

Historical Earthquakes in Western Australia

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Abstract

This paper is a tabulation and description of some earthquakes and tsunamis in Western Australia that occurred before the first modern short-period seismograph installation at Watheroo in 1958. The purpose of investigating these historical earthquakes is to better assess the relative earthquake hazard facing the State than would be obtained using just data from the post-modern instrumental period. This study supplements the earlier extensive historical investigation of Everingham and Tilbury (1972). It was made possible by the Australian National library project, *TROVE*, to scan and make available on-line Australian newspapers published before 1954. The *West Australian* newspaper commenced publication in Perth in 1833.

Western Australia is rather large with a sparsely distributed population, most of the people live along the coast. When an earthquake is felt in several places it would indicate a larger magnitude than one in say Victoria felt at a similar number of sites. Both large interplate and local intraplate earthquakes are felt in the north-west and sometimes it is difficult to identify the source because not all major historical earthquakes on the plate boundary are tabulated by the ISC or USGS. An earthquake on 29 April 1936 is a good example, local or distant source?

An interesting feature of the large earthquakes in WA is their apparent spatial and temporal migration, the latter alluded to by Everingham and Tilbury (1972). One could deduce that the seismicity rate changed before the major earthquake in 1906 offshore the central west coast of WA. There have been more and larger earthquakes since 1906 than in the previous ~73 years of written records although this could be just an artifact of the sparse population and lack of seismographs.

Two hitherto unrecognized moderate earthquakes in 1919 and 1936 near Eyre on the south coast have been identified marking the far south coast as an earthquake zone for hazard assessments. Isoseismal maps of several other significant earthquakes have been compiled to estimate their location and magnitude.

Introduction

Europeans settled the Perth WA area in 1829, nearly a decade before Adelaide and Melbourne were founded and they established their first Perth-based newspaper only 4 years later. They learned that the aborigines had stories of earthquakes handed down from generation to generation over the past ~40,000 years but few were documented. A modern short period seismograph was not installed in WA until 1958 so between then and 1829, the only source of information about earthquakes is that in newspapers and private journals. A low-gain intermediate-period seismograph was in operation at the Perth Observatory from early October 1901, its purpose clearly outlined in the article below from *The West Australian* of Tuesday 17 September 1912: to record large distant overseas earthquakes for foreign interests, rather than local earthquakes in the interest of Western Australia. This lack of local interest was partly because WA was not considered to be in an earthquake zone, despite the largest known Australian earthquake occurring in 1906 in WA where it was felt over a large part of the state.

THE PERTH OBSERVATORY. SCIENTIFIC AND PRACTICAL UTILITY. WHAT FIFTEEN YEARS HAVE WITNESSED. AN INSTITUTION GROWN FAMOUS.

The Seismograph, or earthquake recording instrument.

*In 1898 the Colonial Office, at the instance of the Royal Society, communicated with the Western Australian Government urging that a Milne Seismograph should be mounted at the Observatory, and this was strongly recommended by special resolutions of the Australasian Association for the Advancement of Science. The Government agreed to the request, and the instrument was installed in the basement of the dome (Author - in 1901). In 1909 the Government authorised expenditure necessary to remodel the instrument and introduce certain improvements. A continuous record of all earth tremors is kept and the results disseminated to scientific bodies. **Although not of any practical use as far as Western Australia is concerned, for we fortunately are not in an earthquake zone, the keeping of these records is of very great***

scientific interest and aid to those investigating the causes of earthquake in less favoured countries.

Few of the locally-felt events in the south-west were recorded on this insensitive intermediate-period seismograph. For example, *The Advertiser* Saturday 6 May 1916, page 8 records:

An earthquake shock was felt at Ravensthorpe and Hopetoun on Wednesday morning. At Ravensthorpe crockery on shelves rattled and the miners working underground were alarmed. No damage was done. There was no record of the shock on the seismograph at the Perth Observatory, but the Government Astronomer states that similar tremors, probably caused by the collapsing of subterranean hollows at no great distance from the surface, had been felt in the district in the past.

The Milne was upgraded to a Milne-Shaw seismometer in 1923, again at the urging of the Royal Society. Apparently State Observatory personnel didn't talk often to each other then either, WA Astronomer and state seismologist Curlewis told newspapers that a large earthquake recorded at Perth on 10 June 1936 occurred in Antarctica whereas it was actually in northeast New Guinea, as the relative times at Riverview and Melbourne would have shown. Fortunately it is listed correctly in the ISC's World Earthquake Bulletin.

The various Government Astronomers spoke about earthquakes in WA, probably one of the best informed was Mr H.B. Curlewis who wrote to the *West Australian* newspaper about WA earthquakes, how severe the 1906 earthquake was and where earthquakes were frequent. He wrote about the South-West for example as follows and note the mention of Meckering:

Throughout the South-West from time to time tremors accompanied by subterranean noises have been reported. Of these the most noteworthy are those which occurred near York, Quellington and Quairading, lasting off and on for over three months and causing some damage to buildings, in addition to scaring the inhabitants of the districts. Brookton, Wagin and Meckering have also been subjected to occasional bombardments of 'Barisal Guns'.

Contemporary newspapers are still the best source of information about WA earthquakes between 1829 and March 1958 when a single component vertical short-period seismograph was installed at Watheroo Observatory north of Perth. A geophysical observatory was established at Mundaring just east of Perth by the Commonwealth Government in 1959 and in July it was equipped with a triaxial short period Benioff seismograph. This intervention by the Commonwealth unfortunately led to the closure of the nearby Perth Observatory seismograph and the end of WA State Government involvement in earthquake monitoring apart from a short period when they monitored the Ord River Dam from Kununurra. The Mundaring Geophysical Observatory closed in April 2000, its functions transferred to Canberra leaving WA with no local expertise in seismology, the same situation faced in 1899 as outlined in the following article in which a *type-written communication* is today replaced with a telephone or email message.

The *Perth Daily News* of Thursday 27 April 1899 states on page 2:

If an earthquake were to lay Perth in ruins to-morrow, the Premier wouldn't know anything about it—officially—till he had received a type-written communication, signed by the Commissioner for Public Works.

Despite Australia's largest earthquake occurring offshore Carnarvon WA in 1906 and the largest onshore earthquake striking 500km north of Perth near Meeberrie in 1941, the wake-up call for earthquake engineering was not until the small town of Meckering, 120km east of Perth, was all but destroyed by a major earthquake on 14 October 1968. The Commonwealth Government's Director of Engineering Charles Bubb and Mundaring OIC seismologist Ian Everingham, led this awakening with State geologist Ray Gordon.

Half of the known magnitude 6 or greater earthquakes in Australia and the only known earthquake to exceed magnitude 7, since records commenced, occurred in Western Australia.

Offshore earthquakes in Indonesia on the Sunda Arc plate boundary and the tsunamis generated by them are a threat to buildings and infrastructure in Western Australia and several examples are mentioned here.

Previous studies of earthquake in WA

Everingham and Tilbury (1971 and 1972) tabled the results of a remarkable study of historic earthquakes in WA covering the periods 1849 to 1900 and the early instrumental period 1923 to 1961. They recovered very few of the seismograms recorded in the 1901 to 1922 period and commenced their report:

For this study no attempt was made to search for earthquake reports in every newspaper published before 1900. To locate reports in this manner would be extremely time-consuming and probably inefficient because of the difficulty in reading the archival microfilm copies of the newspapers and because of the haphazard way in which reports were included in these newspapers. Even when the dates of events were known, the authors often found it difficult to locate the reports in the newspapers.

From 1962 onwards, the Annual Reports of the Mundaring Geophysical Observatory by Everingham and others, and then Gregson and others are a very useful resource about earthquakes in Western Australia. The recent publishing on-line by the Australian National Library of their scanned collection of early Australian Newspapers makes the task of searching the early newspapers much simpler. The TROVE site allows users to correct the OCR of the scanned images that can be referenced online by all, but the scanning task is not yet complete so there are gaps still in the record.

Aboriginal earthquake stories

Everingham and Tilbury (1971) prefaced their account of pre-1900 earthquakes in WA with:

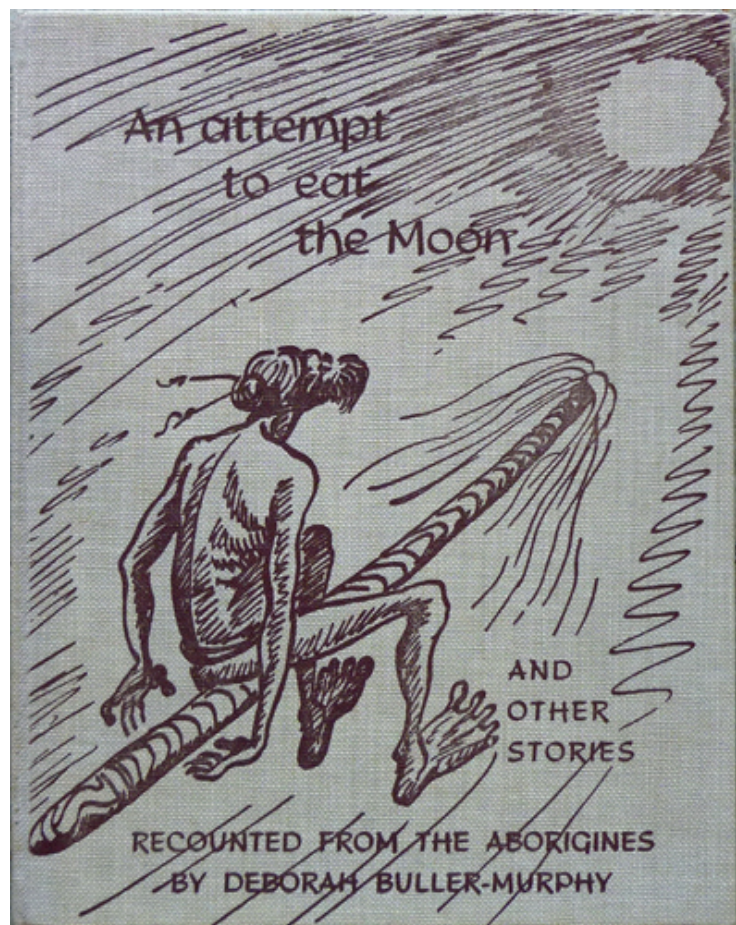
The earliest known reference to Western Australian seismicity is a legend to be found in a book of aboriginal legends named "An Attempt to Eat the Moon", by Buller-Murphy (1958). The legends pertain to the area in the vicinity of Busselton, and the one of interest here, entitled "The Great Shaking", gives a vivid description of earthquake (and perhaps volcanic and weather) effects which were accompanied by changes in the topography and sea level. The existence of the legend suggests that a major earthquake which occurred unknown centuries ago was impressive enough to be permanently recorded in the legends of the local population.

Their stories continue to be collected to this day, an elderly Aboriginal's recollection of an earthquake he experienced in the Ashburton district on 19 November 1906 is recorded in Jack Butler and Peter Austin's Aboriginal history, Vol.10, no.1 (1986), p.78-84.

Figure 1 *An Attempt to Eat the Moon and other stories* (Georgian House, Melbourne, 1958) contains 15 legends from the Dordenup people of southwestern Australia. They were told to Deborah Buller-Murphy when she was living in the Margaret River area in the late 19th century. The legends are about people and places, flowers and weapons, the origin of rainbows, earthquakes and other phenomena, illustrated by Elizabeth Durack.

Post-European arrival earthquakes

We have scoured the newspapers scanned by the ANL to-date, no doubt further earthquakes will be found as Trove is completed. Everingham and Tilbury (1972) were more successful than they might have imagined and only a few new events were uncovered. Their first entry is worth reproducing:



1849 08 03 at 20:15 UTC (4:15 am local time on 4th August 1849), Perth

What is claimed to be the first local earthquake felt in Western Australia was reported in the *Inquirer* Wednesday 8 August 1849, page 3:

On Saturday last, about a quarter past four o'clock a.m., several of the inhabitants of Perth were awoke by what they conceived to be a slight shock of an earthquake; it was momentary, but quite sufficient to make the glasses ring, and to shake the articles of furniture in the rooms, such as the bedsteads, &c. The same phenomenon was observed at Fremantle and Guildford. This is the first time such an occurrence has been noticed in Western Australia, which bears no trace of having been recently a volcanic country, and is not therefore liable to those disturbances of the earth's surface felt in existing volcanic regions. If this were a slight shock, it will most probably be found to be nearly simultaneous with one of greater severity that has happened elsewhere, some great distance away, of which it was a prolongation and perhaps the terminative effect. We cannot hear that any damage was effected, or indeed that any trace of its visit has been left to substantiate the fact of a shock having occurred. The weather at the time was perfectly calm, although there were several heavy showers during the night, and some thunder and lightning.

1855 Perth

The *Cornwall Chronicle* (Launceston, Tas. : 1835 - 1880) Saturday 8 September 1855, page 3.

About one or two o'clock on Monday morning a shock of earthquake was felt at Perth, which lasted two or three seconds. After a brief interval a second shock was experienced, of the same duration as the first.

The same story was in the *South Australian Register* of Wednesday 22 August 1855, page 3 and *The Argus* of 17th August 1855, page 7, but in none of them is the actual date of the earthquake specified, nor which Perth; WA, Tasmania or Scotland, and it is probably the latter.

1877 10 ~10, Pinjarrah

The Inquirer & Commercial News, Wednesday 31 October 1877, page 1S reports an earthquake about 3 weeks ago, that from the felt area was a least ML4.5. It was also felt on the Arthur River:

A distinct shock of earthquake was felt at Pinjarrah on the Murray River. The shock extended about fifty miles round that locality, and was accompanied by a noise resembling the discharge of a cannon.

1877 10 17, evening, Victoria Plains

There was a brief mention of an earthquake at Victoria Plains in *The Sydney Morning Herald* of Tuesday 6 November 1877 page 5 – *on the 18th ultimo*. The *South Australian Register* Monday 5 November page 5 says it occurred on 16th and the *Inquirer and Commercial News* (Perth) says the evening of the 17th, quoting a Victoria Plains correspondent.

We don't have a date for the Pinjarrah event but as Pinjarrah is 70km south of Perth and Victoria Plains 110km NNE of Perth, these must be separate earthquakes since there is no report of an earthquake felt in Perth that year.

1883 08 27-29, King George's Sound, Geraldton and Dongarra – Tsunami observed – Krakatoa Volcano Eruption

The Kiama Independent and Shoalhaven Advertiser of Tuesday 18 September 1883, page 2 reports:

DESCRIBING the extraordinary tidal pheononona observed in King George's Sound, on Monday, Tuesday and Wednesday; August 27, 28, and 29, the "Albany Mail" says :—" As the R.M.S. Rosetta was steaming out of the harbour on Monday afternoon, a great rush of tide, like a tidal bore came in, and the vessel had

to put on full speed to meet it, and on the following day there were two great rushes inward, and then a tremendous rush outward. All the buoys disappeared under water, and then rose to the surface and took moorings and everything out into the Sound. On Wednesday, when the harbourmaster was coming in with the steamer Coniston, at 8 p.m., the tide was running at such a rate that the vessel could hardly make headway going full speed. Such a tide was never known by the oldest nautical inhabitants of the port, and was strange, considering the slight rise and fall of the tide in this harbour, only 3 feet. There must have been a succession of tidal waves, or several shocks of submarine earthquake." Similar phenomena were noticed at Geraldton. A telegram from that place says: " Strange rumbling sounds were heard here and at Tibradden and elsewhere on Monday morning early, and a most unusual rise of tide took place on Monday evening at 8 o'clock and again at half-past 8. The sea receded over a hundred yards, enabling people to pick up fish in quantities. The drawback was of short duration. The sea returned with a great rushing noise, and those who were fish-gathering had to run quickly for their lives. Boats that were high and dry on the beach were washed out and swamped. The Rob Roy and the lighters at anchor were twisted right round. The sea rose about eight feet. In a short time all was quiet again, except that the ocean continued rising and falling till next morning."

It is strange that this event is not noted by Everingham and Tilbury (1972).

1883 10 2? Felt Geraldton and Dongara

Sharp shocks of earthquake were reported felt at Geraldton and Dongarra in October in several newspapers such as *The Capricornian* on Saturday 3 November page 11, without details. The *South Australian Register* Monday 29 October 1883, page 5 says the shocks were felt a few days ago.

1883 12 24 morning, Perth

The *South Australian Register* of Thursday 27 December 1883, page 5 reports:

A slight shock of earthquake was felt at Perth early this morning.

The previous days *Sydney Morning Herald* carried the same story. No further details.

1885 01 05 at 14:30 UTC, Geraldton and Northampton

The *Kerang Times and Swan Hill Gazette* of Friday 16 January 1885, page 3, notes (no date or time):

A severe shock of earthquake has occurred at Geraldton, Western Australia, lasting for about 10 seconds. Houses were violently shaken, the walls rocked, and the sea subsided-three feet in a quarter of an hour.

Recounting his experiences in Northampton on 5th January 1885 Mr. Drew MLC (*The West Australian*, Wednesday 24 January 1940, page 14) stated:

A shock of earthquake was felt at 10.30 p.m. Windows and crockery and household furniture clattered violently. This was followed by a rumbling noise. I may explain that the 'rumbling noise' referred to was such as might be expected from an immense and continuous upheaval of rock by a succession of violent explosions. The direction from which the sound came was about east of Northampton On November 19, 1906, there was an exactly similar experience at Northampton, except that no explosions were heard.

