rolled out in other states in subsequent decades due to growing awareness of seismic hazards nationally.

The irrepressible character of rural Western Australians came quickly to the fore, exemplified by the local publican. He moved his beer and equipment to the Shell Garage, dubbed it the Quake Arms Hotel, and was open for business again within 24 hours of the earthquake, selling beer billed as ‘all shook up’ by the earthquake.

Figure 4. Aerial view of the Meckering Fault looking south. The fault steps across the landscape and in each step the surface is thrust from the east (left) over the surface by up to 2 m to the west. Photo courtesy West Australian Newspapers

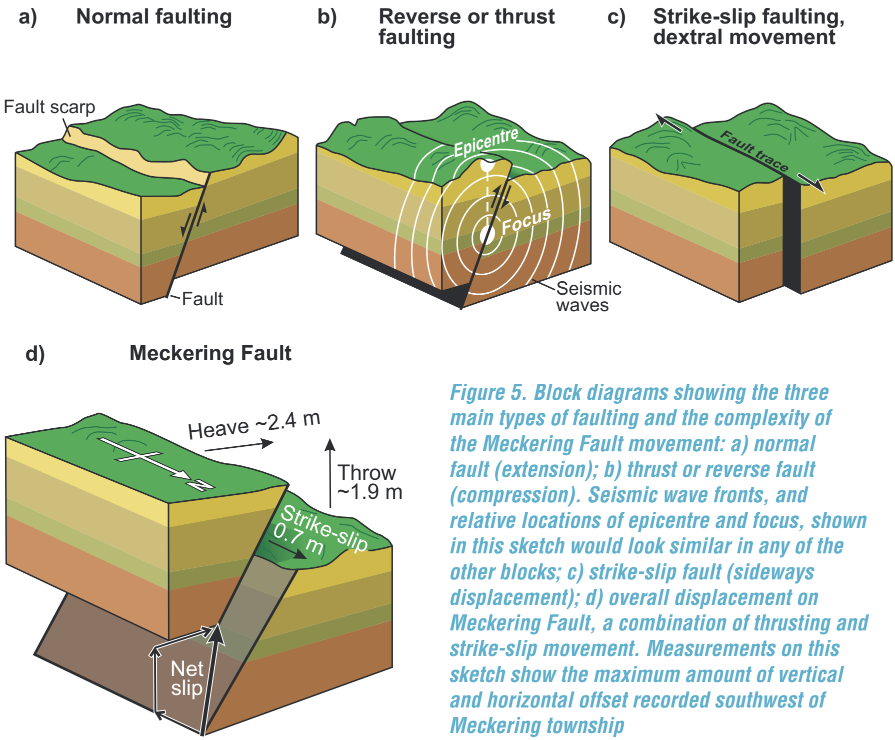


Figure 5. Block diagrams showing the three main types of faulting and the complexity of the Meckering Fault movement: a) normal fault (extension); b) thrust or reverse fault (compression). Seismic wave fronts, and relative locations of epicentre and focus, shown in this sketch would look similar in any of the other blocks; c) strike-slip fault (sideways displacement); d) overall displacement on Meckering Fault, a combination of thrusting and strike-slip movement. Measurements on this sketch show the maximum amount of vertical and horizontal offset recorded southwest of Meckering township

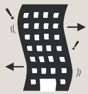
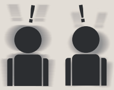
How we measure earthquakes

There are two main measurements — magnitude and intensity.
The **magnitude** or size of an earthquake was traditionally measured on the **Richter scale**, from 1 to 10, with the largest recorded magnitude at 9.5 — catastrophic! The Richter scale is an approximate measure of the energy of seismic waves travelling through the Earth. At the time of the Meckering earthquake, earthquakes were detected on a rotating drum instrument called a **seismo*graph***. The **seismo*gram*** generated from this (see Fig. 3) shows not only that there has been an earthquake, but allows an estimate of how far away it was. These days, earthquakes are recorded digitally and the data are shared via globally networked seismograph stations.

The **moment magnitude (M_w)** scale, which is directly related to the energy released by an earthquake, is now generally preferred over the Richter scale. Whereas the Meckering earthquake was originally measured at 6.9 on the Richter scale, the equivalent moment magnitude is M_w 6.5. Of course, the lower value in no way lessens the impact of the earthquake. The scale is logarithmic, meaning that each step in the scale represents 32 times more energy released. An M_w 6 earthquake releases 32 times the energy of an M_w 5 earthquake, and about 1000 times the energy of an M_w 4 earthquake.

We measure the **perceived intensity** of an earthquake using the Modified Mercalli (MM) scale (Table 1). On this scale, the **felt effects** of earthquakes on people and buildings are rated from I (not noticeable) to XII (total destruction). The closer we are to the epicentre of the earthquake, the greater the visible and felt effects will be. The Meckering earthquake was rated a maximum intensity of MM VIII within a few kilometres of the epicentre near Meckering. The intensity decreased to MM III 500–600 km away at places such as Esperance and Meekatharra.

Table 1. Felt effects of earthquakes

Simplified observations		*Modified Mercalli intensity scale**
Not felt by people		**I**
Felt by a few people		**II**
Felt indoors, particularly upper floors of buildings		**III**
Felt by almost everyone. A few people frightened		**IV** **V**
Felt by all. General alarm. Difficultly walking. Slight damage to masonry. Windows and crockery broken		**VI**
General alarm. Difficulty standing		**VII**
Alarm may approach panic. Steering of vehicles affected. Severe damage or collapse of unreinforced structures		**VIII (maximum felt effects of M_w 6.5 Meckering EQ)**
Most masonry and frame structures destroyed		**IX** **X**
Almost total destruction		**XI** **XII**

* Source: <www.ga.gov.au/scientific-topics/hazards/earthquake>

Geology of an earthquake

The earthquake generated a main fault scarp about 37 km long as well as several secondary fault scarps and numerous other surface fractures (Figs 4 and 7). The Meckering, Splinter, Burges and Robinson Faults all ruptured the Earth's surface during the earthquake as stresses that had built up over thousands of years were suddenly released. Not all earthquakes result in a surface rupture. For this to happen, either the source of the event — the focus located on a fault plane in the subsurface (Fig. 5b) — is relatively shallow, or it is a large magnitude earthquake. For the Meckering earthquake both were true, accounting for the violence of the ground shaking and the pronounced scarp.