If the intensity was similar to that in 1906, then it is rated MM4, though the description might imply MM5 or higher (see discussion in Everingham and Tilbury, 1972 who assigned this earthquake magnitude Ms6.5).

1886 09 09 at 18:10 UTC, Cossack and Roebourne

The Daily News Perth on 11 September 1886, page 3 reported the earthquake felt and heard at ten minutes past two am. The *West Australian* of Saturday 11 September 1886 says on page 4 that the time was 2am

and adds that some people were alarmed enough to turn out of bed and dress though no harm was done. It is hard to explain the duration of one hour reported in the attached newspaper article, perhaps several shocks over a period of one hour. Undoubtedly this was a distant plate-boundary earthquake or series of earthquakes. It not being the monsoon season, there is no reason to suppose it actually was thunder.

The *South Australian Register*, Monday 13 September 1886, page 5:

Perth, September 11.

A shock of earthquake was felt at Cossack and Roebourne early yesterday morning. The vibrations lasted nearly an hour, with reports like very heavy thunder.

1890 12 07 at 06:30 UTC, Roebourne and Cossack

The *Inquirer and Commercial News* Wednesday 10 December page 4 says:

Between two and three o'clock last Sunday afternoon a shock of earthquake was felt at Roebourne and Cossack, the particulars of which are detailed in the following telegram to the Colonial Secretary, from the weather observing station at Cossack : —"Cossack, Dec. 8. Shock as if caused by an earthquake felt here about 2.30 p.m. yesterday. Doors and windows of dwellings shaken. Shock felt for about 50 seconds. Direction of report, N.W. to S.E."

The *Record*, Saturday 13 December 1890, page 3 reports with a few more details:

EARTHQUAKE SHOCK IN WESTERN AUSTRALIA.

On Sunday afternoon a shock of earthquake was felt at Roebourne and Cossack. It was also felt 30 miles eastward and 20 miles westward. The shock lasted half a minute and was followed by a rumbling sound, lasting for a minute. The sound increased to a loud roar, and then died away. It resembled the noise made by an approaching train, and woke several people who were sleeping at the time.

The *Western Mail* of Saturday 17 January 1891 page 21 published the following almost unbelievable account:

TERRIBLE EARTHQUAKE AT ROEBOURNE.

It is barely a month since we were acquainted with the fact that an earthquake of such force was felt in Roebourne as to unroot trees, unroof houses, and shake the most solid buildings in their very fundamentals. The damage then caused now appears not by any means as trifling as it was at first supposed, as it has left behind a scene of desolation with great loss of property. The cause of the disaster must be sought in the volcanic character of the territory, and as usual the attention of scientists is called to these awful phenomena of nature. Yesterday's paper mentions the discovery of magnetic shoal one mile in diameter, near Cossack. Our indispensable cable has been, repeatedly interrupted owing, to earthquakes, the cause of which may be traced many miles away from the scene of action. The cause is remote; but the effect is here.

The rest of the story is an advertisement for a certain 'safe cure' medicine that tends to colour the whole article, unless it was a cyclone, rather than an earthquake, that caused the damage; December is cyclone season.

1893 03 19 at 13:00 and 23:30 UTC, Breaksea Island lighthouse near Albany

The *West Australian*, Wednesday 22 March 1893, page 4 reports:

THE Superintendent of Telegraphs, Mr. Hancock, has received the following telegram from Albany, giving particulars of the earthquake shock felt at Breaksea Island:— "Lightkeeper Breaksea reports, Sunday night, 9 p.m., sudden shook earthquake felt there, accompanied noise like heavy artillery firing. Trembling of island lasted about three minutes. Again at 7.30 a.m. Monday, similar shock felt, but of much heavier nature. Trembling of island lasting five minutes, and the building being severely shaken. No damage was, however, done. Shock

travelled from west to east. Weather was close and sultry. Heavy rumbling noise heard here, both at 9 Sunday night and 7.30 Monday morning, and slight tremor noticed in one or two places."

These two events are obviously very local to the lighthouse which is 12km southeast of Albany and the effects easily warrant nearby events of magnitude ML 3.5 and 4. The lighthouse was built by English convicts in 1858 using rivetted cast-iron sheets but in 1902 the structure was replaced with a cylindrical granite tower.

1893 04 26 22:05 UTC, Roebourne

PERTH, SATURDAY.

The Sydney Morning Herald of Mayday Monday, page 8 carried this story despite the lack of time being mentioned or the miss-spelling of Roebourne.

A shock of earthquake, lasting 20 seconds, is reported to have taken place at Roeburne on Thursday last.

The *Western Mail* Saturday 6 May 1893, page 42 has a message telegraphed from Roeburne on 28 April, that says the earthquake occurred yesterday morning at a few minutes after 6 o'clock.

The reports point to a small earthquake of local origin.

1894 01 04 at 14:00 UTC, Albany

A distinct shock of earthquake was felt last night. Many houses trembled violently (according to *The Maitland Daily Mercury*, Friday 5 January 1894, page 3. *The Barrier Miner* adds that the time was 10 o'clock in the evening.

1896 04 20 at 12:15 UTC, Felt Karridale

This small local earthquake was reported in *The West Australian* on Wednesday 22 April 1896, page 5.

THE EARTHQUAKE AT KARRIDALE.

SEVERE EARTH TREMORS.

VIOLENT EXPLOSIONS.

Karridale, April 21.

A severe earth tremor, accompanied by violent explosions, was felt here about eight o'clock last night, and caused much alarm among the inhabitants. The shock seemed to travel from south to north and lasted for about fifty seconds.

With no other felt reports one assumes this is a close, shallow small earthquake near Karridale and we have assigned the magnitude as ML 3.5 though the reported duration of 50sec suggests something larger. Another paper reporting the Karridale postmaster said the earthquake occurred at 8:15pm local time.

1896 07 02 at 18:00 UTC, Eucla

The Brisbane Courier of Wednesday 8 July 1896 mentions an earthquake:

EARTHQUAKE SHOCK.

A smart shock of earthquake was experienced at Eucla at about 2 o'clock on Friday morning.

We assume this was a small, very local earthquake.

1899 04 07 at 02:20 UTC, Albany

A 'VERY distinct tremor' was reported felt at Albany for a few seconds (*Albany Advertiser*, Saturday 8 April 1899, page 2). We assume this was a local like that in 1893 and assign it a magnitude of 3.0.

1899 10 24 at 04:00 UTC, Felt Wyndham

Several papers including the *Warwick Argus* of Saturday 28 October 1899 page 7 reports (no date or time):

A distinct shock of earthquake has been felt at Wyndham, Western Australia. The tremor lasted a minute.

The Sydney Morning Herald Wednesday 25 October, page 8 gave the date and time as about noon local time Wyndham. "The Post Office and other buildings were terribly shaken." This event precedes the ISC Bulletin and is not mentioned in the NOAA catalogue but assuming it was on the plate boundary, it must have been greater than Ms7.

1901 01 10 at 03:00 UTC, Cossack and Roebourne

The *Albany Advertiser* on Friday 11 January 1901 is the source of the following account:

Earthquake in the North-West. Perth, Friday.

A shock of earthquake was felt at Roebourne, Cossack and Whim Creek at 11 o'clock on Thursday morning. The shock lasted two minutes, at Cossack a number of buildings were shaken.

The Argus of Friday 11 January 1901 page 6, mentions that it was also felt at Balla Balla, near Whim Creek and about 70km from Cossack. It is assumed, because of the duration reported, that this is another in a series of large earthquakes on the plate boundary to the north.

1903 02 13 at 16:00 UTC (Midnight on Monday 13th February local time), Wyndham

The *West Australian* of Tuesday 17 February 1903, page 4 mentions briefly a telegram regarding an earthquake felt at Wyndham:

The postmaster at Wyndham telegraphed as follows :—"Earth tremor lasting about three minutes felt here on 13th, at mid-night."

This is in stark contrast to the following report, also from Wyndham.

1904 05 24 at 11.45 UTC (7.45pm local time), Wyndham

The telegram from the Postmaster at Wyndham to the Government Astronomer stated that an earth tremor was felt there at a quarter to 8 on Tuesday night, lasting about 3 seconds, no further details (*The West Australian* Friday 27 May 1904, page 4). There was no record on the Perth seismograph and with the short duration, we conclude it was a small local, perhaps magnitude ~ML 3.5.

1905 01 16 at 16:00 UTC, Cape Naturaliste

The *Western Mail*, Saturday 21 January 1905, page 32 has a short report about an earthquake felt locally.

Earth Tremor at Cape Naturaliste.— The Government Astronomer has received a telegram from the head lighthouse-keeper at Cape Naturaliste reporting that a severe earth tremor was felt there at midnight on Monday. The lighthouse and quarters were shaken, but no

damage was done.

This earthquake could not have been smaller than 3.5 even if right under the lighthouse, to have caused the effects mentioned.

1906 11 19 at 07:18 UTC, Offshore Geraldton WA

This is the largest known Australian earthquake, its magnitude revised down by Abe (1983) to Ms7.2, from the Ms 7³/₄ attributed to it by Gutenberg and Richter (1954). Everingham and others (1987) also quote this value of Ms 7.2. Gregson and Everingham (1991) investigated the effects of this earthquake in Australia using local newspaper reports, drew an isoseismal map, and concluded that the Gutenberg and Richter solution was consistent with the felt data.

The *Northern Times* 01 December 1906, page 2 had a few additional reports of the shaking.

THE RECENT EARTHQUAKE.—Reports by the country mails show that the earthquake on the 19th inst. was experienced at Glenburgh, Clifton Downs, Williambury, Mungarra, Middalya, Hill Springe, Wogoola, Yanrie and other stations. In no case was any damage done.

The *Western Mail* also reported on the earthquake, Saturday 24 November 1906, page 15:

Geraldton, November 19.

Two shocks of earthquake were felt here this afternoon. The first was at 3.20 p.m., and was slight. The second was felt at 3.25, and was much more severe, the oscillations lasting about 10 seconds, with a south-west to north-easterly directions. Buildings vibrated, and some alarm was caused, but no damage was done. The shocks were felt at Newmarracarra, Narra Tarra, and at Minyanooka.

Busselton, November 19.

A severe earthquake, lasting for 10 seconds, was felt here at 3.35 p.m., considerable consternation being occasioned.

Cue, November 19.

Two distinct shocks of earthquake were experienced in the Cue district this afternoon. The first occurred at 3.27 p.m., and lasted for a minute and a half. After a few seconds' interval it was followed by the second shock. Many buildings trembled and windows rattled. A telegram received from Peak Hill states that several shocks of earthquake were experienced there at 8.28 p.m.

Port Hedland, November 19.

Two earthquake shocks were felt here between 8 o'clock and 3.30 this afternoon. The tremors were most perceptible in various business places.

This year 1906 is intriguing, it is a standout in world seismicity for the unusually large number of magnitude 8 or greater earthquakes, all along the Circum-Pacific belt. The ISC Bulletin says there were 6, the USGS only 4 after downgrading the Honshu and Californian events; compared with an average of one per year.

The Government Astronomer made the interesting point when talking about this earthquake that it was the first felt in Perth in his 11 years experience. He didn't have to wait long for the next one.

1907 01 04 at 05:19 UTC, Sumatra, Felt Cocos Is and tsunami observed there

An earthquake and tidal wave were reported from Cocos Is and Rodrigues Is in the Indian Ocean about noon Cocos Is time (Zeehan and Dundas Herald, Monday 7 January 1907, page 3). The ISC Bulletin quoting Gutenberg and Richter (1954), have a location in North Sumatra and magnitude of Ms 7.6. The Perth Observatory recorded a P-wave at 05 26 48 UTC, reportedly a very fine record.

1907 04 10 at 08:00 UTC, Felt Perth

The Register Thursday 11 April 1907, page 5.

EARTHSHOCK IN PERTH.

PERTH, April 10.

This afternoon, about 4 o'clock, what was thought to be a slight earthquake was felt in Perth. On enquiry at the Observatory Mr. Cooke stated that undoubtedly an earth tremor had occurred, as the needle of the seismograph was moving. Whether the shock was severe he could not say yet, as it was impossible to remove the films.

The Kalgoorlie Miner of 11 April 1907, Page 5, repeats the story almost verbatim but headlines the date as April 1, though the stories immediately above and below carry the Perth April 10, date. *The Daily News* of Wednesday 10 April 1907, page 7, also has an April 10 date, as does *The Argus*.

1907 08 09 at 12:40 UTC, Marble Bar

The West Australian of Monday 12 August 1907, page 7 mentioned an earthquake at Marble Bar:

A DISTINCT SHOCK. Marble Bar. August 10. At 20 minutes to 9 o'clock last night a distinct shock of earthquake was felt in this district. The rumbling was the loudest yet heard here. The sound resembled that made by a wagon passing over a bridge. The shock lasted 15 seconds. Glassware rattled in most places and the shock was heard and felt distinctly.

This sounds like a local in the vicinity of Marble Bar, rather than a distant plate boundary earthquake (cf isoseismal map of the 24 July 1975 mb 5.1 event near Marble Bar by Gregson and Smith, 1976).

1907 08 12 time?, Perth

Townsville Daily Bulletin, Wednesday 14 August 1907 reports:

PERTH, August 13.

The city on the Swan has had another earth tremor. Nothing serious —only a few empty Porter's Bulldog Ale and Stout bottles 'rattled' a bit; that's all.— (Advt.)

‘Advt.’ is most probably an abbreviation for ‘Advertisement’ rather than Advertiser so this should be taken as just an advertisement for a beer! However it was reported as earthquake shocks in other papers such as the *Barrier Miner* of Tuesday 13 August 1907, page 4, without the (Advt.).

1908 05 09 at 08:00 UTC, Felt Turkey Creek (Warmun)

The Newcastle Herald of Tuesday 12 May 1908, page 7 mentions an earthquake in the north-west of WA. No other towns such as Wyndham 170km to the northwest, nor Darwin NT, reported a similar problem so we assume the earthquake was local.

A severe earthquake shock occurred at Turkey Creek, in the north-west of West Australia, at 4 p.m. on Saturday. Houses rocked violently, the earth rumbling very loud. It lasted about three minutes. The disturbance appeared to come from the west-north-west.

The description fits a local moderate earthquake limited by the lack of other reports. A local earthquake of magnitude 5.3 should have been felt at Wyndham so we assume it was smaller than that but larger than ML 4 given the duration and intensity. This event is interesting because of its vicinity to Lake Argyle.

1909 04 18 16:37 UTC, Balline Station Murchison Region

Mr. C.S. Palmer of Balline Station Northampton District reported that all five residents felt the earthquake that caused a lamp to swing back and forth (*Western Mail*, Saturday 01 May 1909, page 4). This event was, according to the Observatory, recorded on the Perth seismograph, faintly, at 12:37 am but the further

comment that it continued off and on until seven minutes past 3, would indicate that other events were responsible for the seismogram, probably distant large earthquakes on the plate boundary to the north. To have been recorded at this distance from the Perth Observatory, the magnitude had to be at least 4.3.

1909 10 12 at 06:50 UTC (or Oct 11 at 18:50 UTC), Marble Bar

The *West Australian* of Thursday 14 October 1909, page 4 reports:

Earth Tremor.— The Government Astronomer (Mr. W. E. Cooke) yesterday received the following telegram from the Postmaster at Marble Bar :—"A distinct earth tremor felt 2.50 yesterday. Lasted 10 seconds."

The time we have assumed is afternoon, but that is not stated, if morning then the date and time in brackets are correct. A large earthquake on the plate boundary would have been felt at the same time in other centres such as Darwin or Derby, and recorded at Perth Observatory, so we assume this was a local earthquake.

1910 10 14 at 22:15 UTC (Oct 15 at 06.15 WST), Marble Bar two locals

EARTHQUAKES IN THE WEST.

PERTH, October 17.

Two distinct earthquakes were felt at Marble Bar on Saturday morning. The first occurred at about a quarter to 6, and 10 minutes later a sound as of distant thunder was heard by people living 20 miles apart. The shock travelled from a southern to a northerly direction, and caused crockery to rattle in almost every dwelling.

Interesting to speculate on how far this event was from Marble Bar and how big it was. The ten minutes delay is too long to be an S-P time. If the S wave was the first phase felt, its velocity about 3km/s and the distant thunder was the sound wave travelling at 0.3 km/s, the epicentral distance would have been about 200km. We assume the alternative here, that it was a small local and only felt over that 30km range mentioned in the newspaper so the estimated magnitude is ~ ML3.

1911 08 04 earthquake swarm at Quellington, minor damage

The *Daily News* on Saturday 12 August 1911, page 6 notes:

Earth Tremors at Quellington. — A correspondent to the York paper writes: — Some of the settlers in this district have been greatly agitated of late by a number of loud reports coming from a north-westerly direction, and a series of earth tremors, which have been distinctly noticeable, especially by those who at the time have occupied buildings. They were first noticed on the afternoon of the 4th inst, and again at night, when the windows and doors of buildings rattled and cracks opened in the walls. One shock occurred during the progress of Mr Baxter's meeting at the Agricultural Hall on Friday evening, and two or three of the audience, becoming alarmed, immediately left the building. It was subsequently noticed that the walls of the hall had been considerably damaged. The results of the shocks, which have occurred at frequent intervals since, were keenly felt at the homesteads of Mrs. Cook, Messrs. J. C. Carter, Cook, Sherry, and others throughout the Quellington and Malebellington districts, and, needless to say, the settlers are greatly concerned, and in some instances alarmed, at this strange visitation? It will be interesting to hear whether similar shocks were experienced in other parts of the State. Mr. W. Brownlie states that on the 4th inst, while seated in his office, the report and tremors were very distinct, and Mr. Charles Edwards had a similar experience at his residence; 'Hart-leap,' on Tuesday night.

The largest event of the swarm may not have been much larger than magnitude 3 but there were obviously lots of them.

1912 02 13 at 00 UTC, Tsunami observed at Cossack

The following story from the *Sunday Times* of 18 February 1912, page 7 is a familiar account of a tsunami but the cause is as unknown today as it was at the time.

PHENOMENAL TIDES.

CAUSES ATTRIBUTED TO SUBMARINE DISTURBANCES. MENACE TO SHIPPING.

('Sunday Times' Special.)

Mr. Raymond, the officer in charge of the Sydney Observatory, when seen by a 'Sunday Times' representative yesterday regarding the report received at Melbourne from an observer on the north-west coast of Australia, stating that the tide at Cossack ebbed and flowed three times between 8 a.m. and 11 a.m. on Tuesday last, with a rise and fall of three feet each time, was emphatic in declaring that such an occurrence was a meteorological impossibility. 'The influence of the moon, which is the cause of the tidal rise and fall,' said the astronomer, 'is as regular in its recurrence as the rising and setting of the sun. The peculiar movement noticed by the observer at Cossack was caused, in all probability, by a submarine earthquake, or other submarine movement, causing one or perhaps a series of tidal waves. 'Such disturbances when they happen are frequently associated with considerable danger to navigators, and form a serious menace to navigation. Several months ago a similar event took place at Nukualofa, the capital of Tonga where a tidal wave, originated by a sub-aqueous disturbance, caused the ship 'St. George' to be put out of her course, and to be subsequently wrecked in those latitudes. 'It is more than likely that the phenomenon reported to have taken place at Cossack was of a similar nature to this. . It is generally believed in Sydney shipping circles that the large 6000-ton steamer 'Pericles,' that was recently wrecked, was the victim of one of these unusual tidal waves. One well-known navigator, when asked for his opinion upon the subject, said: 'I think that the explanation given by Mr. Raymond is beyond doubt the correct one. During 'my life I have sailed many strange seas and can recall several similar cases. I remember a tidal wave, brought on by a submarine earthquake, which arose off the coast of Chili while we were lying, at anchor in the harbor at Calloa, in 1883. The tide rose and fell three times in as many hours, and so great was the volume of water which these changes carried with them that large vessels were moved far up on the beach, and then, as the tide receded, they were left high and dry until the rapid return of the tidal wave once more floated them into deep water.'" Other well-known mariners feel assured that Mr. Raymond's theory is the correct one, and many cite similar instances in corroboration of their belief. Dr. W. E. Woolnough, assistant professor of Geology, at Sydney University, also considers that the phenomenon was caused by some submarine disturbance, or volcanic eruption, which has not yet been reported. He cited in support of the theory the fact that a big tidal wave followed the earthquake at Martinique in 1883.

1912 04 25 at 10:36:30 UTC, Albany

The Daily News Perth, Tuesday 30 April 1912, page 2 reported that an earthquake shook furniture and other articles at 7pm last night. It was reported to have been very severe at Grassmere, seven miles away. The Albany Advertiser of Saturday 4 May 1912, page 3 has more:

Earth Tremor.—Shortly before 7 o'clock on the evening of Friday of last week a number of residents of Albany were startled by evidences of an earthquake. Windows rattled violently, articles of furniture were shaken and in more than one instance clocks were stopped. At Grassmere, it is stated, even more serious consequences attended the shock. The occurrence was brought under the notice of the Government Astronomer (Mr. W. E. Cooke) by the local Meteorological Observer (Mr. John Norman) and that officer now reports :—"This is interesting, because it is one of the very few local disturbances which have given rise to a real earth wave which would affect a seismograph.

The Perth Observatory P arrival was at 06h 37m 24s and Albany is about 400km away. We estimate that the magnitude was at least ML 4 to cause the effects described.

1916 05 03 at 01:45 UTC, Ravensthorpe

The Register (Adelaide, SA : 1901 - 1929) Saturday 6 May 1916 page 9.

STRANGE EARTHQUAKES.

PERTH, May 5. An earthquake was felt at Ravensthorpe and Hopetoun on Wednesday morning. Crockery on the shelves of the houses rattled, and the miners working under ground were alarmed at the shock. No damage, however, was done. There is no record of the shock on the seismograph at the Perth Observatory, but the Government Astronomer states that similar tremors, which are probably caused by the collapsing of subterranean hollows formed at no great distance from the surface, and which did not extend far, had been felt in the district in the past.

The *Albany Advertiser* of Wednesday 10 May 1916, page 2 has more:

Earthquake at Ravensthorpe.—Telegrams received from the Warden at Ravensthorpe and the postmaster at Hopetoun indicate that at a quarter to 10 on Wednesday morning a distinct shock of earthquake was felt throughout the district. The Ravensthorpe message states that the courthouse and other buildings shook, crockery on shelves rattled, and miners working underground were alarmed by the shock. No damage was done. Mr. H. B. Curlew, the Acting Government Astronomer, states that, on examining the seismograph sheet, he could find no distinct earthquake record. There were several, erratic movements of the boom, but these were probably caused by workmen who were engaged in altering the electric light wires in the dome, walking up and down the stairs leading to the basement in which the seismograph is kept.

The earthquake was not recorded at Perth, ~440km away, nor felt at Esperance 160km to the east.

1917 10 25 at 21:00 UTC, Derby

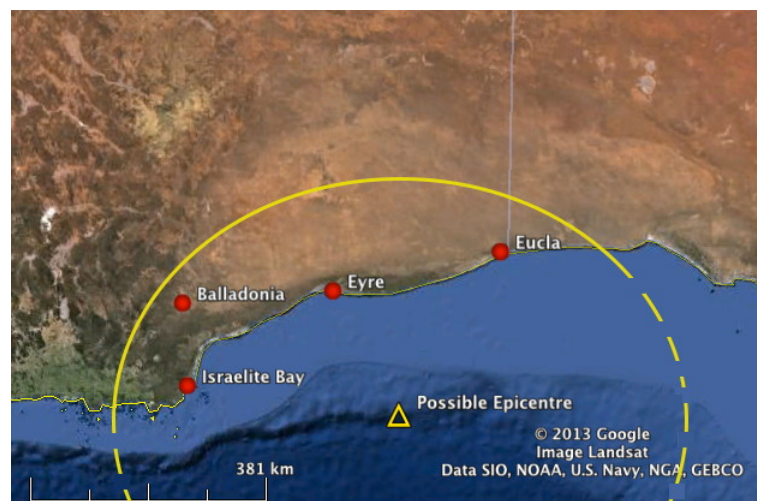
The *Western Mail* of Friday 2 November 1917 reports that an earthquake lasting half a minute shook houses at Derby at 5am but there was no damage. Perhaps a plate boundary event.

1919 01 07 at 21:35 UTC, Eyre and district

The *West Australian* of Saturday 11 January 1919, page 6 mentions an earthquake felt reasonably widely from Israelite Bay to Eucla at the head of the Bight:

Earth Tremor.—An earth tremor of some intensity was reported from Israelite Bay, Balladonia, Eyre, and Eucla on January 8 at 5.35 a.m. No trace appeared on the Perth seismograph sheet, and it is considered that the movement was probably due to some disturbance at no great depth—possibly a slipping of the continental shelf at the head of the Bight.

Figure 2 Red dots mark the places where this earthquake was felt but did no damage. The yellow isoseismal is an indicator of the possible felt area for an offshore epicentre.



The felt radius is more than 350km! the corresponding earthquake magnitude is approaching Ms6. The epicentre location is quite uncertain but can't be near any of the places where it was felt since no damage was reported. It could have been equally on the continent-ocean boundary at the foot of the continental shelf south of Eyre as suggested in the newspaper, or on the northern edge of the Eucla Basin an equal distance north of Eyre. We have assigned it a COB origin to the south, as shown on the isoseismal map,

subject to more information becoming available.

1919 05 01 time??, Sharks Bay WA

The Government Astronomer and seismologist of the time, Mr Curlewis, attributed a report of large numbers of dead deep-sea fish in the south passage of Sharks Bay to a severe earthquake there on 1 May 1919, and recorded on the Perth seismograph (*Western Argus*, Tuesday 20 May 1919, page 28). There is no mention of this event in the ISC Bulletin, nor were there any felt reports so we have tentatively assigned it an offshore epicentre on the continental shelf too far to be felt at magnitude 5. A submarine landslide might have triggered the fish kill.

1920

An earthquake in 1920 reportedly extinguished the Cape Leveque lighthouse light. *The Daily News* Saturday 17 August 1929, page 6. This earthquake occurred in 1926, not 1920, as discussed below.

1920 02 08 at 05:24 UTC, SW Coast, Ms 6.2 according to Gutenberg and Richter (1954).

The epicentre of this large earthquake off the SW coast is 370km from land on the edge of the Naturaliste Plateau. No mention is made of this earthquake in the newspapers digitised by TROVE as yet.

1923 09 30 at 08:42 UTC, Kwolyin near Quairading

Tucked away on page 28 of the *Western Mail* of Thursday 11 October 1923, is the following:

Earth Tremor at Kwolyin.—The Government Astronomer (Mr. H. B. Curlewis) advises having received the following report from Mr. J. H. Greer, of Kwolyin :—"An earth tremor passed through from north-west to south-east between 4 p.m. and 5 p.m. on September 30. The afternoon was particularly fine and still, which made the shock to the house unmistakable." Mr. Curlewis stated that Kwolyin, which was situated midway between Quairading and Bruce Rock, was noted for local shocks of great intensity, due to the peculiar formation of the district. He understood that the district was alluvial in character, for the bed of an old river could be traced from somewhere near York, eastwards through Quairading, and it was well known that in this type of country earth tremors were felt most severely. As instancing this it might be mentioned that San Francisco was built on an old alluvial plain. The tremors felt at Quairading some years ago, and the one at Kwolyin, probably originated in a strain of the earth crust not far from Mr. Bakewell, near York, for the contours of this hill were typically those of a block-faulted mountain. The earth tremor at Kwolyin was probably registered on the Perth seismograph, for at 4.42 p.m. on September 30 there was a distinct, though very small, movement of the boom. The shock therefore must have been more severe than those felt at Quairading, as no indication appeared on the instrument on that occasion. Shortly an improved and more sensitive seismograph would be installed at the Perth Observatory, when it was hoped that the local tremors felt from time to time at various places in the State would be recorded.

It is a pity the seismograms have not survived to check whether this event, 180km due east of Perth, was indeed recorded on the Perth Milne seismograph. Had it been larger than magnitude 3.5 it would have been felt at Quairading, and there is no record that it was.

1926 07 23 at 10:10 UTC, Cygnet Bay King's Sound

The West Australian, Tuesday 10 August 1926, page 5 embeds the following story in its Country News.

Boats at Cygnet Bay, King's Sound, reported an earth tremor on July 23, between 6 p.m. and 6.20 p.m. It caused numerous fish to jump out of the water, and travelled from east to west, and its duration was between two and three minutes. The shock was moderately severe. Men ashore

report the shock. Levigued light reported it at 6 p.m. travelling from north-east to south-west. It put the light out and stopped the mechanism. Boats at the Lacepedes at that hour reported a dead calm but no tremor. Off Pender Bay the boats at sea experienced three big waves.

There is no large earthquake listed in the ISC Bulletin at this data and time, not anywhere. The intensity at Cape Leveque was quite strong, dousing the light and stopping the mechanism, perhaps MM6 at least, so the epicentre must have been close. The fact that it wasn't observed at the Lacepedes, 100km away, limits the magnitude to below ML 4.8.

1927 06 03 at 07:12:11 UTC, Banda Sea, Felt Wyndham

The *Geraldton Guardian* of Tuesday 7 June, 1927, page 3 reports that an earthquake shook buildings in Wyndham at 3:18pm local time. The epicentre of a magnitude Ms 7.4 at 150km depth was located by Gutenberg and Richter and catalogued by the ISC at -7°S, 131°E at that time. The epicentral distance is just under 1000 km to Wyndham.

1928 09 08 night, felt Onslow and 30 miles south

The West Australian of Tuesday 11 September 1928, page 12 reports on an earthquake felt on the NW coast of WA:

Earthquake Felt at Onslow. Unusual in Western Australia, a distinct earthquake shock was experienced at Onslow, and more severely about thirty miles south of there, on Saturday night. As the disturbance was not recorded by the seismograph at the Perth Observatory, it appears that the earth movement was a purely local one, confined to the immediate surface at some spot south of Onslow.

If this was a local earthquake south of Onslow as suggested in the article, as a minimum solution we can assume the earthquake was at least magnitude ML 4 located perhaps 40km south of Onslow.

1929 08 16 at 21:32 UTC (17th at 5:32 am WST) felt at Broome and La Grange (50km south of Broome).

The West Australian Tuesday 27 August 1929, page 16.

North-West Earthquake. Our Broome correspondent writes: — The earth tremor felt here on August 17 stirred up the seabed, tearing away large quantities of seaweed and discolouring the water. The captain of the Minderoo reported that the sea was very dirty outside the bay.

The Daily News of Saturday 17 August 1929, page 6 ran with:

Japanese Very Scared BROOME, Saturday.

A distinct earth tremor was felt here, being of two minutes' duration, between 5.24 and 5.26 a.m., today. Houses shook and windows and shutters rattled, The large Japanese population was very scared, and ran from their dwellings into the street. When asked why they left their houses they explained that they felt the first small tremor at 4.10 a.m., and when the second and larger tremor was felt later they thought they had better profit by experience of numerous earthquakes in Japan and get into the open and safety. 'White residents, not having experienced 'quakes previously, did not pay much attention at the time, therefore they are hazy regarding the rumbling, but Japanese and other Asiatics who graduated in the school of bitter experience swear that the second tremor was accompanied by rumblings like distant thunder. News is now awaited from the pearling fleet, the divers of which will be able to discover anything affecting the sea bottom. Such happenings are very rare here. The records only show two tremors previously in 25 years, but the second in 1920 extinguished the Cape Levigued light.

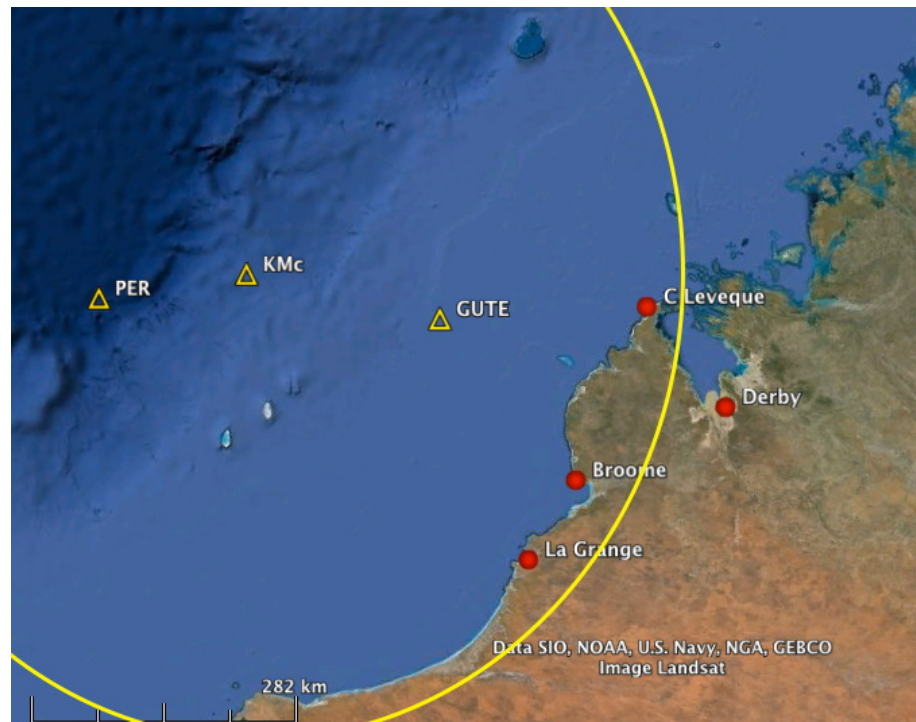
The P-wave was clearly recorded at PER at 213243 UTC and Curlewis, the Government Astronomer computed an epicentral distance, variously reported as 950 to 1100 miles He estimated it was located 300 to 400 miles west of North-West Cape (the epicentre approximately PER on the map). Several aftershocks were apparently recorded on the Perth seismograph, but not the foreshock mentioned in *The Daily News*.

Everingham and others (1987) computed a magnitude of Ms 6.8 whereas the PAS magnitude in the ISC Bulletin was Ms 6.2 with an epicentre (GUTE) at (16.5°S, 121.0°E), about 1800km (1100 miles) from Perth.

This location of GUTE would seem at odds with observations at Broome where the intensity would have been stronger, and at Derby and Cape Leveque equally strong but where there were no felt reports.

There were no reports that the earthquake was felt at Derby or Cape Leveque. If we assess the intensity at Broome and La Grange as MMIV, then using Ms6.2 and the Greenhalgh and others (1989) relationships between R_{IV} and M, we arrive at an epicentral distance of 400 km. Satisfying the reported intensities and distance gives an epicentre as shown in the table, and on the figure as KMc, on the edge of the continental shelf between the Perth and GUTE epicentres.

Figure 3 Isoseismal Map, earthquake 16 August 1929 offshore Broome WA. The yellow circle is the MMIV isoseism. It was only reported felt at Broome and La Grange. At the early morning, 5:32 local time, any shaking warranting only intensity 3, would not stir most people from asleep.