The Meckering Fault

The 37 km-long arcuate scarp formed during the earthquake was the most obvious signature of the underlying geological structure — the Meckering Fault. As seen on the front cover of this book, and in Figures 4 and 7, the surface trace of the fault was complex, comprising multiple, mostly arcuate, segments from a few hundred metres up to about 10 km long. Sections of the fault showed different features such as thrust and normal faulting, strike-slip (mainly dextral, or right-lateral) displacements, and combinations of these (see Fig. 5a–c for types of faults). There were also extensional fissures, surface bulging, and en echelon (oblique ladder-like) tension fractures. The sequence of movement on the Meckering Fault was not simple. Offset features such as roads and fencelines indicate that the ground on the eastern side was thrust over ground on the west, and the western side was shunted northwards relative to the eastern side (Fig. 5d).

The photos in Figure 6 show some of these surface features: a thrust fault scarp at least 1.5 m high, a section of the fault where the ground bulged upwards, and an extensional fracture with a small vertical displacement zig-zagging across the landscape.

A broad zone of slumping and normal faulting east of the Meckering Fault, and extending between each end of the surface scarp, is called the Backscarp Zone (Fig. 7). Most of the major ground disturbance was recorded between the crescent-shaped Meckering Fault scarp and this Backscarp Zone. Combined with the angle of the fault plane, this suggests the rock mass affected by the earthquake was a 'saucer-shaped' or wedge-shaped block.

In the years immediately after the earthquake, the location of the epicentre was revised several times, based on different information.

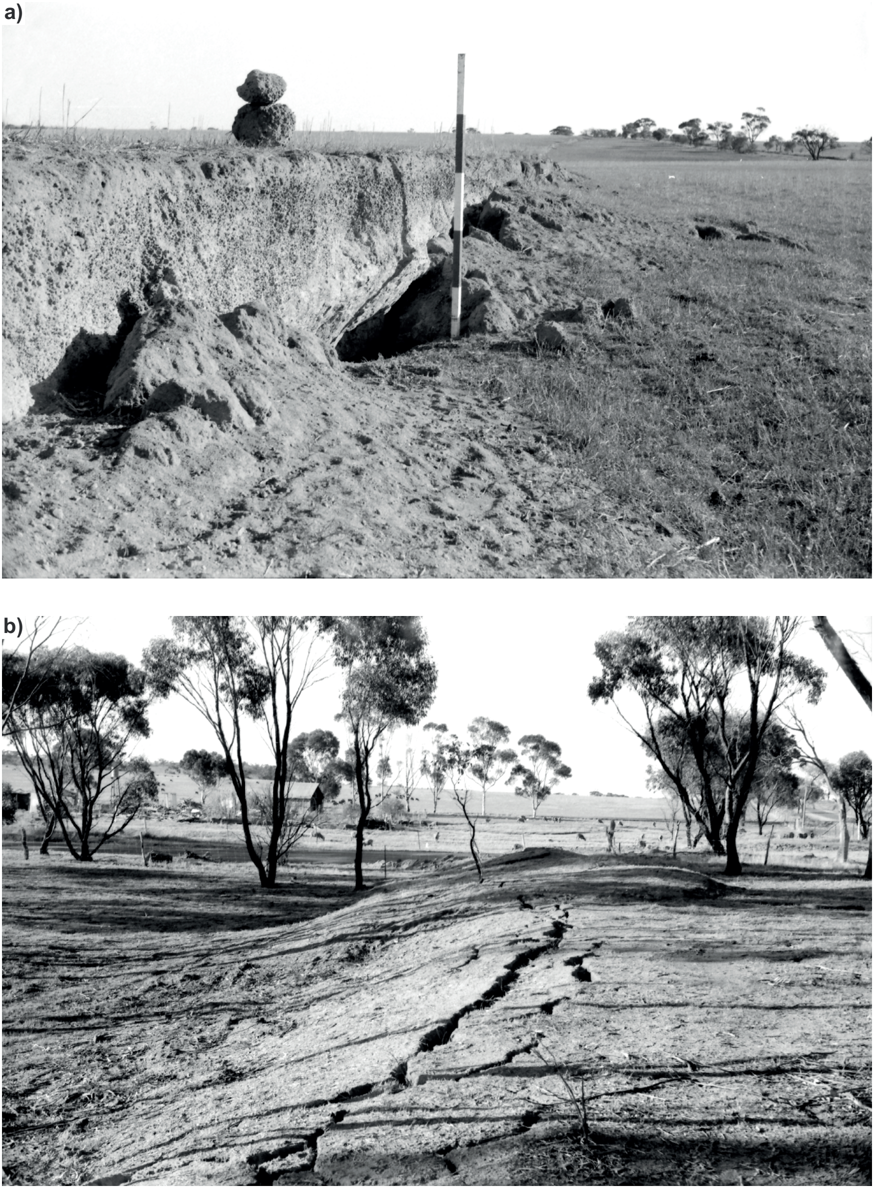
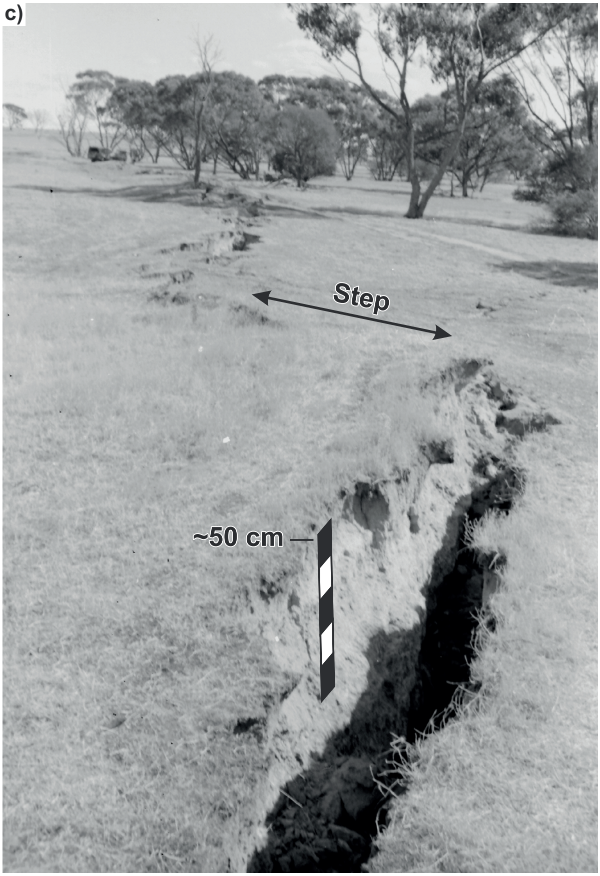


Figure 6. Close-up photos of Meckering Fault: a) thrust fault scarp nearly 1.5 m high; b) bulging of the surface above a section of the fault that didn't quite break through; c) an extensional fissure with small vertical offset that stepped across the paddock (see page 10)

Figure 6 continued



By 1980, GSWA geoscientists had settled on an epicentre location about 2.5 km northwest of Meckering and slightly to the west of the fault (see red star on the map, Fig. 7). However, with later work, the complexity of the earthquake and the sequence of fault movements have become better understood. A publication in 2010 by seismologists from URS Corporation, United States, and GA confirmed there had been more than one movement during the event. They revised the calculations and concluded the main epicentre was probably about 6.5 km south-southwest of Meckering at a depth of about 3 km (see yellow star on the map, Fig. 7).

That the epicentre was close to the town and the focus was so shallow, combined with multiple fault movements, help to explain why residents experienced such severe shaking.

In 2005, geoscientists from GA and The University of Western Australia excavated two trenches across the fault scarp. The trenches were located north and south of the Great Eastern Highway close to where fault displacement was maximum. The approximate position of the southern trench, dug to about 3.5 m depth, is shown on the map in Figure 7. Sketches of the trench walls clearly show the Meckering Fault and confirm overthrusting of more than 2 m at this locality (Fig. 8).

The trenches show the surficial layers that were affected and one shows that the fault continues into weathered bedrock (granite) at an angle of about 35–45° (Fig. 8). This is evidence that the Meckering Fault is not simply a near-surface feature but that the fault plane must extend into solid bedrock at depth. The geoscientists also noted evidence of a pre-existing fault zone, as suspected by the GSWA geologists in 1980.

Related secondary faults

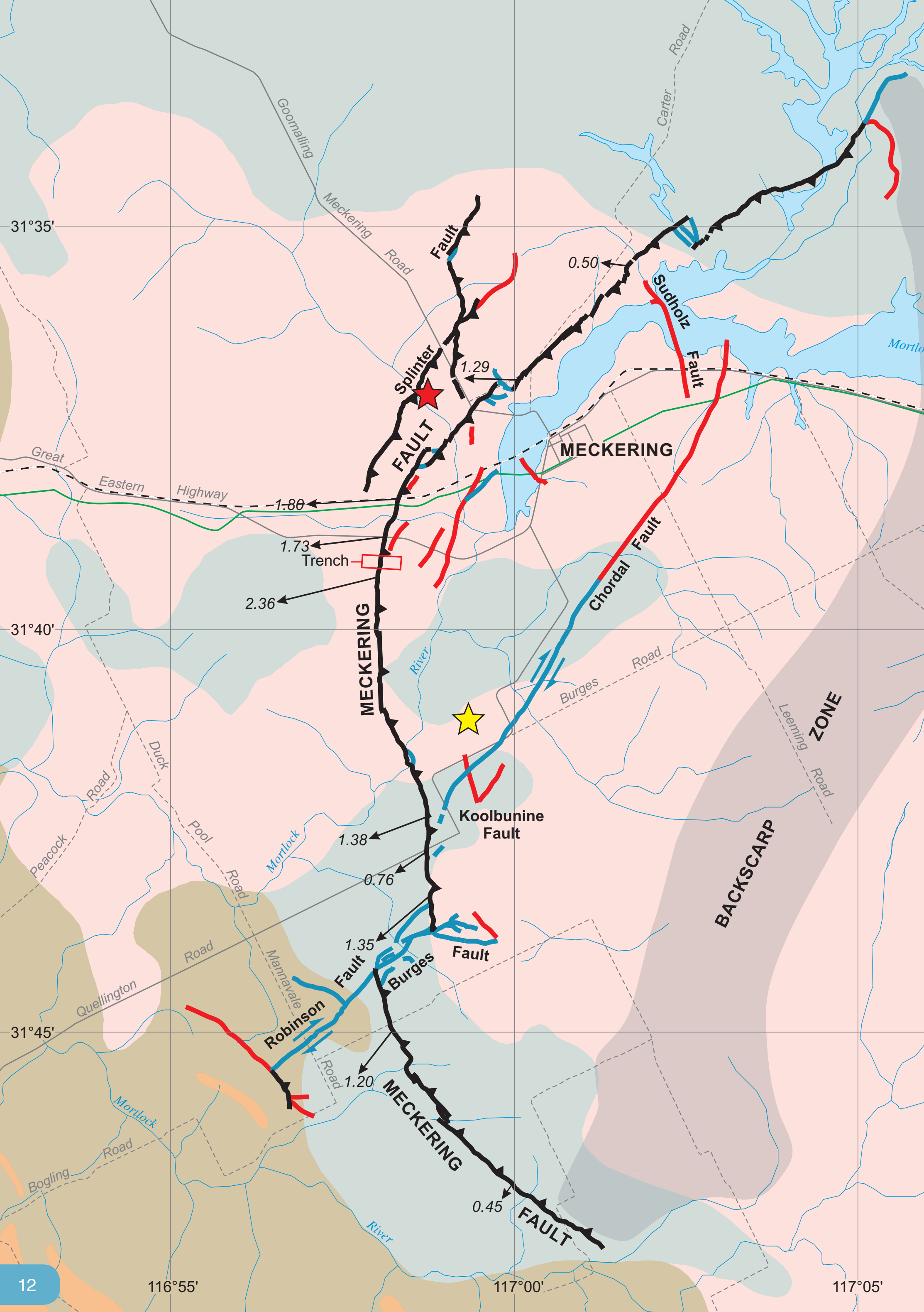
Several secondary or minor faults developed at the time of the earthquake or in the following days, weeks and months. These faults probably formed to relieve stresses that were not released on the Meckering Fault itself, or in response to secondary stresses set up as a result of the main earthquake. They are named on Figure 7.

Splinter Fault

This dextral thrust fault is aligned with, and 1.5 km northwest of, the Meckering Fault. It is possible that this fault merges with the Meckering Fault at a depth of about 1.6 km. Maximum uplift (vertical displacement) was a modest 33 cm.

Burges and Robinson Faults

The Burges Fault is a short, dextral strike-slip fault that links two sections of the southern part of the Meckering Fault. The Robinson Fault comprised many short extensional fractures linked up to produce the overall effect of a dextral strike-slip fault. It was described as a southwest extension of the Burges Fault continuing radially 3 km outwards from the Meckering Fault. Movement along the Robinson Fault was minor, but a pipeline ruptured by the faulting required the addition of 23 cm of pipe during repairs. The Robinson Fault terminates (in the west) against an unnamed tensional fault almost at right angles to the Robinson and Burges Fault trends.