1931 02 03 at 13:00 UTC, Beverley WA

Felt at Balkuling, 2km east of Beverley and by neighbours out to 10 miles away at about 9pm local time. The Government Astronomer said it was not recorded on the seismograph.

The assigned magnitude is ML3.

1931 02 10 at 06:34:25 UTC, Southern Sumatera, felt Cocos Island

The Government Astronomer, Mr. H.B. Curlewis, noticed a severe earthquake on the seismograph and later learned that it was distinctly felt on Cocos Island, its origin off Southern Sumatera (*The West Australian* Thursday 12 February 1931, page 7) as he had surmised. Gutenberg and Richter assigned it a magnitude of Ms 7.5. He notes that this was the 7th severe earthquake since December 24th.

1931 03 28 at 13:00 UTC, Felt Wyndham, Derby and Broome WA, strong in Darwin NT

Picture goers in Darwin evacuated the Don Stadium cinema without panic at 10.30 pm on Saturday night but returned when the shaking stopped. *The Sydney Morning Herald* Tuesday 31 March 1931, page 11.

EARTHQUAKE.

Probably in Banda Sea.

Father O'Leary, officer in charge of the Riverview Observatory, stated yesterday that, whilst the record was not sufficiently clear to enable him to calculate the exact location, the large earthquake registered on Saturday night had occurred about 2400 miles north-west of Sydney. He thought it

possible that the centre of the disturbance had been somewhere in the Banda Sea (north of Timor). The absence of reports of damage made it likely that it had been sub-oceanic.

A message from the Wellington (N.Z.) correspondent of the "Herald" states that the shock was recorded at the Observatory there.

Our Darwin correspondent telegraphs that the earthquake, which was reflected by a severe tremor there, has been explained, in terms of native lore, by the Larrakeyah aboriginals. They state, he says, that a large stone close to the sea at Casuarina is the King God, the first aboriginal and the creator of all others. Occasionally the tides reach the stone, and they say that the King God must have turned over in his sleep, "big fish been bitum," thus causing him to stir mightily.

RECORDED IN W.A.

PERTH, Monday.

The earthquake was recorded at the Government Observatory here, and the Government Astronomer (Mr. H. B. Curlewis) calculates that it occurred in the ocean floor midway between Darwin and Timor. Substantial changes, he said, were likely to have occurred in the ocean bed. Wyndham, Derby, and Broome reported having experienced earth tremors.

The ISC lists the Gutenberg and Richter solution under the southeast Banda Sea as Father O'Leary had surmised, -7.0°S, 129.5°E, 80km deep and magnitude Ms 7.3 (PAS), the origin time at 12:38:37 UTC.

1931 04 09 12:45 UTC, Leonora

Heard and felt generally in Leonora, crockery rattled etc., at about 8:45pm local time (12.45 UTC). A second smaller earthquake was also felt there about 5 or 10 minutes later. Further reports were received from Laverton and Kookynie (*Western Mail*, Thursday 16 April 1931, page 20), though the 2nd event is not mentioned so we suppose the epicentre was nearer Leonora. A location about 40km east of Leonora (28.9°S, 121.8°E) and about equidistant from Laverton and Kookynie would satisfy the observations with the smallest magnitude.

The Milne seismograph at Perth Observatory was too insensitive to record the ground shaking.

This felt area yields a magnitude of ~ML4.3.

1931 09 25 05:59:44 UTC, Sumatera, felt Cocos Island

The Daily News (Perth) Friday 25 September 1931, page 6 has a quirky approach to the news:

'QUAKE AT COCOS ISLAND

Cable Staff Perturbed ?

"Hallo! Perth Observatory here. You'll be interested to know that an earthquake is now in progress." Everything seemed normal in St. George's-terrace when the above telephone call was made to 'The Daily News' shortly after 2.30 o'clock today. It was ascertained from the official of the Observatory that a message from the Cottesloe cable station intimated that advice had been received by cable from Cocos Island to say that an earthquake had commenced at 2.10 p.m. Perth time. The Observatory stated that the seismograph instrument was then recording the disturbance, and the sheet would be developed tomorrow morning when the intensity of the disturbance would be known.

'It is interesting to note,' Mr. Curlewis said, 'that this is the fifth disturbance that has taken place in this area and two of them in the southern extremity of the area have been felt at Cocos Island. It is also interesting to note that following the disastrous earthquake at Napier, on February 3, two upheavals occurred in the Cocos area on February 10 and 12 respectively. They were in turn followed by the second severe earthquake in New Zealand on February 13, which has been followed by two more disturbances near Cocos Island — one on February 14 and the present one.

The ISC, quoting Gutenberg and Richter (1954) list this shallow major magnitude Ms7.4 earthquake as occurring off the south coast of Sumatera, 1000km to the northeast. It should also have been felt on Christmas Island which is only 680km away.

1932 05 13 at 13:18 UTC, Indonesia

On 14th May 1932 at 9.18pm (13.18 UTC) the WA Observatory reported on a large earthquake off the coast of Western Australia within 400 miles (600 km) of Perth (see Newspaper article attached).

The epicenter of this great shallow Ms 8.0 earthquake was, according to the ISC, actually in the Molucca Sea, Indonesia and was not reported felt in Australia.

Mr Curlewis' summary of previous, large near coastal earthquakes is useful though and this correction to the record is made in case some other overly sincere historian comes across this newspaper article again and wonders why it is not in the Australian earthquake database.

Western Australia has hosted the 3 largest Australian earthquakes recorded since 1788; in 1906 offshore magnitude Ms7.2, in 1941 at Meeberrie magnitude Ms6.8, and in 1968 at Meckering magnitude Ms6.8.

Figure 4 Western Mail article, Thursday 19th May 1932, p21. Fortunately the epicenter was in Indonesia, not "400 miles from Perth", and it was not reported felt in Australia.

1932 11 01 night time, Northam

A swarm of earth tremors rattled Rock Vale, 12km NNE of Northam on 1st and 2nd of November. These are discussed later under swarms but little is known about swarms and what chance exists that, in Australia, they may contain an embedded large earthquake like that at L'Aquila Italy on 6th April 2009.

This swarm was not mentioned by Everingham and Tilbury, 1972.

1933 02 19 at 02:05 UTC (20th at 10.5 am local time), Felt Broome

The Advertiser Tuesday 21 February 1933, page 9 reports:

EARTH TREMORS AT BROOME

Buildings Shaken But No Damage PERTH, February 20.

A message from Broome states that an earth tremor, lasting about 20 seconds, occurred at 10.5 a.m. today. Buildings were shaken, but no damage was done. The Government Astronomer stated that the earthquake was only of a minor type, but sufficiently intense to transmit its tremors more than 1,000 miles to the observatory seismograph.

There is no corresponding event in the ISC Bulletin but we can safely assume this is a local event as it was recorded at Perth (seismogram from the newspaper attached) and the duration of shaking was short. The magnitude is limited by the lack of other reports from nearby towns such as Derby 165km to the northeast.

OCEANIC UPHEAVAL.

Within 400 Miles of Perth.

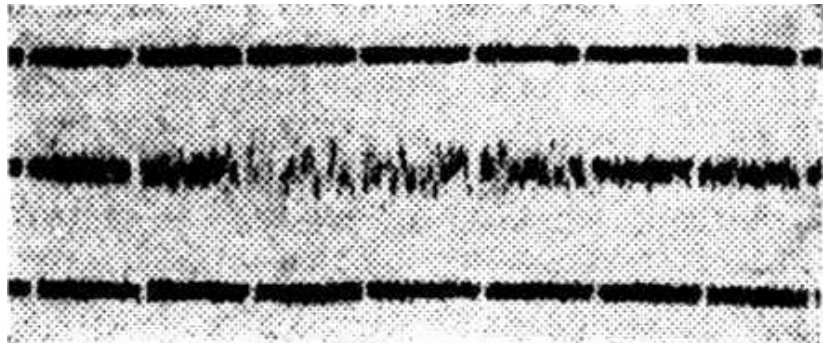
On Saturday at 9.18 p.m. a severe upheaval of the floor of the Indian Ocean occurred at a point less than 400 miles from Perth. "The record," stated the Government Astronomer (Mr. H. B. Curlewis) on Monday "shows that the earthquake was of distinctly severe type, for under the influence of the maximum shocks, which continued for over 14 minutes, the boom swung repeatedly close on seven inches. For nearly 30 minutes the boom was violently oscillated, following which marked diminution began, but it was not until three and a half hours afterwards that the instrument had settled down to normal. This is the most severe and also the nearest to Perth of those earth disturbances recorded on the seismograph that have been within a thousand miles of the station. (I am not taking into account the many surface tremors that are frequently recorded throughout the State).

"Of distinct earthquakes within 1,000 miles of Perth, only five have been recorded. In 1906 the mail steamer Omrah, when about 400 miles from the North-West Cape, was jarred throughout her whole length by a sub-marine quake. In 1909 another ocean quake was felt at Northampton, north of Geraldton. A few years later a big collapse of the continental shelf was felt at Albany. In 1919 an oceanic upheaval occurred near Shark Bay, and in 1929 another submarine disturbance took place on the floor of the Indian Ocean, some 300 miles from our north-west coastline, being felt at all towns. Some of these, however, judging by their records, can compare in the slightest degree with the severity of the recent happening."

National Library of Australia

Cossack and Roebourne are nearly 650 km to the southwest. We can compute an estimate of M_s , the Perth station amplitude is $\sim 8\text{mm}$ and the epicentral distance about 1600km ($\Delta=14.7^\circ$). Using the IASPEI formula we get M_s 5.8, and using the Marshall and Basham formula with $T = 12\text{s}$, we obtain an identical value of 5.8.

Figure 5 Seismogram recorded at the Perth Observatory reproduced in a local newspaper showing the 1933 Broome earthquake. The blanks every 15mm are the minute marks.



The magnitude formulae used are from McGregor and Ripper (1976). This magnitude is compatible with the adopted epicentre and intensity observations. A copy of the actual seismogram would be useful.

1934 07 12 at ~14:00 UTC, Onslow

Everingham (1968) lists a large earthquake off the NW coast of WA but makes no mention that it was felt onshore. *The West Australian* of Wednesday 18 July 1934, page 8 has the following short note that would have been difficult to find without TROVE:

The residents of Onslow report having felt an earth tremor about 10 o'clock last Thursday night. It seems to have been felt mainly in the higher part of the town. This is the third experience of its sort in five years.

Gutenberg and Richter rated the earthquake magnitude M_s 6.0. There are no other felt reports. The last comment in the extract is interesting, the earlier two felt at Onslow perhaps were the large earthquake offshore Broome on 16 August 1929 and the major earthquake in the Banda Sea on 28 March 1931.

1934 10 18 at 19:00 UTC, Northam

The Daily News of Saturday 20 October 1934, page 17 headed its story about a series of earthquakes, a swarm, at Northam:

Loud Explosions Heard NORTHAM, Saturday.

During the last three days distinct earth tremors have occurred in the Spencer's Brook section of the Northam district. Mr. R. McMillan said that at his farm shocks had been experienced periodically during Wednesday, Thursday and Friday. On Friday at 3 a.m. the tremors were accompanied by loud explosions that appeared to come from underground. The disturbances were sufficient at times to rattle small articles in the house. It is understood that similar occurrences have been noticed at Muresk Agricultural College.

There is no knowing how many events occurred in this swarm, nor when it started and ended but the largest event on Friday at 3am seems to have been about $ML_{3.5}$, judging by the description and the assumption that the swarm was very close to Northam. This event is not listed by Everingham and Tilbury, (1972).

1935 09 01 at 14:23 UTC, Yanrey Station, south of Onslow

A local earthquake was reported from Yanrey Station, 100km south of Onslow on Sunday 1 September 1935 after 10 pm. (*The West Australian*, Tuesday 10 September 1935). It was reported as most severe and was distinctly recorded on the seismograph at Perth, 820 km to the south, though not reported felt elsewhere such as Exmouth or Onslow about 100 km away, which limits the magnitude to less than 4.5. This earthquake is not listed by Everingham (1968).

Severe Tremor Felt on September 1

A report received yesterday by the Perth Observatory by airmail from Mr. de Pledge, of Yanrey station, which is about 60 miles south of Onslow, stated that on Sunday, September 1, one of the most severe earth-tremors ever experienced in that district occurred after 10 p.m. 'It is interesting to note,' comments the Government Astronomer (Mr. H. B. Curlewis) 'that the Perth seismograph sheet disclosed a distinct earth movement at 10.24 p.m. on that date, and this was probably the surface waves from the disturbance felt at Yanrey. From the fact, that no preliminary or secondary movements are discernible, though these might easily be lost in the microseisms that were fairly strong then, it is most likely that the earthquake was purely local, of small intensity, and confined to the surface rocks. It is not often that one of these local earth movements is registered by the seismograph, and, therefore, this 'quake must have been of more than ordinary severity.'

If we assume the amplitude on the Perth seismogram (distinct) was at least 5mm, then using Marshall and Basham's (1973) formula we get a magnitude of Ms 4.6±0.2 depending on the path factor, ie like North America or Eurasia, the value in the same range as the intensity based ML.

1936 04 29 at 09:00 UTC, Java, Felt at Red Hill Station and Port Hedland

The following letter and report were printed in the Western Mail on Thursday 28 May 1936, page 50 (where it would have been hard to find with a visual search):

Earth Tremors in W.A.

R.B. (Red Hill Stn., Onslow).—I am at an outcamp about 22 miles from the main station and on April 29, between 4.30 and 5.30 p.m., a rather peculiar thing happened. There was a noise like thunder and the ground trembled for about eight seconds. It seemed to start in the west and finish in the east, the noise gradually fading. It was also noticed at the station where the boss described it as being like an elephant walking on the verandah. He stated that all the windows shook.

Your letter was referred to Mr. H. B. Curlewis, who states that it was a very interesting report as the tremors were recorded on the Perth seismograph. He said that they were simply entered as "Tremors" as there were no preliminary or secondary movements. Evidently faulting of some severity, at least as far as Western Australia is concerned, took place to the West of Red Hill—a line of weakness in the earth's crust runs for a short distance Southwards from Mt. Darnell. The noises like thunder are usual with the earth movements that occur in this State. The tremors were recorded as lasting from 4.31 to 4.44 p.m.

The West Australian of Saturday 11 April 1936, page 15 also has a report that this earthquake was slightly felt at Port Hedland, 275km to the north-east.

PORT HEDLAND , April 3.— Last Friday afternoon at about 4.40 several residents of Port Hedland were startled by the shaking of their dwellings caused through a slight earth tremor.

If this had been a distant earthquake on the plate boundary south of Java it should have been felt at Broome and/or Onslow, and been reported by the ISC. A possible intraplate source can be inferred, if the Red Hill station Onslow referred to in the newspaper is the same as listed in the GA Gazetteer about 100km ESE of Onslow then a plausible epicentre that fits the observations would be a magnitude 5.5 earthquake on the edge of the Hammersley Range, east of Onslow and Red Hill Station and SW of Port Hedland. The magnitude is consistent with the observation that it was recorded slightly at Perth.

1936 05 04 at 10:15 UTC, Eucla

Newspaper reports indicate that another strong earthquake occurred along the south coast of WA but closer to Eucla, where there was damage, than the earlier one in 1919, and smaller because it was not felt as far as Balladonia. Even so the felt radius is at least 210km, warranting a magnitude of 5.5 or more. The *Examiner* of 6 May 1936, page 8 reports:

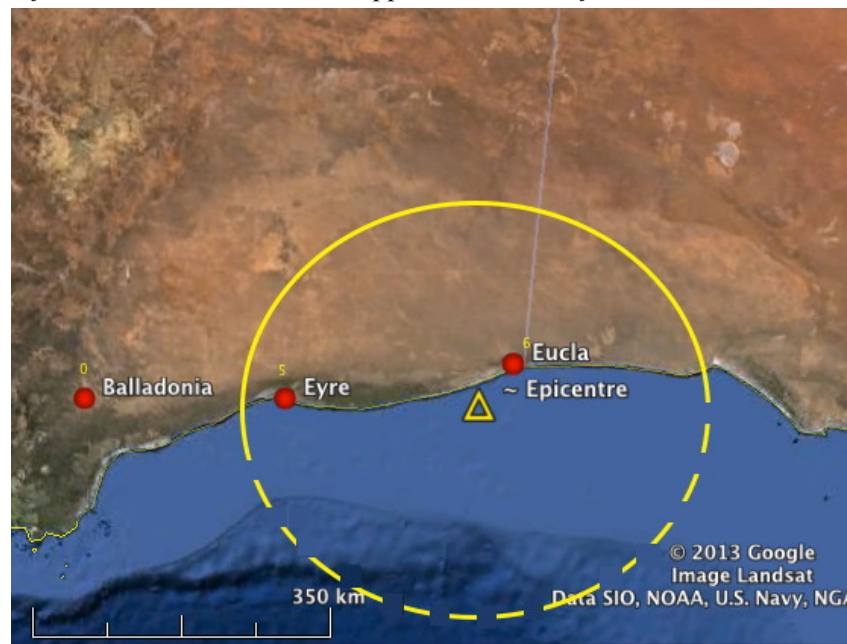
EARTH TREMOR SHAKES NULLABOR PLAIN

EVERY WINDOW SHATTERED Natives Want to Go Bush ADELAIDE, Tuesday. According to station managers, a severe earth shock, lasting sixty seconds, was felt along the Nullabor Plain about 8 p.m. yesterday. Mr. Phil Simon, owner of Eucla Station, 340 miles west of Ceduna, timed the first shock at 7.50 p.m., and says it shattered all the windows in his homestead, a solidly-built eight-roomed stone house and formerly the postmaster's house when Eucla was a repeating station on the overland telegraph line. According to reports from other station managers, the disturbance travelled from south-west to east-north-east at a rate of thirty miles a second. Mr. J. Carlyle, manager at Eyre, said the first shock shook everything violently for more than a minute. There are twenty natives there, and the younger men, who were terrified, were with difficulty prevented from going bush.