31°35'
31°40'
31°45'
116°55'
117°00'
117°05'
Goomalling
Meckering
Road
Carter
Road
Fault
Splinter
FAULT
MECKERING
0.50
1.29
1.80
1.73
Trench
2.36
Sudholz
Fault
Mortlock
MECKERING
Great
Eastern
Highway
Chordal
Fault
River
Burges
Road
Leeming
Road
ZONE
BACKSCARP
Koolbunine
Fault
1.38
0.76
1.35
Fault
Burges
Fault
Robinson
Duck
Pool
Road
Peacock
Road
Mortlock
Quellington
Road
Mannavale
Road
1.20
MECKERING
FAULT
0.45
Mortlock
Road
Bogling
River

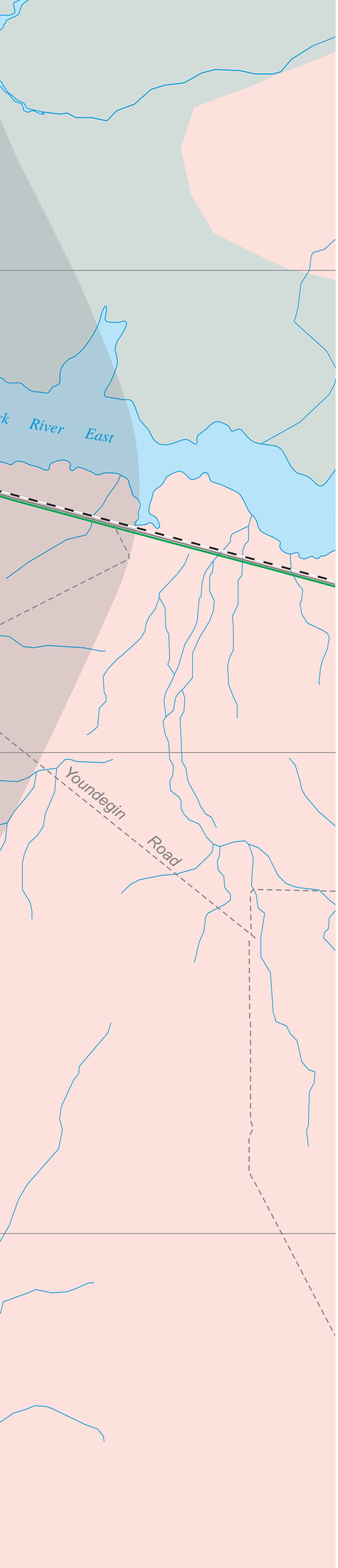


Figure 7. Simplified map of the Meckering Fault and related faults drawn over interpreted bedrock geology. Arrows pointing west or southwest from the main fault show the amount in metres the eastern side was thrust over the western side. The two stars show the estimated epicentre locations: red star is the location estimated by GSWA geoscientists in 1980; yellow star is the location determined in a study published in 2010 by geoscientists at URS Corporation, United States, and Geoscience Australia. One of the trenches excavated in 2005 is shown just south of Great Eastern Highway (see Fig. 8)

> "The Meckering, Splinter, Burges and Robinson Faults all ruptured the Earth's surface during the earthquake as stresses that had built up over thousands of years were suddenly released"

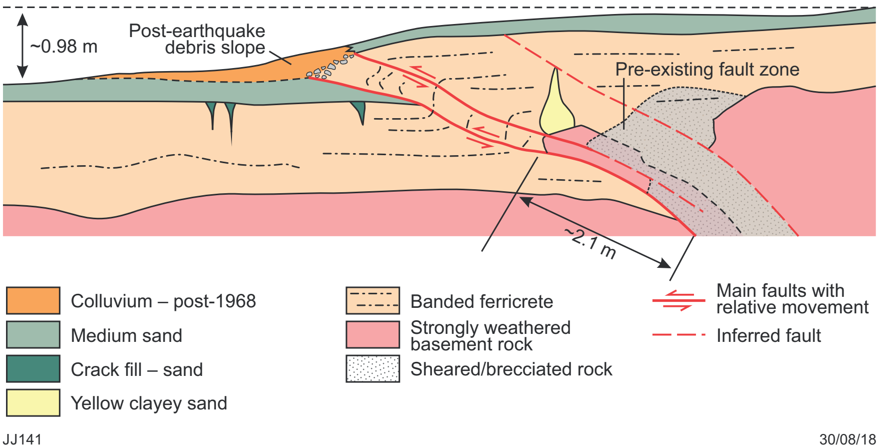


Figure 8. Cross-section sketch of the southern trench dug by geoscientists Dan Clark (GA) and Mike Dentith (The University of Western Australia) in 2005 to inspect the fault scarp below the surface

Across the arc — Chordal Fault

This fault was so named because it forms a chord across the arc of the main Meckering Fault trace. It is a secondary fault first noticed about six weeks after the earthquake. Traced for 13 km, it has small strike-slip and normal (vertical) displacements in the southern section, which transitioned into extensional fractures and strike-slip faulting farther north. There is a gap of about 250 m between the southern end of the Chordal Fault and the Meckering Fault.

Late fracture — Koolbunine Fault

This is a short fracture just 100 m long, but with several interesting features. It was the only fault observed by FR Gordon in 1968 in fresh rock, and it was a late fracture, formed after the main faulting event. Over a two-year period it grew longer and its opening increased to nearly one metre. The fracture is within a zone of complex minor faulting about 1 km wide and 1.5 km long at the southern end of the Chordal Fault.

Their stories

Every person living in, or visiting, Meckering on 14 October 1968 had a story to tell of that day. Here are some of their personal descriptions

"there were several periods of violent **shaking**"

"a noise like an **EXPLOSION**"

"we had **BURNING** sensations on the skin and there was a slight smell of carbide"

"trees along the main road whipped **violently**, and a 2.5 m-high scarp suddenly disrupted the road"

"a fault scarp 1.8 m high **disrupted** the Goomalling Road, and a smaller fault scarp 0.3 m high appeared"

"vehicles were thrown into the air and **DUMPED** back down"

"people were being **thrown** up into the air and knocked down again"

COUNTRY FORECAST: SCATTERED SHOWERS NEAR WEST COAST. ISOLATED FALLS ELSEWHERE

The West Australian

ESTABLISHED 1833

PERTH, TUESDAY, OCTOBER 15, 1968.

36 PAGES 5c

QUAKE HAVOC: 20 HURT

An earthquake which swept across the southern half of W.A. at 11 a.m. yesterday flattened the wheatbelt town of Meckering (population 250), 84 miles east of Perth.

More than three quarters of the town was reduced to rubble and the remaining houses have sections of wall missing as a result of the shock which lasted about 40 seconds.

Twenty people from Meckering and York, with injuries ranging from broken legs to concussion, cuts, bruises and shock, have been admitted to hospitals at Cunderdin, York and Perth.

About 12 other people from

Seismic readings at the Mundaring Geophysical Observatory showed that the earthquake began at 10.59 a.m. It was recorded as magnitude 6 on the Richter scale and is the most severe to hit W.A. since April, 1941, when an earthquake of 6.75 magnitude was recorded.

The Civil Emergency Service sent a van, equipped with two-way radio to Meckering about 3 p.m. It carried emergency stoves and other cooking facilities for about 100 people.

C.E.S. director F. Falconer said that no request had been made for other supplies.

Supplies Sent

The Red Cross and the Seventh Day Adventist Church at Northam also sent vehicles and supplies.

By 4 p.m. these workers had arranged billets for

The whole business section of Meckering was either destroyed or reduced to an unsafe condition and the police had sealed off the town by early afternoon.

Most of the exterior walls of the Railway Hotel collapsed in the earthquake and a wardrobe and bed on what had been the first floor were clearly visible from the street.

Bricks from the hotel crushed a utility in the street, but an occupant, Mr D. Casey, a bulldozer driver, escaped serious injury.

So did the four people who were in the hotel at the time.

Mrs Peter Kelly (34), who is expecting twins in about a month, was in bed at her farm home about seven miles south of Meckering, shortly before the earthquake.

The bedroom wall collapsed, covering the head of the bed in which she had been

shock as the day was quite warm, wandered about the pavilion area with blankets wrapped around their shoulders.

One said: "This is the end of Meckering."

Most agreed that the earthquake gave little warning of its arrival.

However they added that slight tremors were felt in the town from 7 a.m.

Only eleven days ago Meckering was shaken by three earth tremors in quick succession, and towns 50 miles around felt the effects.

The last of the three tremors recorded 4.1 on the Richter scale.

"We have had two or three smaller tremors in the past week but this one just lifted everything up and smashed it down again," said Constable D. Skehan, of the Meckering police.

Newspaper clipping courtesy West Australian Newspapers

"along the main street ground **CRACKS** up to 5 cm were opening and shutting again"

"two distinct **groundwaves** moved easterly across the main street"

Foreshocks

In the years prior to the earthquake on 14 October, the area had been seismically quiet. However, during the months leading up to October, there were many minor shocks in the region (Fig. 9). On 31 August 1968, patrons at the Meckering Golf Clubhouse felt a solid bump and saw a whitish cloud mushroom up from the rubbish dump about a kilometre away. On 29 September three strong shocks were felt northwest of Meckering. The local policeman reported on 3 October 'the ground seemed to turn to jelly' and he had difficulty keeping his balance. It was later confirmed a severe tremor had occurred, estimated at magnitude 4.2, at a depth of 7 km. Three kilometres north of Meckering strong shocks were also felt. On 14 October, early shocks were felt at 1.00 am and 7.15 am, before the main earthquake at 10.58.50 local time (Western Standard Time).

Aftershocks

There was considerable immediate aftershock activity, culminating in a magnitude 5.7 earthquake at 11.30 am local time a day later on 15 October. Shocks of magnitudes between 4.1 and 4.9 continued for a month, and a single shock on 28 November measured ~4.0. Seismic activity then gradually declined over the next four months. On 28 April 1969, a small tremor was felt within the townsite only (it didn't register at the Mundaring Observatory). In October 1976 (eight years after the main event) a quake of magnitude 4.7 was registered. Some 150 earthquakes >2.9 were recorded around the Meckering district up to November 1978 (Fig. 9).

Aftershocks have a variety of causes. Ground settling after the movement of the fault block was probably responsible for many small local tremors, whereas most of the larger aftershocks represented release of secondary stresses that accumulated along the Meckering Fault after the main earthquake, or in adjacent rock. Many of the aftershock epicentres were located on the mobile block between the arc of the Meckering Fault and the Backscarp Zone.

There were local concentrations of aftershock tremors in two peripheral areas — near Quellington, deemed to be due to the Robinson Fault, and near Mawson (Fig. 9). Around Mawson, 45 km southeast of Meckering, aftershocks began in January the following year and intense local seismic activity continued for five months (the ten largest shocks were magnitude >3).

Other large earthquakes in the region were felt at Calingiri on 10 March 1970, magnitude 5.7 with a very shallow focus of 1 km, and Cadoux on 2 June 1979, magnitude 6.1 and depth of focus ~3 km.

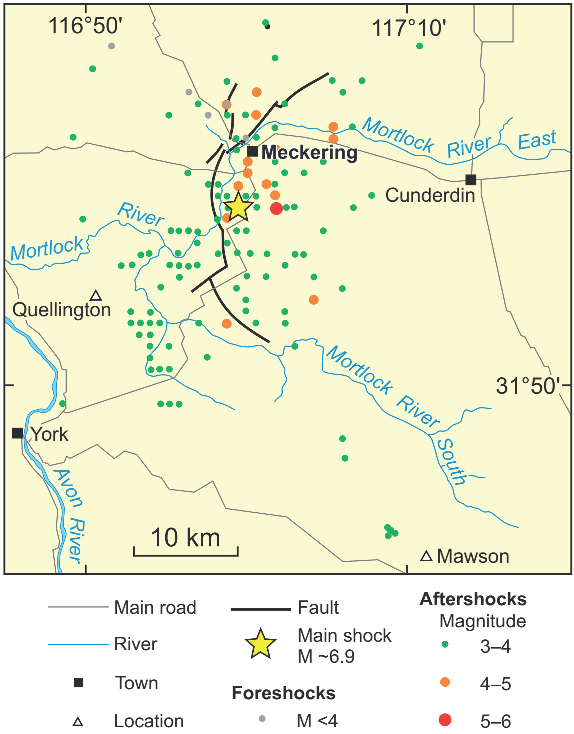


Figure 9. Distribution of foreshocks and aftershocks in the vicinity of Meckering. The main shock is shown in the revised location determined in 2010. This figure combines aftershock locations published in 1980 with a dataset provided by GA for the years 1967–2018. About 90% of the aftershocks were recorded before 1990. The grid-like pattern in some areas is an artefact of the limits of precision for foreshock and aftershock locations. Magnitude of the earthquakes is based on the Richter scale

The damage

Unfortunately for Meckering, the focus was shallow and the epicentre of the quake was only 6.5 km from the town, so the town took the brunt of the ground shaking as well as some direct effects of faulting. Figures 1 and 10 show pictures of the damage and the box *Their stories* tells some of the experiences of that day.

Damage from an earthquake can be caused by:

- faulting — the surface rupture is directly under or through infrastructure
- ground shaking
- other ground failure, such as slumping, bulging, and fissuring
- liquefaction — the saturated soil temporarily acts like a fluid.

The severity of damage is determined by:

- magnitude of the earthquake
- depth of the focus
- distance from the epicentre
- intensity and duration of the shaking
- type of ground or surface material
- quality of the buildings and other structures affected.

Building types were varied in the Meckering region before the earthquake, and there were only two two-storey buildings in the town. Some of the structures included timber frame with wood, asbestos, or brick-veneer cladding; steel frame with corrugated iron cladding; reinforced concrete; double brick, concrete or granite block; mud brick; and various combinations of these. Timber-framed and steel-framed houses survived the earthquake the best, but buildings constructed from a combination of materials proved unsound because of the differing responses of each material to the shaking. It is noteworthy that galvanized iron roofs had better structural integrity, sometimes remaining intact although the building below had collapsed.