The other station reports may turn up when more newspapers are scanned to tighten the epicentre. *The West Australian* of Friday 5 June 1936 reports on page 29 that:

EARTH TREMORS AT EYRE. Government Astronomer's Theory An officer of the Aborigines Department stationed at Eyre has reported to the Perth Observatory officials by letter that on May 4, at 6.15 p.m., violent earth tremors were experienced, causing crockery and other movable objects to rattle. Loud rumbling noises lasting for 15 seconds accompanied the tremors, and shortly afterwards the sea was observed to be unduly agitated with unusually high waves breaking on shore, not due to wind, which was north-east at the time, tending to a calm sea. "I have examined our seismograph sheet for the above date," said the Government Astronomer (Mr. H. B. Curlewis) yesterday, "and can see no sign of any movement due to earth tremors, so evidently another near-to-the-surface disturbance, such as occurs from time to time throughout Western Australia, has taken place at Eyre, and on this occasion on the floor of the ocean immediately to the south-west, for the tremors and noises appeared to come from that direction. The fact that Balladonia, 90 miles from the coast and 160 miles west of Eyre, felt nothing, supports the opinion that the occurrence was of a purely local nature. "Five days prior to this happening Red Hill station, 90 miles east of Onslow, reported severe earth tremors and loud subterranean noises.

Figure 6 Felt area of the May 1936 earthquake near Eucla where building windows were shattered. It was not reported felt at Balladonia. An approximate epicentre is shown.



The fact that it wasn't recorded in Perth would limit the magnitude range to Ms4.6-4.8, so maybe it was closer to Eucla than suggested here to inflict this amount of damage.

1939 04 26 at 06:00 Meckering

There is a brief note in *The West Australian* on 8 May 1939, page 3 that an earth tremor occurred in the Meckering district about 2p.m. on April 26. No details are given but this event must be added to those in 1911 and 1916 mentioned by Everingham and Tilbury, 1972 as events preceding the major earthquake there on 14 October 1968.

1939 06 23 evening, East Gascoyne

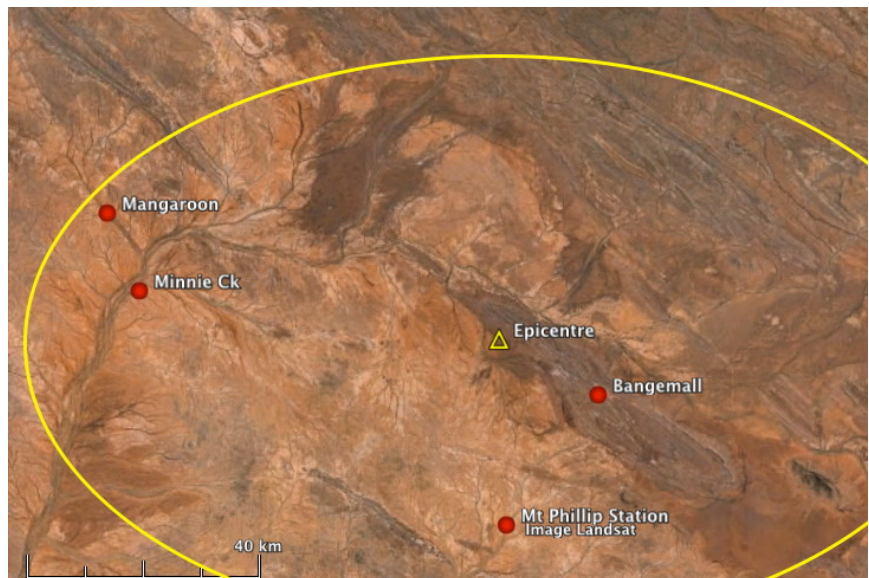
The *Northern Times* of Friday 30 June 1939 reports the following incident:

EARTH TREMOR AT EAST GASCOYNE.

Residents living in the east Gascoyne district were startled to experience a distinct earth tremor last Friday evening. The tremor was felt over a distance of 100 miles, from Mangaroon to Mt. Phillip and from Bangemall down as far as Minnie Creek.

Figure 7 The yellow triangle marks the hypothesized epicentre, the shaking was reported felt at the places indicated by the red dots.

It is considered that Cobra experienced the greatest force of the shock, where it is believed to have cracked a brick and cement wall. Some miners camped half a mile from Bangemall had the experience of having a saucepan and contents knocked off a table. The noise which lasted for about two minutes was described by one witness to resemble the passing of half a dozen motor trucks.



Cobra seems to be at Bangemall, both of which reported strong shaking so were near the epicentre. The equivalent area of the yellow felt-ellipse corresponds to a magnitude of ~4.3

1940 01 19 at 19:30 UTC (3:30 am Local time on 20 January), Northampton

This earthquake rated front page listing in *The Daily News* of Saturday 20 January 1940.

Northampton district was shaken by an earthquake today. The vibrations seemed to remain at their greatest intensity for about four or five seconds, but the preliminary warning and subsequent rumblings extended for more than a minute. The vibrations started soon after 3.30 a.m.

Northampton Hospital officials state that it sounded as if an explosion had taken place in the railway yards. Windows rattled in their frames, and crockery on shelves was shaken. Portion of the ceiling of a Northampton house fell. The shock was felt severely in the Ajana and the Galena districts.

The West Australian reported the earthquake in its edition of Monday 22 January 1940, on page 12.

EARTH TREMOR. Shocks in Geraldton District. GERALDTON, Jan. 20.—Early this morning an earth tremor, which was apparently most severe some distance north of Northampton, was felt at various centres over an extended area. The tremor was felt in Northampton at 3.30 a.m. The preliminary noise and subsequent rumblings lasted for over a minute, and the maximum intensity of the shock was over in about four seconds.

At the Northampton Hospital the sound appeared to come like an explosion from the north-west. Windows rattled and crockery was shaken, while part of a ceiling in a house in Stephen-street came down. A resident of Binu Mr. G. Turner, said that he observed two tremors at an interval of a few seconds, and his house, which is built of reinforced concrete, was badly shaken. The vibrations gave him the impression of the bursting of a big shell.

In Geraldton the tremor was felt in widely separated parts of the town. There has been a lot of speculation about the cause of the movement. There are many old mines in the district north of Northampton, and the tremor may have been due to a sudden subsidence.

There was no trace of the earthquake on the Perth Observatory seismogram but given the felt area, we have assigned the earthquake a magnitude of 3.9.

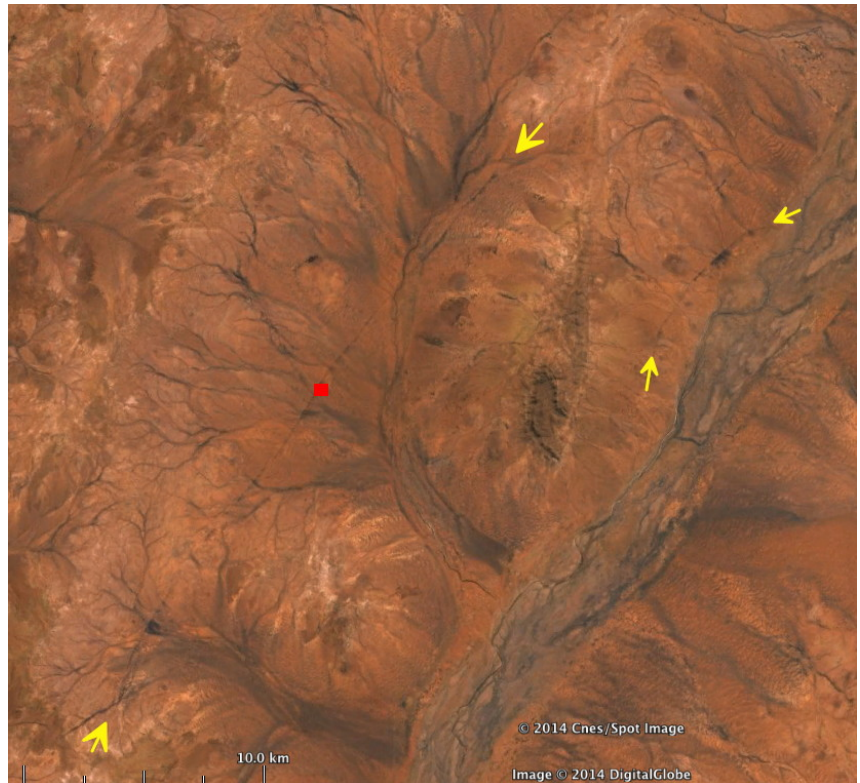
Articles about this earthquake led to Mr. Drew's letter to the *West Australian* on Wednesday 24 January 1940 concerning his experience of the earthquake there in 1885.

1941 04 29 at 01:35 UTC, Meeberrie

This is the largest known onshore Australian earthquake, magnitude Ms 6.8 (PAS), similar to Meckering but smaller than the offshore 1906 earthquake mentioned above. Several isoseismal maps have been compiled subsequently by different authors, the most recent by Everingham, in Everingham and others, (1982) but there is probably more information, more readily available now via TROVE warranting a review.

There is a spectacular surface fault with multiple segments in the epicentral area (Gordon, 1972; Williams, 1979) as seen on the Google Earth photo attached here. The scarp orientation and thrust mechanism are consistent with the known ESE principle stress direction, and the length and displacement are compatible with a magnitude Ms6.8 earthquake, but the evidence linking the two is not convincing.

Figure 8 Two segments of a Recent fault scarp, are shown between the yellow arrows, the longer one ~33km long, the shorter one ~11km long. The red dot near the centre of the western scarp is at 26.51°S, 116.29°E, about 60 km NE of Meeberrie Homestead where the shaking was intense. The scale bar is 10.0 km long.

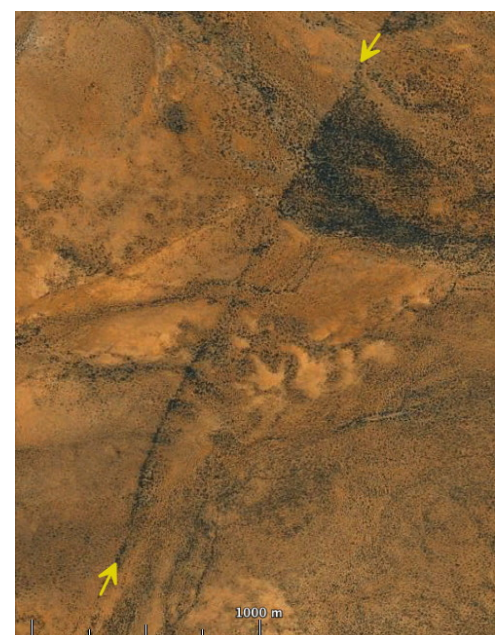


At the many stream crossings the drainage has been disrupted as indicated by the stands of acacias growing there, appearing as dark patches on the photograph, the extensive evidence of water flowing across the landscape reflecting the 3-yearly cyclonic rain dumps with few rain events in-between. These flooding events have no doubt greatly modified the on-ground appearance of the scarps.

Figure 9 Detail near the southern end of the segmented western branch of the Mt Narryer Fault scarp, downthrown to the south-east, the drainage in the same direction. The scale bar is 1 km long.

The West Australian of Saturday 28 June 1941 reports on page 8 a discussion with the Government Astronomer, Mr Spigl:

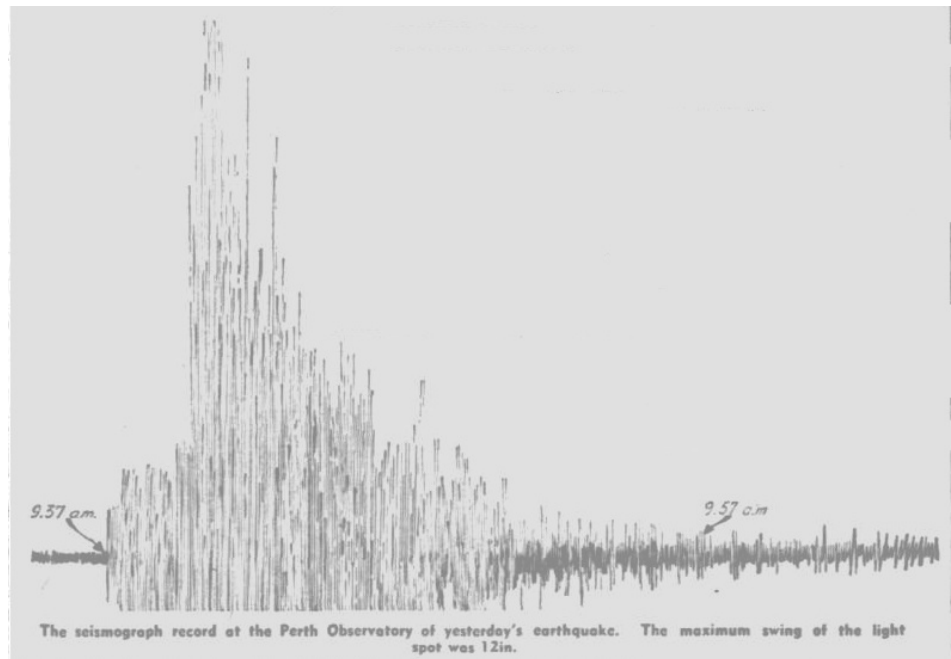
From local information which had come to hand there seemed little doubt that the area of greatest intensity at the surface was in the vicinity of Meeberrie, Wooleen and Narryer, he said. At Meeberrie every wall in the homestead quarters and other buildings was cracked, in some cases right through from floor to ceiling. The ground over a wide area was cracked, in some cases the cracks being three inches wide and 60 feet long. In the breakaways tons of



rock were dislodged from the faces. Aftershocks and loud reports were felt and heard for weeks afterwards, another indication that the area was close to the epicentre. Strong earthquakes were invariably followed by a number of aftershocks confined to the area containing or immediately surrounding the epicentre. Discussing a map which he has compiled from the information received, Mr. Spigl said that owing to the depth at which the earthquake originated the distribution of intensity was rather irregular.

The high intensity at Geraldton was particularly noteworthy. The information to the north of the epicentre was at present decidedly scanty, and as a closer investigation was contemplated further local information was essential. To this end a circular was to be distributed to public officials, post offices and pastoralists over a wide area, and it was hoped that those who were able to furnish accurate and carefully considered remarks on their personal experiences during the earthquake would assist by forwarding the completed circulars.

Figure 10 Perth Observatory Milne-Shaw seismogram of the Meeberrie earthquake of 29 April 1941 recorded at a distance of ~600 km (Reproduced from *The West Australian* newspaper Wednesday 30 April 1941, page 9).



Obviously Mr Spigl drew up the first isoseismal map though it has not been published, nor have any responses he may have had to his questionnaire. The ground motion has not saturated the recorder so a Richter or local

magnitude can be computed using a magnification of 250 for the Milne-Shaw, a ground amplitude $A_{o-p} = 300/250\text{mm}$ and period $T=4\text{s}$.

The equivalent Wood-Anderson amplitude at $T=4\text{sec}$, gain ~ 100 , is $(300/250) \times 100 = 120\text{mm}$. Using the nomogram in McGregor and Ripper (1976 Plate 2) we get ML 7.0, but correcting for the Wood-Anderson gain being 1500 rather than 2800, this value drops to about ML 6.8, identical to the $M_s 6.8$ of Gutenberg and Richter (1954).

1941 08 12 at 04:40 UTC, Broome

The West Australian of Wednesday 13 August reported on page 4 that the town had been shaken by earth tremors:

EARTH TREMORS. Houses Shaken at Broome. BROOME, Aug. 12.—Earth tremors were felt at Broome about 1.40 p.m. today. Being of light iron framework, the majority of houses were shaken by the shock, which in some cases dislodged utensils from shelves. Other more substantial buildings were rocked from the foundations. The shocks lasted only a few seconds on each occasion, but the apparent dull explosions caused some concern in the town.

No corresponding event is listed in the ISC Bulletin so it must have been a local earthquake(s), commensurate with the observed duration, magnitude 3.5 at least.

1942 06 16 at 08:00 UTC, Albany

The *Albany Advertiser* of Monday 29 June 1942 mentions:

Another Earth Tremor: It has been reported that Albany experienced yet another slight earth tremor on June 16. The approximate time of the occurrence was stated to be 4 o'clock in the afternoon. The tremor was of a brief duration, but quite a number of local people felt the shock.

The emphasis here for consideration of a hazard analysis should be on the “yet another slight earthquake”. Surely this doesn't refer to our last listed event in the region, 30 years ago.

1946 09 17 at 15.12 UTC, Brookton

This earthquake is tabulated by Everingham and Tilbury (1971) with a queried epicentre at Pingelly but their stated accuracy is $\pm 0.5^\circ$.

Figure 11 *The Daily News* of Wednesday 18 September 1946 had the epicentre clearly centred on Brookton in a map of the felt area shown here.

There are not enough felt reports to draw an isoseismal map.