Additional local aftershocks continued to exacerbate building damage for a few months after the fateful 14 October 1968 main shock. Other infrastructure, such as pipelines, roads, and railways also suffered intermittent and ongoing damage.

The bigger geological picture

Do we know what caused the Meckering earthquake and can we expect more earthquakes like this in future? Some geological background may help answer these questions.

Meckering is located close to the western edge of the large Archean Yilgarn Craton (see map inside front cover) which, with the Pilbara Craton to the north, forms the ancient core of the Australian continent. Rocks of both cratons are mostly metamorphosed granite, granitic gneiss, and metamorphosed volcanic and sedimentary rocks that formed between about 3730 and 2620 million years ago. The Yilgarn Craton is surrounded on all sides by younger rocks and its western boundary is the Darling Fault — a long-lived structure not thought to be active at the present day.

a)

b)

Figure 10. Examples of damage to infrastructure and the land: a) both the standard and narrow gauge rail lines were severely warped; b) houses and public buildings were extensively damaged or destroyed, although the framework of some houses remained upright; c) fences were offset across the fault; d) farmers had to deal with sizable fractures that opened in their paddocks (see next page)

c)

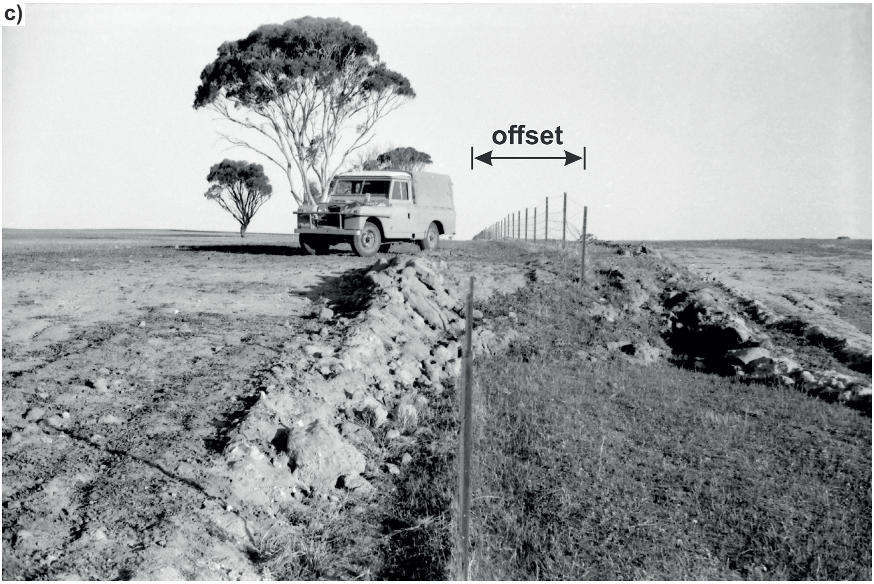
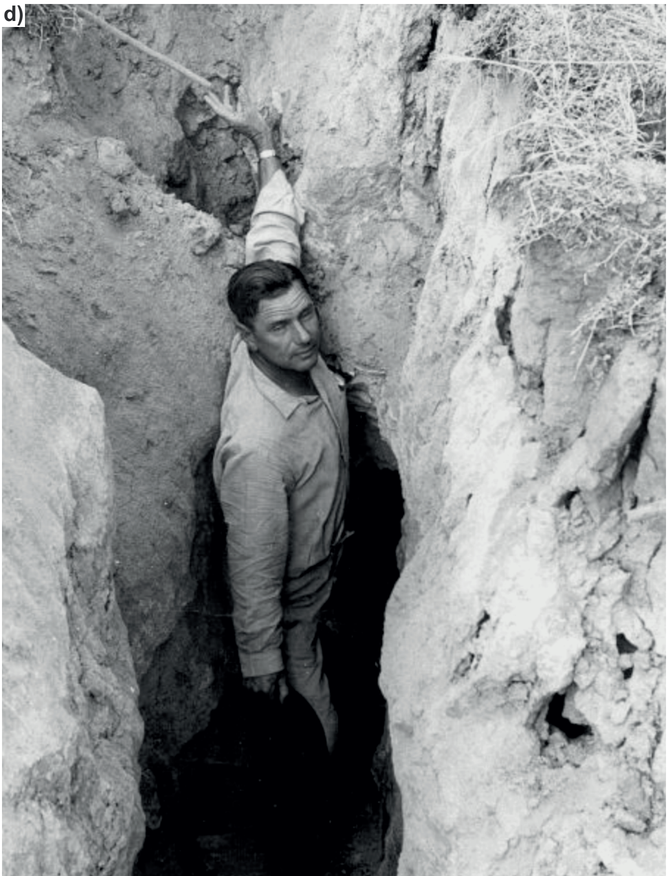


Figure 10 continued

d)



The immediate area around Meckering is mostly granitic rock and its weathered products, with some highly metamorphosed Archean sedimentary rocks. This belt of metamorphic rocks stretches all the way from Moora in the northwest towards Bremer Bay in the southeast. For the most part, the bedrock is overlain by a few to several metres of regolith — loosely consolidated or iron-cemented material derived from weathered bedrock.

Geoscientists investigating the Meckering earthquake noted the trace of the Meckering Fault roughly coincides with the 'Meckering Line'. This is a physiographic feature trending northwards through Meckering that marks a divide between an ancient landscape to the east and a 'rejuvenated' landscape to the west. The change in character of the Mortlock River reflects this — occupying a paleochannel with salt lakes east of Meckering, and a more youthful incised river valley as it flows west. However, the significance of the approximate coincidence of the Meckering Fault with the Meckering Line remains unclear.

Ancient continental cores such as the Yilgarn Craton are normally considered quite stable and earthquake free because, globally, most large earthquakes occur at tectonic plate boundaries. The largest earthquakes are generally where plates are colliding (see box *Plate tectonic setting*), such as along the margins of Southeast Asia (the Java–Sumatra trench), the western Pacific Ocean, or the west coast of South America. However, monitoring of seismic activity around the planet shows that earthquakes *within* tectonic plates — called intraplate earthquakes — are more common than once thought. Intraplate earthquakes are more distributed and the direct causes for these earthquakes differ from those at plate boundaries.

South West Seismic Zone

Western Australia has experienced more potentially damaging earthquakes of magnitude 5 or greater than the rest of Australia combined, and the South West Seismic Zone (SWSZ; Fig. 11) is an unusually seismically active region in an intraplate setting. Recent investigations, including direct observations from GPS networks, have shown that the Australian plate is drifting steadily northwards at a 'rapid' rate of up to 7 cm per year, and colliding with Southeast Asia. As a consequence, the continent is gradually tilting northwards — the Kimberley coast is sinking and drowning while the south coast is rising.