According to the *Kalgoorlie Miner* of Thursday 19 September 1946, page 4:

AN EARTH TREMOR

Brookton-Pingelly Area Affected BUILDINGS SHAKEN, SLEEPERS AWAKENED

Perth, Sept. 18.— Accompanied by a roaring noise, described as being like an artillery bombardment, a severe earth tremor shook the Brookton-Pingelly district on Tuesday night. Buildings rocked, pictures were shaken from walls and people were aroused from their sleep, as the earth began to shake at 11.12 p.m. The tremor, which lasted for 22 seconds, was felt over a radius of about 20 miles.

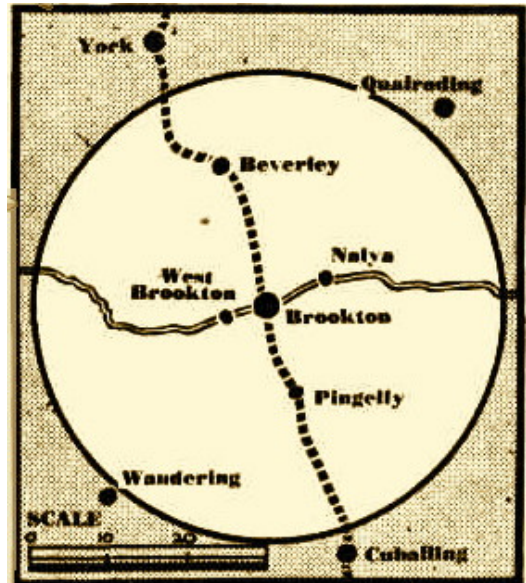
Although the movement was felt at Beverley it seemed to be near Brookton. Discussing it to-night Constable K. Martin said that he was visiting a private home, and that shortly after 11 o'clock there was a terrific roaring noise like the sound of a huge number of guns, followed by a heavy shaking of the earth.

"Although we are getting more or less used to these shakes, as we have had several during recent months, this was easily the most severe," he said. "The building in which I was shaken so severely that a trophy standing on the mantelpiece was flung to the floor. The noise seemed as if it were coming from a terrific depth under ground, and it continued, gradually dying away, for about 15 minutes. Several people were awakened from their sleep, but there was no panic."

The Government Astronomer, Mr. H. Spigl, said to-day that the tremor had been recorded by the seismograph at the Perth Observatory shortly after 11.12 p.m. on Tuesday. The tremor had been recorded for a period of 22 seconds but had exhibited no distinct phases. It was apparent, however, that the movement has been near the surface and of fair severity. Many reports had been received from Brookton, Beverley, Pingelly and adjacent towns. These stated that buildings had been rocked, and that pictures had been shaken from the walls.

This sequence at Brookton may have started at least as early as 12 November 1939 when a number of earth tremors were felt there (*The West Australian*, Saturday 18 November 1939, page 12.)

The magnitude computed from the felt area is about ML4 compared with the magnitude computed by Everingham and Tilbury (1971) from the PER seismogram of 4.5. At 11:12 pm many people may have slept through the MM3 region, thereby reducing the apparent felt area and magnitude derived from it.



1949 05 02 at 10:02 UTC, New Norcia

This earthquake was quite strongly felt in New Norcia and over a considerable area around the town. It was not felt in Perth or at the Watheroo Observatory.

The West Australian of Tuesday 3 May 1949, page 2 covered the earthquake.

EARTH TREMOR SHAKES COUNTRY TOWNS Buildings swayed, furniture moved, crockery rattled and several persons were alarmed when an earth tremor shook New Norcia soon after 6 o'clock last night. Wongan Hills and Ballidu also reported a tremor. No damage was caused.

The dining room of the hostel at New Norcia was full when, heralded by a deep rumbling noise described as being like that made by the passage of a fleet of very heavy trucks, crockery on the tables began to chatter and tapestry on the walls billowed and swayed. Several young persons in the room became alarmed and dashed from the building, but they were not in any danger. A member of the staff who was outside said later that the whole of the two-storey building seemed to sway for about 30 seconds. Those in the upstairs rooms said that the furniture "beat a miniature tattoo on the floor" while the shake was at its height.

The tremor also shook the Cathedral, the Benedictine Monastery, St. Ildephonsus' College and St. Gertrude's Convent, but no damage was reported and, so far as could be learnt last night, none of the students was alarmed.

No further tremors were experienced, but rumbling noises in the hills surrounding the town continued for some time. Old residents of the settlement recalled that there was a similar tremor some years ago (Ed. Perhaps the 1941 Meeberrie earthquake).

Wongan Hills residents were thrown into consternation when windows and houses shook with the earth tremor at 6.2 p.m. In the bar of the State Hotel bottles rattled on the shelves and beer was spilt from glasses. Two hanging lanterns at the local garage swayed and clashed together. One householder fled from her home in alarm

Another thought that his place had fallen down and the young daughter of another resident, hearing the rumble, called to her father that the bath-heater was alight. The tremor lasted for nearly half a minute. Reports from the Ballidu and Moora areas said that the tremor was felt there and was accompanied by loud rumblings.

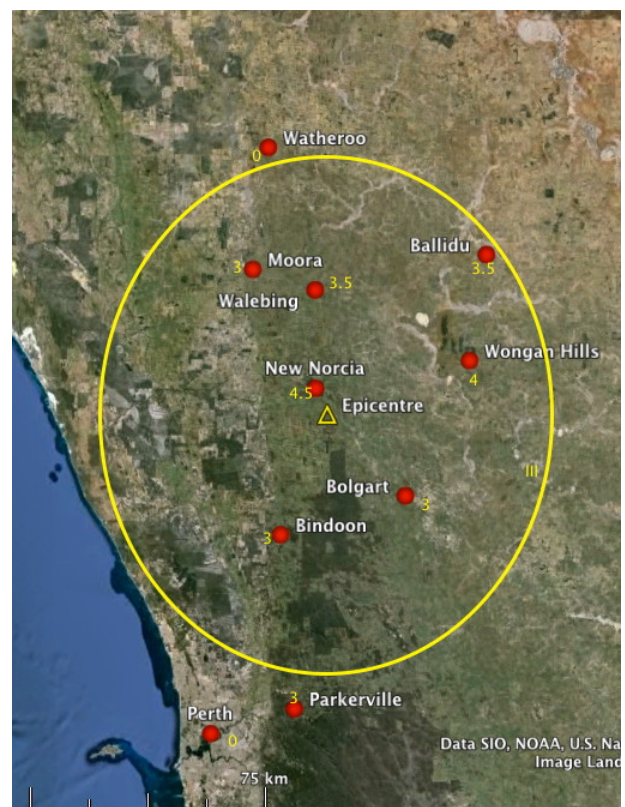
No tremor was felt at the Watheroo Magnetic Observatory, which is 36 miles from Moora. The observer-in-charge (Mr. F. W. Wood) said last night that there was no seismograph at Watheroo but he would check on magnetic instruments today to see if they showed any recording of the tremor.

Figure 12 Isoseismal map of the New Norcia earthquake of 2 May 1949. It was not felt at Watheroo to the north or Perth to the South, and did no damage in the epicentral area. Only the MM3 Isoseismal line is shown. The Darling Scarp is well delineated by the vegetation, 20km west of the supposed epicentre.

The PER seismogram amplitude was reported as $\frac{1}{2}$ in., ie $\frac{2}{7}$ th the amplitude of the mainshock (see below) so the magnitude of this aftershock is $5.2 - \log(7/2) = 4.7$, slightly larger than the magnitude estimated from the felt area shown in the isoseismal map of ML 4.5.

1949 09 29 at 18:16, Perenjori

The Western Mail of Thursday 6 October 1949, page



14S has an earthquake story:

Perenjori

MILD Shake-Up: What is generally supposed to have been a mild earth tremor was felt at Perenjori at 2.16 a.m. last Thursday, when windows, iron and loose objects rattled. Dogs barked and roosters crowed. The duration was estimated at 15 seconds. No record of the disturbance was made on the seismograph sheet at the Perth Observatory.

A magnitude of 3.5 would be appropriate considering the report.

1950 11 02 at 15:27 UTC, Major earthquake in Banda Sea, felt Derby

The Northern Times, Thursday 9 November 1950, page 5.

The earth tremor on Thursday night was reported by most stations, and quite a number of town residents who were still up wondered what was happening, whilst others were awakened from their slumber.

The ISC lists a major Ms 7.5 (PAS) earthquake on 1950 11 02 at 15:27 UTC (11:27 pm local time) at intermediate depth (100 – 223 km) on the plate boundary in the Banda Sea, estimates of the location varying from 6 to 7.5°S and 129 to 129.6°E. Damage was caused in Darwin inspiring McCue (2013) to produce an isoseismal map.

1950 11 30 at 23:10 UTC, Onslow

The West Australian, Saturday 2 December 1950 reported a slight tremor with the interesting comment that it lasted for only about ‘half a minute’, suggesting they often feel stronger earthquakes for longer. There is no event in the ISC catalogue at this date and time and the description is more typical of a local small intra-plate event.

EARTH TREMOR AT ONSLOW, Dec. 1: A slight earth tremor was felt at 7.10 a.m. today. It lasted for only about half a minute and caused buildings and furniture to shake.

We assume this was a local earthquake and have assigned it a magnitude of 4 with an epicentre north of Onslow since it wasn't reported felt at Exmouth.

1952 03 11 at 06:09 UTC, Bolgart sequence, mainshock

This, the first earthquake and mainshock, caused damage in Bolgart and Calingiri and was strongly felt in Perth, 100 km away, though rating an intensity of only MM2 to MM3 on the isoseismal map in Everingham and others, 1982.

Figure 13 Seismogram of the mainshock on 11 March recorded on the Perth Observatory Milne-Shaw seismograph PER, the amplitude 1¾ in. The automatic minute marks, annotated in WST, are the blank spaces, 15mm apart. The origin time was, within the clock error, 06:09:00 UTC or 02:09:00 WST.

Several tall city buildings were apparently shaken for about half a minute. The isoseismal map below shows no evidence of ground motion amplification in the Perth Basin compared with the Yilgarn block across the Darling Fault (marked by the arrows in Figure 12).

A local newspaper reported that the earthquake was felt at Watheroo Observatory, 110km NNW of the presumed epicentre at Bolgart, though it is shown as not-felt there on the published isoseismal map (Everingham and Tilbury, 1952). It was decided to draw another version of the map for better reference to others in this series of reports.

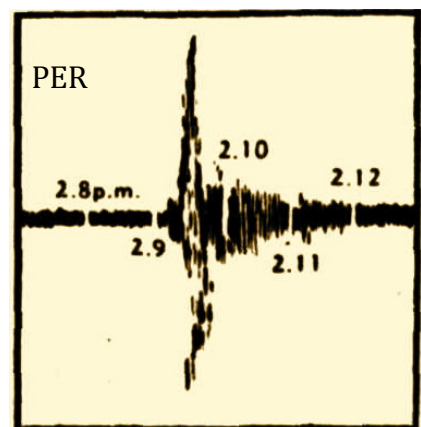
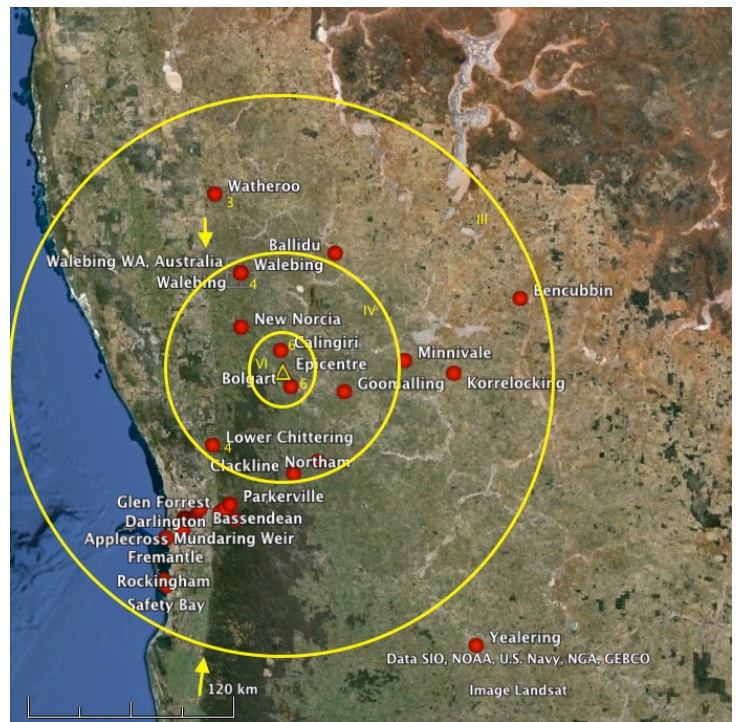


Figure 14 Isoseismal map of the Bolgart mainshock on 11 March 1952. It was felt throughout the suburbs of Perth, as far west as Bencubbin, north to Watheroo and south to Yealering. Isoseismal lines of MM3, MM4 and MM6 are shown. The arrows show the line of the Darling Scarp.

Many aftershocks were observed through to 2 May 1952, seemingly the end of the sequence, and one of the largest.

The magnitude computed from the felt area is approximately ML 5.2 which is in good agreement with Everingham's measurement from the seismogram of 5.1. For any aftershock at this distance to be detectable, its amplitude on the seismogram should be at least 0.5mm, or 1/100th the amplitude of the mainshock, i.e. ML 3. This might be too optimistic! If the level of detectability is 1.0mm then the minimum magnitude would be 3.3. We will assign the magnitudes of the reported aftershocks that were not recorded at Perth as 3.0.



1952 04 28 at 00:15 UTC (08:15 Monday 28 April local time), Bolgart

The *West Australian* of Thursday 1 May 1952, page 5 reports another strong shake in Bolgart:

NEW EARTH TREMORS AT BOLGART BOLGART, Wed.—Since the first earth tremor recorded here on March 11, there has been a continuance of earth movements. The movements have been frequent and of varying severity and, sometimes, there have been up to eight in a 24-hour period. At 8.15 a.m. on Monday there was a tremor, almost as bad as the first. The shaking of houses alarmed residents. This tremor has been followed by eight more. Walls and ceilings in many houses have been cracked. [Last night, in Perth, the Government Astronomer (Mr. H. S. Spigl) said that these were apparently the "after-shocks," likely to follow earth disturbances. He believed they would diminish in force].

1952 05 01 at 00:25 (Thursday at 08:25 local time), Bolgart

The *West Australian* Friday 2 May 1952, page 9:

Tremor At Bolgart BOLGART, Thurs.—Another violent earth tremor was felt at 8.25 a.m. today. It was more severe than any previous tremor. Slight damage has been caused by items falling from shelves, and further cracks in buildings have been reported.

Earthquake Swarms

What is an earthquake swarm? Curlewis' definition of so long ago is as good as any: '(earthquakes) extend over a long period of time and they gradually become less frequent and finally subside without any violent outbreak, the lesson to be learned: 'nothing alarming will eventuate.'

Swarms of earthquakes are relatively common in Western Australia, South Australia and NSW, even the ACT has experienced a swarm within 12 km of the centre of the Nation's capital. Dent (2008, 2009) has catalogued several recent swarms in WA but they are nothing new as the following stories show.

The West Australian, Monday 19 December 1932, page 12:

EARTH TREMORS. More Shocks Near Northam.

The Government Astronomer (Mr. H. B. Curlewis) referred on Saturday to a continued recurrence of earth tremors near Northam. He recalled that earth tremors, accompanied by underground rumblings, occurred in the vicinity of Mr. Lawrence's farm, Rock Vale, about eight miles from Northam on November 1 and 2, adding: "A report of this appeared in 'The West Australian,' it being stated that the tremors were purely local, and must have originated at no great depth, and been of only small intensity, for not the slightest trace appeared on the Observatory seismograph. The collapsing of the roofs of underground caverns was suggested as a possible cause, or again they may have been true earthquake movements, tectonic in origin but of feeble intensity, due to sudden release of strain within the crust of the earth.

"From a report received on Saturday, it seems that the tremors and rumblings have been experienced at intervals ever since. Miss Doreen Lawrence writes that they were particularly severe from November 19 to November 21, and again from 9 a.m. last Tuesday until midnight on Thursday, when they were not only violent, but came at frequent intervals. The tremors shook practically everything in the house, as well as verandah posts, and two very large tanks. She states that the subterranean noises accompanying the tremors sounded some times like a very loud explosion, and at others they more nearly resembled rumblings like distant thunder. They did not always come from the same direction.

"I do not think there need be any fears that these tremors and rumblings presage any serious movements of the earth's crust, because Western Australia is on the whole so flat that extreme strain of the crust due to unequal weighting cannot develop. Similar tremors and rumblings have frequently been experienced before in different parts of the State, especially in the south-west portion, without anything alarming following.

"In the present instance they have continued for a long time. Quellington and Quairading have both experienced even more severe tremors extending over a longer period, and they gradually became less frequent and finally subsided without any violent outbreak taking place. So it may be surmised that nothing alarming will eventuate at Rock Vale. Curiously enough, the caretaker at the Observatory heard several peculiar rumblings during the mid-week in the north-east, and evidently occurring at a great distance.

"The tremors and rumblings at Quellington and Quairading in 1910 would have been more severe than those being experienced at Rock Vale, for at those places walls were seen to crack and foundations to split apart with loud reports, there has been nothing of this violence at Rock Vale I understand. A careful geological reconnaissance of the rock structure in the vicinity of this farm would be helpful in assigning a cause for these strange happenings."

The following is worth reporting:

The West Australian, Friday 13 October 1911, page 8.

EARTH TREMORS. INVESTIGATIONS AT YORK AND QUELLINGTON. REPORT BY GOVERNMENT ASTRONOMER. The Government Astronomer (Mr. W. E. Cooke) in a report dated October 9 to the Colonial Secretary (Mr. J. Drew) regarding the earth tremors in the Eastern districts, states:—

"I went to York and Quellington in order to investigate the earth tremors which had been reported, and find that the reports apparently are not in the least exaggerated. The whole matter is extremely interesting, and I propose to undertake further investigations. A great deal of information was furnished by Mr. Gentle and by Miss Kitchin, the local public schoolmistress, but in addition I met a number of neighbouring residents, who each corroborated the main features, and agreed also in most of the details. Whatever may be the cause, the outbreak appears to be quite recent, and the present disturbance originated on July 11, 1911. Prior to that occasional noises had been heard, especially, I believe, at Wilberforce, and I have written to Mr. Hamersley for further particulars. But on the above date occurred the first of the violent tremors which are now alarming the entire neighbourhood. Since then they have been experienced frequently, but at irregular intervals. One of the most severe occurred on August 25, and was

repeated over and over again at hourly intervals throughout the evening and night. The last ones were felt on Monday and Tuesday last (October 2 and 3), but these were comparatively mild, though recorded by several people. The last severe one occurred on the previous Saturday, September 30, and was felt all over the district. The effects seem to be confined mostly to within a radius of about 20 miles, though the most severe ones are felt farther. So far I have not heard of them to the west of the Great Southern or north of the Eastern railway, though they have been felt on both those lines, at York, Spencer's Brook, and Meenaar.

The following is a general description of the disturbance:—A sudden violent explosive noise is heard, apparently always from the same direction in any given locality. Then follows a rumbling noise, passing underfoot, accompanied by shaking of floor, cracking of buildings, rattle of crockery, etc., and then passing on. Each shock apparently lasts only a few seconds, and starts with a violent explosive sound, like the discharge of a great gun. On one occasion Mr. Gentle noticed a second discharge, in the direction towards which the rumble travelled. He says that it seemed to hit a certain hill and 'split it open.' That is merely a description of the impression produced. On another occasion he heard a terrific crash from his front verandah, as if the whole verandah had been blown up, and on investigation found that the foundations, made of granite, had been split from top to bottom. One of these quakes occurred during the progress of a meeting at the Agricultural Hall, and caused some consternation. The floor shook, and even the piano was seen to rock. A crack opened in the wall, and a lot of plaster fell down. A window was smashed, and upon examination the walls were found to be cracked in several places. In one instance I noticed the crack passing right through a solid block of stone. At the Government schoolhouse, built solidly of brick, Miss Kitchin actually saw a crack form during a shock, and this was found to be not merely a plaster crack but to go right through the wall. Every house I saw was cracked in several places, and I was told that not a house in the district had escaped. Many people have given up their sleeping quarters and moved their beds outside, and a few are talking seriously of leaving the neighbourhood. On one occasion Mr. Gentle heard a noise in the direction towards which the vibration travelled, like a heavy gale, lasting for about half an hour, and yet it was an absolutely calm night, with not a quiver in the leaves."

No previous swarm has had an embedded destructive earthquake, not in Australia anyway. Could they? Recent experience in Italy suggests that they could, so precautions should be taken. Highly vulnerable local buildings could be closed, should be closed if they are a hospital or school, until the swarm is over. Then thought should be given to strengthen those buildings in case a large earthquake was to follow.

The case of Meckering, 52 years earlier, almost to the day, might be cited:

The Western Australian, Saturday 7 October 1916, page 8.

EARTH SHOCKS AND SUBTERRANEAN NOISES. EXPERIENCED AT MECKERING. Mr. H. B. Curlewis, the Acting Government Astronomer, writes:— "October 6. From the manager of the Union Bank and from the Postmaster at Meckering – I have just received letters giving particulars of a series of sounds and shocks which have been felt in the district during the last four weeks, and referring especially to a very distinct shock which occurred on the night of October 4, and is thus described: 'From midnight until 1 o'clock this morning fully a dozen shocks were felt, two of which rattled the windows and appeared to shake the building (the bank). This was followed by a very distinct shock at 10 o'clock in the morning—usually the shocks take place at night. The noises which accompany them resemble a distant explosion or the bumping of a heavy object on a wooden floor. From inquiries made in the district, no explosives are being used, and therefore the cause of the noises and shocks cannot be explained in that way. The general opinion in the town is that the disturbance is underground, and one of the residents has suggested that the phenomenon may be due in some way to the action of air in the large water pipes of the Coolgardie scheme, which pass through the town.'

"As the Perth seismograph has not recorded any of the shocks, they were almost certainly quite local, and, if of terrestrial origin, were due to some action taking place comparatively close to the surface; for had their origin been deep-seated, then the effect would have certainly been more widely felt. In countries subject to earth quakes, slight tremors are of frequent occurrence, and rumbling noises are often heard, especially where the soil is hard and rocky—such being naturally favourable to the production of sound. In this connection it has been noticed that a wide-spread earthquake, coming from a deep-seated source, produces

no sound phenomena in the places where it is generally felt, whereas a comparatively feeble shock of limited extent and shallow depth may cause rumblings without any appreciable movement of the earth's surface. This alone should be sufficient to dispel any anxiety that residents of Meckering may entertain about what the future may have in store for them, in the shape of an earthquake catastrophe. In 1911 the residents of Quellington, which lies about 30 miles to the south-east of Meckering, experienced similar phenomena, perhaps of an even more alarming nature. For the noises there were described as deafening, and the shocks were of a destructive nature, cracking walls and shattering plaster. Mr. Cooke visited the district, but arrived at no satisfactory solution of their cause. It is rather curious that the Quellington earth tremors occurred in September and October, and therefore the cause might be looked for in the season of the year, and an explanation might be sought in the expansion of moisture in the rocks near the surface due to sudden increase of temperature and their consequent dislocation, thereby producing tremors and rumbling. The heavy rain of June, July and August would account for the complete saturation of the soil and rocks and the record dry conditions, with accompanying high temperatures in September would supply the heating conditions. Another explanation might be found in the wearing out of hollows under the surface by water percolation—the collapsing of rocks and soil into the hollows thus formed, causing tremors of the earth's crust and rumbling noises. Seeing that the country round Meckering is, I believe, of limestone formation, the last theory is probably the correct one, for subterranean deterioration by means of water takes place rapidly and extensively in such formations. Without, however, thoroughly examining the district, it is impossible to give a definite explanation of the happenings there, and the solution to the problem depends almost certainly on geological data, perhaps Professor Woolnough might be induced to visit the district and give the residents the benefit of his expert knowledge."

Katanning experienced a swarm in 1936 (*The West Australian*, Saturday 22 August 1936, page 15, and there are other examples (see Dent; 2008, 2009)

Human induced earthquakes

There is no doubt that humans induce earthquakes through various processes including building large reservoirs, fluid injection and mining. The first death underground was due to a mining-induced earthquake (Government Astronomer, Mr. H.B. Curlewis in *The West Australian* Thursday 25 January 1940, page 3).

On August 29, 1917, the most serious of these happened along the Golden Mile, resulting in the death of one man and injury to several others. In this case the tremors caused a collapsing of rock masses from the roofs of tunnellings. They were accompanied by loud reports and peculiar rumblings.

The following extract from the *Townsville Daily Bulletin* of 11 March 1929 is a good example of another acknowledged mining-induced event.

BIG FALL OF EARTH.

In Kalgoorlie Mine.

Tremor Felt, at Good Distance.

KALGOORLIE. March 8. A severe earth tremor on the Golden Mile, was more or less, severely felt in Kalgoorlie and Boulder, as a result of a fall of ground which occurred in the South Kalgoorlie Mine on the east side of the main shaft in the vicinity of no 14 and 15 levels. Men were being lowered down the shaft at the time. John Hasties, who was on the platform of no 15 level, sustained a fractured left forearm and head injuries, which necessitated his removal to hospital. At no 14 level G. Bremen had one foot pinned, under a fallen rock, and after first aid treatment, was taken home. After an inspection of the lower levels it was decided to remove all the men from the levels below no 12 for a few days till the mine settled down, and minor repairs had been effected to the shaft. It is hoped that work in the lower levels will be resumed early next week. The tremor was severely felt in Kalgoorlie and Boulder and in some houses plaster was shaken from the ceiling.

In many newspaper articles about earthquakes in WA, it has often been suggested by authoritative sources that the local earthquakes could have been caused by the collapse of underground caves or mines, so the following extract from a letter by Mr. Drew to the *West Australian* on 24 January 1940 page 14 is pertinent:

It has been suggested that the recent tremors may have been due to the subsidence of some of the old mines. As a matter of fact, nearly all the old and deep mines at Northampton subsided years ago without any convulsive effect, and without disturbing the serenity of the surrounding atmosphere for more than half a mile. In the latest case, the tremors were felt from Geraldton to Binu - a distance of over fifty miles!

In the early 20th century the mines would usually admit that their activities deep underground were the direct cause of local earthquakes. In recent decades it seems that the onus of proof has swapped to those whose homes or buildings have been damaged, whilst mining companies deny any responsibility, citing tectonism as the cause.

Tsunamis

Prehistoric

The first time it occurred to Dr Phillip Playford, former director of the Geological Survey of WA, that tsunamis could have hit the WA coast was when he saw giant blocks of limestone stranded above cliffs on Legendre Island as he sailed past the Pilbara landmark in 1977. Then in 2009 the geologist was sailing past Koks Island, near Shark Bay, on the Leeuwin when he noticed similar limestone chunks on the flat surface of the island.

But it was not until 2010, while surveying at Shark Bay, that he claims to have found evidence the blocks were the result of huge tsunamis that pummelled the WA coast before white settlement, eroding cliffs and throwing the giant boulders up to hundreds of metres inland. The waves would probably have killed thousands of Aboriginal people he said when they slammed into the coast from Shark Bay to beyond the Northern Territory border.

Playford said the tsunami deposits in WA were some of the biggest anywhere in the world and were probably from tsunamis that reached about 20m high with a run-up height of up to 35m. He said the biggest block he knew of, on Dirk Hartog Island, weighed about 700 tonnes.

"That's been moved about 250m inland and 15m above sea level and the only way it could have been moved there is by a huge tsunami," he said.



Figure 15 A tsunami allegedly pushed this 700 tonne rock on Dirk Hartog Island 250m inland and 15m above sea level. Picture: Dr Phillip Playford

Dr Playford said the most recent tsunami deposits had been dated as from 2900 years ago and the oldest from more than 5000 years ago. "But there's one date that suggests as recently as 600 years ago," he said. "There clearly have been several tsunamis."

Figure 16 Boulders are lodged on a column at Cape Dommert near Wyndham. Picture: Dr Phillip Playford

"Most tsunami deposits are subtle but these ones along here sure aren't," Dr Playford said.

"And the amazing thing is they've gone almost unreported, left to a fellow like me in the closing phases of my career to have found them."

It is not known what caused the tsunamis but Dr Playford has three theories about what could be responsible - movement along local faults, the impact of one or several asteroids in the Indian Ocean or landslides on the slope of the Continental Shelf.



He said there was no telling when another tsunami of the same magnitude might hit WA.

"If it hit today it would have catastrophic consequences . . . but it might be tomorrow or it might be 10,000 years, no one knows," he said.

1883 Krakatoa eruption and caldera collapse, 2.4m tsunami on NW coast and in King's Sound

The *South Australian Weekly Chronicle* Saturday 8 September 1883, page 9 states:

Perth, August 31.

Further particulars received from Geraldton respecting the tidal wave shows that the sea receded at 8 o'clock on Monday evening over 100 yards, enabling people to pick up fish on the beach in numbers. The drawback was of short duration, the sea returning with a rushing noise, and those picking up fish had to run for their lives. No serious damage was done.

South Australian Weekly Chronicle, Saturday 6 October 1883, page 8 reports:

OUR WEST AUSTRALIAN LETTER.

[From our own Correspondent.]

Perth, September 18, 1833.

The Ferret arrived two days ago from the north-west, bringing news which relieved us from great anxiety regarding the northern ports, which it was feared might have suffered severely from the effects of the late tidal wave. The township of Cossack, which serves as port for the Roebourne district, is built on ground almost level with high water, and Carnarvon, at the mouth of the Gascoyne, lies equally low. Had the tidal wave, which, even so far south as Geraldton, rose nearly 8 feet, swept in upon either of these two townships during high water, they must both have been completely swamped out, with great loss of property and probably of life. Happily, at Cossack the tidal disturbance took place when the water was low and caused no damage, though the sea kept rushing in and out of Cossack Creek in an eccentric manner for some days afterwards, while reports, resembling the discharge of artillery, were heard throughout the district. Lower down the coast, at the mouth of the Ashburton, the Laughing Wave was landing some valuable rams just imported from South Australia when the tidal

phenomena occurred. A number of these stud sheep had been placed in a boat, which was making for the shore when, without any warning, a great wave rushed in, swamped the boat, and drowned ten of the imported stock. At Carnarvon the inhabitants were as fortunate as at Cossack — the wave came in at low tide and no harm was done ; but shocks of earthquake were felt, and re- ports like guns firing at a distance were heard as far inland as Derry Creek, 130 miles from the sea shore. These reports, or underground rumblings, were heard in every part of the colony from which news has been received, and caused no little astonishment, and even alarm, until after the circulation of the news received by telegram respecting the earthquake and disturbances in the Straits of Sunda, which occurred about the same time. One very curious phenomenon is reported by the officers of H.M. survey vessel Meda, which was at sea, a hundred miles or so in a westerly direction from the North-West Cape, when these earthquake shocks, rumblings, and tidal waves were experienced on shore. On turning out one morning the ship, decks, rigging and all, was found to be thickly covered with a strange kind of fine calcined substance, in appearance much resembling fullers' earth. The wind had been blowing all night from the ship to the shore. This dust, therefore, could not have come from the mainland, and Captain Coghlan and his officers are of opinion that it had been borne across from the eruptions at Sunda, some thousand miles distant.

The *Queenslander* Saturday 22 September 1883, page 492 quoted the Albany Mail with the following story about tidal phenomena in King's Sound (the *Albany Mail* was not available in Trove).

Tidal Phenomena.

DESCRIBING the extraordinary tidal phenomena observed in King George's Sound on Monday, Tuesday, and Wednesday, 27th, 28th, and 29th August, the Albany Mail says :—"As the R.M.S. Rosetta was steaming out of the harbour on Monday afternoon, a great rush of tide like a tidal bore came in, and the vessel had to put on full speed to meet it; and on the following day there were two great rushes inward, and then a tremendous rush outward. All the buoys disappeared under water, and then rose to the surface and took moorings and everything out into the Sound. On Wednesday, when the harbour-master was coming in with the steamer Coniston, at 8 p.m., the tide outwards was running at such a rate that the vessel could hardly make headway going full speed. Such a tide was never known by the oldest nautical inhabitants of the port, and was strange considering the slight rise and fall of the tide in this harbour —only 3ft. There must have been a succession of tidal waves, or several shocks of submarine earthquake." Similar phenomena were noticed at Geraldton. A telegram from that place, dated 30th August, says:—"Strange rumbling sounds were heard here and at Tibradden and elsewhere on Monday morning early, and a most unusual rise of tide took place on Monday evening at 8 o'clock and again at half-past 8. The sea receded over 100 yards, enabling people to pick up fish in quantities. The drawback was of short duration. The sea returned with a great rushing noise, and those who were fish-gathering had to run quickly for their lives. Boats that were high and dry on the beach were washed out and swamped. The Rob Roy and the lighters at anchor were twisted right round. The sea rose about 8ft. In a short time all was quiet again, except that the ocean continued rising and falling until next morning."

Compare that with the description of the volcanic episode on Krakatoa below from Wikipedia http://en.wikipedia.org/wiki/1883_eruption_of_Krakatoa

By 25 August, eruptions further intensified. At about 13:00 (local time) on 26 August, the volcano went into its paroxysmal phase. By 14:00 observers could see a black cloud of ash 27 km (17 mi) high. At this point, the eruption was virtually continuous and explosions could be heard every ten minutes or so. Ships within 20 km (12 mi) of the volcano reported heavy ash fall, with pieces of hot pumice up to 10 cm (3.9 in) in diameter landing on their decks. A small tsunami hit the shores of Java and Sumatra, some 40 km (25 mi) away, between the time of 18:00 and 19:00 hours.

On 27 August four enormous explosions took place at 05:30, 06:44, 10:02, and 10:41 local time. At 5:30 A.M, the first explosion was at Perboewatan volcano, triggering a tsunami heading straight to Telock Botong. At 6:44 A.M, Krakatoa exploded again on Danan volcano, with the resulting tsunami stretching eastward and westward. The largest explosion, at 10:02 A.M, was so violent that it was heard 3,110 km (1,930 mi) away in Perth, Western Australia, and the Indian

Ocean island of Rodrigues near Mauritius (4,800 km (3,000 mi) away), where they were thought to be cannon fire from a nearby ship. Each explosion was accompanied by large tsunamis, which are believed to have been over 30 meters (100 ft) high in places. A large area of the Sunda Strait and a number of places on the Sumatran coast were affected by pyroclastic flows from the volcano. The energy released from the explosion has been estimated to be equal to about 200 megatons of TNT, roughly four times as powerful as the Tsar Bomba (the most powerful thermonuclear weapon ever detonated). At 10:41 A.M, a landslide tore off half of Rakata volcano causing the final explosion.