This tilting and uplift of the south coast flexes the relatively rigid continental crust. Flexing induces stresses in the upper crust and abrupt release of those stresses, commonly on pre-existing faults, is the main cause of shallow earthquakes in southern Western Australia.

Plate tectonic setting

The crust of the Earth comprises a jigsaw of tectonic plates. Earthquakes and volcanoes are very common along the edges of these plates where they collide with, slide past, or pull apart from each other in a continual global dance (Fig. 11). The huge Pacific Plate (comprising the Pacific Ocean) has the most, and the biggest, earthquake and volcano sites around its edges — this is called the 'Pacific Ring of Fire'. Many earthquakes arise here, affecting New Zealand, Papua New Guinea, the Philippines, Japan, and the west coasts of North and South America.

However, the Meckering and other earthquakes in the South West Seismic Zone (SWSZ), and across southwestern Australia generally, are far from any tectonic plate boundary and are described as **intraplate**, or within-plate, earthquakes. These arise from tilting and gentle flexing of the Australian continent as it collides with the Eurasian and Pacific plates (see text for further explanation).

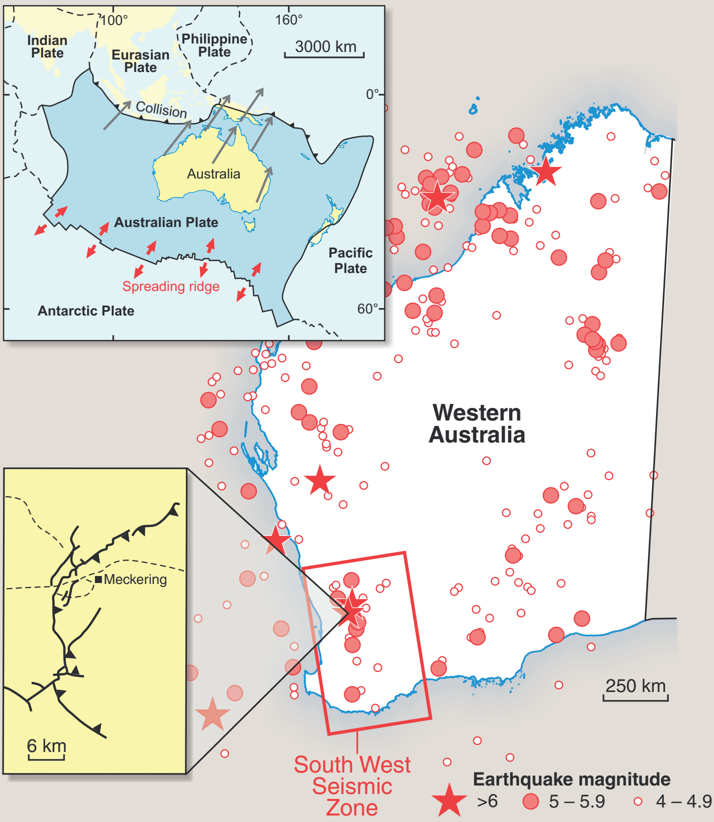


Figure 11. Historical earthquakes in Western Australia with magnitudes >4 (since recording began in the 1890s; Richter scale for M 4 to 6). Stars show earthquakes with estimated magnitudes 6.0 or greater. The plate tectonic map at top left places the Australian continent within the Australian Plate. Grey arrows show the drift of Australia northwards into Southeast Asia. The red frame is the outline of the South West Seismic Zone (SWSZ). At lower left, the location of the Meckering Fault is pinpointed within the SWSZ

Earthquakes — past and future

Aboriginal oral history includes hints of significant earthquakes in Western Australia centuries ago, and there are written records of earthquakes with magnitudes greater than 5.0 dating back to 1849. In addition to the 1968 Meckering earthquake, there were significant earthquakes in 1885, 1906, 1917, 1941, several between 1955 and 1963, several from 1970 to 1979, and as recently as 2001, 2010, 2014 and 2016. Some of these have been within the SWSZ, which is notable for ‘swarms’ of earthquakes with magnitudes up to 4 (e.g. the town of Burakin with some 400 earthquakes, and Beacon with about 250 earthquakes).

A magnitude 5.0 earthquake hit Kalgoorlie–Boulder on 20 April 2010 at approximately 8.17 am local time. Kalgoorlie is just east of the SWSZ. The shaking, which lasted 10–15 seconds and was felt up to 1000 km away, caused major damage to some of the historic buildings in the town. It was the largest magnitude earthquake ever recorded in the Eastern Goldfields region and one of the largest in Australia in terms of felt effects and damage, as measured on the Modified Mercalli scale (see Table 1 in box *How we measure earthquakes*). Several of the local gold mines, including the Kalgoorlie Super Pit, were temporarily closed. There were two slightly smaller earthquakes near Kalgoorlie and Coolgardie in February and October 2014, respectively.

A magnitude 6.1 earthquake in the Petermann Ranges area in 2016 generated a 1 m-high scarp that was reported by geoscientists from GSWA and GA. Centred just over the border in the Northern Territory, the earthquake is thought to have ruptured an older fault called the Woodroffe Thrust, which extends into Western Australia — these events do not respect State borders!

Thus, we should expect that Western Australia will continue to experience earthquakes from time to time. When and where is difficult to predict, but the historical and seismological evidence indicates that the SWSZ has developed since historical earthquake records have been kept. This suggests that regions of pronounced seismic activity may be transitory, and migrate over time. Large earthquakes might be expected almost anywhere in the western and northern parts of the State, although they are the exception rather than the rule. It is to our advantage that Western Australia is only sparsely populated, and in most cases even quite large earthquakes are unlikely to affect towns or cities. This may not be very reassuring for the residents of Meckering who remember their lives being turned upside down on 14 October 1968, but their experiences have helped us better prepare for similar events in future.

Echoes of the earthquake

The earthquake has become a touchstone for the town and its history. In 2018 geological remnants of the fault scarp generated by the earthquake could still be traced in some places. The segment along Quellington Road (about 11 km southwest of Meckering) has been preserved due to the foresight of the late Mr Merv Reynolds. From a small corrugated iron-roofed information sign on the former Reynolds property, visitors may follow scarp markers to walk the remains of the Meckering Fault scarp. Despite 50 years of farming activity and weathering, a subdued scarp plus a remnant showing part of the fault plane are still visible (Fig. 12).

Acknowledgements

Our thanks to Dan Clark and Geoscience Australia for access to published and unpublished work, including photographs, and for discussions during the course of writing. Thanks also to the Meckering Action Group (Inc.) for permission to use photographs and their invitation to contribute to the Meckering 50th Anniversary event.

“Breaking news: Magnitude-5.7 earthquake hits near Walpole!

— ABC News, 16.09.2018”

Geoscience Australia

Located in Canberra, GA is one of Australia’s leading geoscientific organizations, responsible for recording, researching, and alerting us to Australia’s geohazards, including earthquakes. GA monitors seismic data from more than 60 stations in the Australian National Seismograph Network, and in excess of 300 stations worldwide in near real time, 24 hours a day, seven days a week. In 2016, GA revised the magnitudes of some of Australia's historical earthquakes as part of an international project to reassess the magnitude estimates of earthquakes around the globe, based on current measurement techniques. These revisions mean the sizes of historical earthquakes can be more accurately compared to present-day earthquakes (see inside back cover *Ten largest earthquakes in Australia*).

Visit the GA website (www.ga.gov.au) to read the most comprehensive and up-to-date information on earthquakes in Australia, their causes, their prediction, and their geology. There is also a ‘storymap’ of earthquakes in Australia dating as far back as 20 000 years!

a)

b)

Figure 12. Two views from a similar angle of an exposed section of the Meckering Fault on the former Reynolds property southwest of Meckering. Weathered rock on the left has been thrust up and over the ground on the right. The photos compare the site in 1968 and 2018 — in 2018 the scarp is still about 1.4 m high (but smoothed)

Further reading

Anon., undated, Meckering earthquake 1968: a brief history of the earthquake that hit the small town of Meckering on the 14th October 1968, 29p.

Blewett, RS (ed.) 2012, Shaping a nation: a geology of Australia: Geoscience Australia and ANU Press, Canberra, ACT, 571p.

Clark, D, McPherson, A and Collins, C 2011, Australia's seismogenic neotectonic record: a case for heterogeneous intraplate deformation: Geoscience Australia, Record 2011/11, 100p.

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Gordon, FR and Lewis, JD 1980, The Meckering and Calingiri earthquakes October 1968 and March 1970: Geological Survey of Western Australia, Bulletin 126, 229p.

McCue, K 2014, Historical earthquakes in Western Australia: Australian Seismological Centre, Canberra, ACT, 46p. <www.aees.org.au/wp-content/uploads/2014/02/Historical-Earthquakes-in-Western-Australia.pdf>.

Meckering Action Group 2010, Meckering earthquake October 14, 1968 Souvenir Booklet: Meckering Action Group (Inc.), 14p.

Sandiford, M 2007, The tilting continent: A new constraint on the dynamic topographic field from Australia: Earth and Planetary Science Letters, v. 261, p. 152–163.

Sippl, C, Kennet, BL, Tkalčić, H, Spaggiari, CV, and Gessner, K 2016, New constraints on the current stress field and seismic velocity structure of the eastern Yilgarn Craton from mechanisms of local earthquakes: Australian Journal of Earth Sciences, v. 62, p. 1–11.

Somerville, P, Graves, R, Collins, N, Song, SG, Ni, S and Cummins, P 2010, Source and ground motion models for Australian earthquakes: Geoscience Australia, Canberra, ACT, 9p. <www.aees.org.au/wp-content/uploads/2013/11/Somerville-et-al.pdf>.

Woodside, J and McCue, K 2017, Early history of seismic design and codes in Australia: Australian Earthquake Engineering Society, Victoria, 14p. <www.aees.org.au/wp-content/uploads/2017/02/History-of-Seismic-Codes-in-Australia-Rev.pdf>.

Useful websites

Australian Earthquake Engineering Society (AEES): established after the 1989 Newcastle earthquake to improve seismic design for buildings in Australia;
www.aees.org.au/wp-content/uploads/2014/02/Historical-Earthquakes-in-Western-Australia.pdf

Australian Geographic:
www.australiangeographic.com.au/topics/science-environment/2011/10/earthquakes-in-australia

Australian Seismometers in schools program: videos on YouTube and Facebook;
(@ausisnetwork) or www.facebook.com/ausisnetwork

Earth Science Western Australia (ESWA): of particular interest to geoscience teachers and students;
www.earthsciencewa.com.au

Geoscience Australia (GA):
Recent earthquakes page; https://earthquakes.ga.gov.au; also on Twitter @EarthquakesGA
More information about earthquakes; www.ga.gov.au/scientific-topics/hazards/earthquake

International Seismological Centre (ISC): maps of the global distribution of historical and present-day earthquakes;
www.isc.ac.uk

Woodside Australian Science Project (WASP): encouraging the study of science in schools in Western Australia;
www.wasp.edu.au

United States Geological Survey (USGS) Earthquake Hazards Program:
Animations for earthquake terms and concepts (for kids); https://earthquake.usgs.gov/learn/animations
The Science of Earthquakes; https://earthquake.usgs.gov/learn/kids/eqscience.php

Table 2. Ten largest earthquakes in Australia with epicentres on the Australian mainland or adjacent to the Australian coast. The Meckering earthquake is highlighted red

Location	*Date*	*Richter scale magnitude (M_L)*	*Moment magnitude (M_W) post-2016 revisions*
Tennant Creek, NT	1988	6.7	6.6
Meckering, WA	1968	6.9	6.5
Simpson Desert, NT	1941	5.6	6.4
Tennant Creek, NT	1988	6.4	6.3
Meeberrie, WA	1941	7.2	6.3
Collier Bay, WA	1997	6.3	6.2
Tennant Creek, NT	1988	6.3	6.2
Cadoux, WA	1979	6.2	6.1
Petermann Ranges, NT	2016	N/A	6.1
West of Lake Mackay, WA	1970	6.0	6.0

Source: Geoscience Australia (www.ga.gov.au)

Understanding the Meckering earthquake is a Geological Survey of Western Australia publication written to mark the 50th anniversary of the earthquake that struck Meckering in October 1968. There are descriptions of the earthquake's geological features, its effects on the land, and the lasting impact it has had on the people in a small Western Australian town. We ask, 'Could another such earthquake happen again?'

Historical information about the earthquake has been updated by incorporating current seismological analysis, and the results of recent excavations across the fault. Placing the Meckering earthquake in a plate-tectonic context, and relating it to the long-term seismic record, highlights the unpredictability of earthquakes in Western Australia.

Quality photos, colour diagrams, a geological map identifying the fault traces, and detailed explanations of how earthquakes happen have been packaged into a compact colourful book that will be of interest to residents, visitors and specialist readers interested in Western Australian geology.

Details of geological publications and maps produced by the Geological Survey of Western Australia can be obtained by contacting:

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Department of Mines, Industry Regulation and Safety
100 Plain Street
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www.dmp.wa.gov.au/GSWApublications

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