1977 08 19 at 06:08:55 UTC, Sumba earthquake and Indian Ocean tsunami

On 19 August 1977 a great earthquake Mw 8.3 (revised by EHB) occurred west of Sumba Island, Indonesia. At least 100 were killed, 89 reported missing and 75 injured. Several villages were completely destroyed. The tsunami generated wave heights in excess of 10 metres along the Sumbawa island coastline and caused damage along the coasts of Sumba, Sumbawa, Lombok and Bali. Wave heights of 6 metres were reported on the coast of northern Australia. Most of the casualties and damage were caused by the tsunami.

The earthquake caused damage to office and school buildings, a mosque and a market in Sumbawa and Bima. The quake and the tsunami caused 107 deaths in the entire Nusa Tenggara region. 54 more people were reported missing and presumed dead. A total of 440 houses were destroyed or heavily damaged, 467 boats were missing or damaged and 5 school buildings collapsed.

The quake was felt very widely in Western Australia from Port Hedland, where the power was cut, to Albany where it was slight. In Perth people in high-rise buildings more than 2000 km south of the epicentre evacuated their offices, the measured ground motion of about 4mm/s^2 at 1Hz undoubtedly amplified several times up the building. A tsunami swept along the WA coast, measured in the northwest from 2 to 6m high. Gregson and others (1979) catalogued the effects of this earthquake and tsunami and made the following recommendations which were very slow to be acted upon in the first case and still not done in the second case:

- consideration should be given to installing accelerographs in selected buildings in Perth, and
- to providing a tsunami warning service for the northwest coast.

Damage, felt reports and isoseismal map

Isoseismal maps for Australian earthquakes are compiled in three atlases by Everingham and others (1982), Rynn and others (1987) and McCue (1997) which include 20, 4 and 17 maps of Western Australian earthquakes respectively. Large intraplate earthquakes in the 20th century in 1906, 1941 and 1968 shook Perth strongly as shown below which does not seem to have occurred in the 19th century between 1829 and 1901, the period when written records became available.

Perth - Felt Earthquakes and Hazard Assessments

Until 1906, Perth does not seem to have been shaken much, or regularly, but the following century things were different. Take the following newspaper extract from 1941, front page news:

The Daily News (Perth, WA : 1882 - 1950) Tuesday 29 April 1941, page 1 was headed:

Perth Shakes

Thousands of people were seriously alarmed, business was temporarily halted in many places when Perth today experienced one of the most severe earth tremors in its history. The tremor took place about 9.40 a.m. Buildings swayed windows rattled, chairs rocked, calendars and pictures swung on the walls.

Many people rushed from the upper floor, of buildings to the ground floor. While the tremor was felt particularly in Perth reports of earth movement have come from Carnarvon (570 miles

north), Wongan Hills, Laverton, Pingelly (130 miles south). The tremor was distinctly noticeable at many points in the metropolitan area. At Cottesloe three plate glass windows of a block of flats near the beach were cracked. At East Perth, buildings swayed, windows rattled, people 'felt giddy.' One of the lifts in the C.M.L. building, Perth's tallest (Author: 11 storeys), was ascending when the tremor took place. The liftman later said that the lift swayed perceptibly. He thought at first that the mechanism of the lift was affected and stopped it on the ninth floor and got out. He then noticed the building sway. The staff of Rankin Morrison and Company, on the ninth floor were so alarmed by the swaying of the building that they rushed downstairs. In several other city buildings business people ran downstairs because of the swaying. The Under-Secretary of the Premier's Department (Mr. L. E. Shapcott) said that the whole building at the corner of Barrack-street and St. George's-terrace seemed to rock. Shutters in the telephone switchboard dropped and handles on the bookcase in his office developed an appreciable swing.

Last Tremor

Mr. Shapcott said that when he was an officer in the Mines Department (before 1914) he had had a similar experience (Author: 1906). The tremor was proved later to have been due to a disturbance in the Indian Ocean. The shock seemed to have been noticed most on upper floors. At the top of Boans a 900lb. oven was moved out of place by the tremor. On the second floor of Foy's there was a perceptible rocking. On the top floor water in buckets swished from side to side. Tools hanging on the wall fell to the floor.

'Giddy'

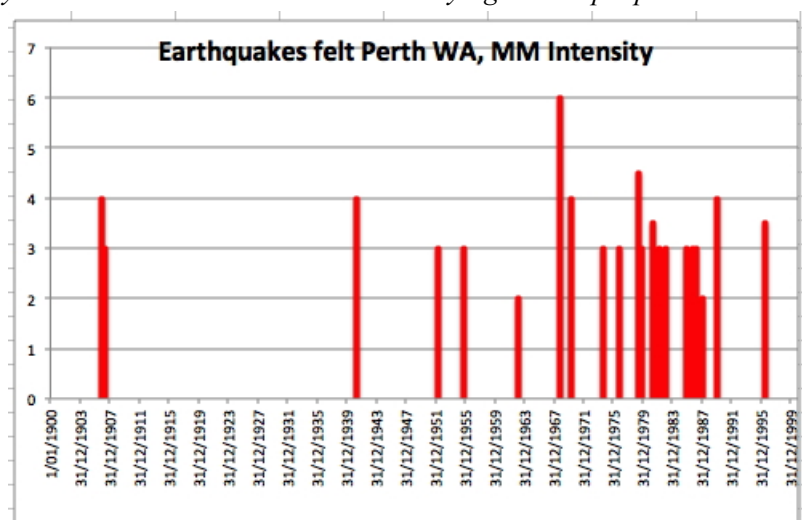
Most people imagined they were going to faint. On the upper floor of one large building a customer said to an assistant, 'I feel as though I'm going to faint. The assistant said 'Funny thing, I feel like fainting myself.' One man who lived for many years in New Zealand said that to day's tremor reminded him of many he had experienced there. But today's tremor did not have the regular 'flutters' which seemed typical of the New Zealand "shakes." Mr. M. D. Mears, Deputy Commissioner of Taxation, said: 'To me it felt as if I were standing on the deck of a yacht which was caught in a gentle roll. I felt the tremor and had quite a giddy feeling. The building shook and the windows rattled.' As a boy, Mr. Mears experienced similar tremors in the south east of South Australia and in Adelaide.

Dummies Dance

Unclad dummy dress models danced weirdly in a room on the third floor of the Economic Chambers. They were seen through a letter slot by Mr. T. W. Coultas, a tailor in a nearby room, and by Mr. Jim Hills, to whom he was talking. Noise of their movement was first mistaken for a rat. 'We were in the passage and did not notice the shake,' said Mr. Coultas. 'Noises from the room caused us to investigate, and we enjoyed a free ballet, which we first attributed to wind. Nickel shop fittings kept there by the Economic Stores were also swaying. Other people in the building soon told us what had happened.'

Figure 17 Earthquakes felt in Perth since 1900 using the MM Intensity scale.

As mentioned in the newspaper this was not the first time residents of Perth had been strongly shaken, nor was it the last time. The Meckering earthquake on 14 October 1968 had a similar impact on Perth and incredibly, great earthquakes on the plate boundary 2000km to the north shake tall buildings enough to cause their evacuation.

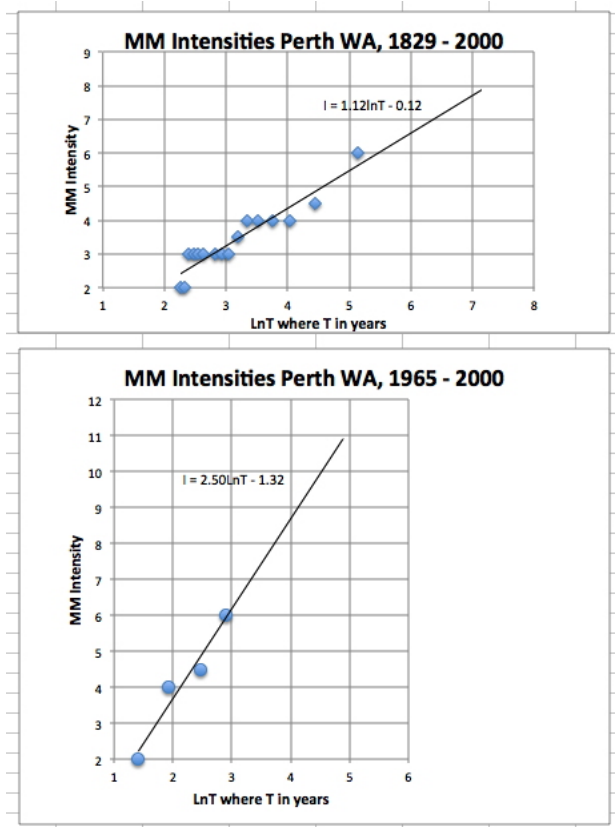


Hazard Maps The first earthquake hazard map of WA was compiled by McCue (1973) using data compiled by Mundaring Geophysical Observatory in the period 1906 – July 1970 and Everingham and Tilbury (1971 & 1972). McEwin & others (1976) published a version, Gaull and others (1990) another, and more lately Burbidge and others (2012) have re-evaluated the hazard in WA using the post-1965 historical data in the delineation of seismic zones.

The effect of neglecting the pre-1965 seismicity data can be seen in Figure 18 where the effects of earthquakes on Perth are rated by their modified Mercalli intensity in Perth over the whole period since European arrival compared with the post-1965 period. The raw histogram of MM Intensities in Perth clearly shows the strikingly clustered nature of the ground shaking at Perth. Obviously any hazard assessment of Perth is very sensitive to the period chosen for data sampling and modeling.

Figure 18 The distribution of intensities in Perth plotted in the form of extreme value statistics for the whole period 1829 to 2000 and the shorter period 1965 – 2000.

This form of hazard assessment integrates all source zone, recurrence relation and attenuation information that goes into a probabilistic seismic hazard assessment. The downside is that intensity is not a useful design parameter but it is very useful as a qualitative and relative measure of hazard and risk.



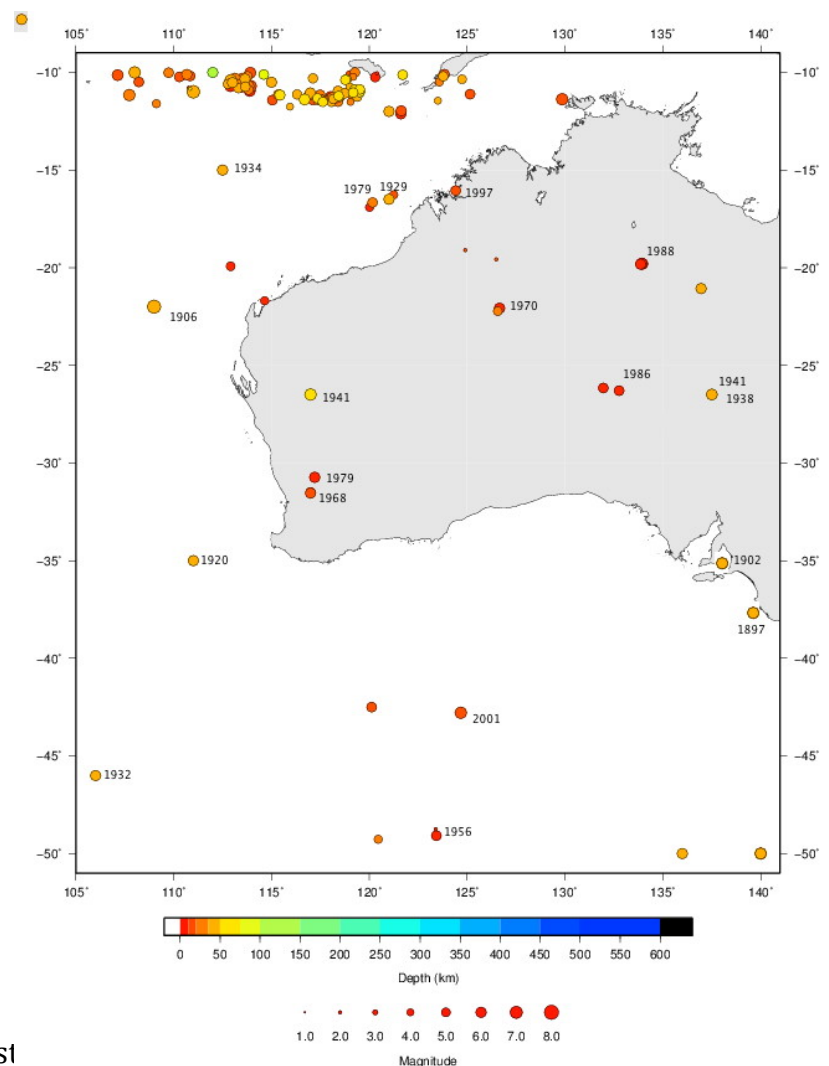
Discussion

The record of earthquakes in the second half of the 19th century seems to be significantly lower than that of the 20th century. This could be due to the lack of seismographs prior to 1901 or to a genuine decrease in the number of earthquakes, or the lack of urbanization north of Perth (Broome for example was not settled until 1883 and Wyndham in 1886).

Figure 19 Large earthquakes in Western Australia and region since 1897 (mainly from the ISC on-line Bulletin). The northern plate boundary is reasonably clear but the southern one trends from bottom right of the plot (50°S, 140°E) to near-bottom left (45°S, 105°E).

We can test this by looking at the record of reported felt intensities in Perth over the longest post-1829 period of European occupation.

Reliable accounts of earthquake effects have consistently come from several regions since 1904, and it is apparent that recently recorded



earthquakes have for the most part occurred in these regions of past activity. This observation by Everingham (1971) reflects similar observations in South Australia that gives some confidence most future earthquakes will occur where they have in the past.

There is a suggestion of a migration of large earthquakes from the NNW to the SSE through Western Australia linking the plate boundaries. This seems to have started about 1906 and stretches between the 1934 and 2001 events marked. The reverse is true in South Australia starting with the large Kingston/Beachport earthquake of 1897, the seismicity migrating to the NNW through the cluster of events near the 1997 Collier Bay epicentre.

Other scientists have made similar observations, e.g. Doyle (1971) proposed a fracture pattern that is very similar to that suggested here, the main difference is that he didn't link it to a rupture process in time. Cleary and Simpson (1971) proposed a different breakup geometry of the continent.

Great historical earthquakes along the Australian plate boundaries should be better studied to assess their damage and tsunami risk potential. The review of the 1938 earthquake north of Darwin (McCue, 2012) is just the start of this project.

Human activities are increasingly leading to earthquakes, whether pumping fluids underground for waste disposal or geothermal reservoir production, filling large reservoirs and mining. Historically mining has shown a capacity to induce earthquakes, the coal mines of NSW and Queensland as well as the hard rock mines in NSW, SA and WA and more recently fracking operations in coal rich areas. Such operations should be monitored closely with dense networks of seismographs, the data made publicly available.

Table WA earthquakes discussed in the text, 1829 - 1957

Date yyyymmdd	Time UTC	Lat °S	Long °E	Mag	Place
1849 08 03	20:15				First earthquake felt in Perth MM3
1855					Perth, Scotland or New Zealand?
1877 10 ??	??	32.6	115.9	4.5	Pinjarrah, 70km south of Perth
1877 10 17	evening	30.9	116.4	>3	Victoria Plains, 110km NNE of Perth
1883 08 30					Krakatoa eruption, heard Geraldton and Dongarra, 2.4m tsunami observed at Geraldton.
1883 10 ??	??	29	114.6	>3.7	Sharp shock felt Geraldton and Dongar(r)a
1883 12 24	morning				Felt Perth in morning, slight MM3
1885 01 05	14:30	28.3	114.6	6.5	Felt Geraldton, Northampton but not Perth
1886 09 09	18:10			>6	Plate boundary, felt Cossack and Roebourne
1890 12 07	06:30			>6	Plate boundary, felt Cossack and Roebourne
1893 03 19	13:00 & 23:30	35.1	118.0	3.5 & 4.0	Felt at Breaksea Island and Albany.
1893 04 26	22:05	20.7	117.4	3.5	Roebourne, lasting 20 sec
1893 12 ?	??				Felt Perth??
1894 01 04	10 pm local time	35.1	118.0	3	Albany

1896 07 02	18:00	31.7	128.9	3.5	Eucla
1896 04 20	12:15	34.2	115.0	3.5	Karridale
1899 04 07	10:20 am Local time	35.1	117.9	3	Albany
1899 10 24	04:00			>7	Banda Sea, felt Wyndham, Darwin
1901 01 10	03:00			>6	Felt Cossack, Roeburn, Whim Ck., and Balla Balla
1903 02 13	16:00			>6	Plate boundary felt Wyndham
1904 05 24	11:45	15.5	128.1	3.5	Wyndham
1905 01 16	16:00	33.5	115.0	3.5	Cape Naturaliste
1906 11 19*	07:18	22	109	7.2	Offshore Exmouth, GUTE. Largest known earthquake in Australia.
1907 01 04	05:19	2N	94.5	7.6	Northern Sumatra, earthquake and tsunami observed Cocos Is.
1907 04 10	08:00	?	?	-	Felt Perth MM3, recorded on seismograph but no details, Nothing in ISC bulletin.
1907 08 09	12:40	21.2	119.8	4	Marble Bar
1907 08 12					Perth
1908 05 09	08:00	17.0	128.2	4.5	Turkey Creek, near Lake Argyle
1909 04 18	16:37	26.8	116.0	4.3	Balline Station, Murchison Shire, recorded Perth
1909 10 12	06:50 (?)	21.2	119.8	3	Marble Bar
1910 10 14	22:15	21.15	119.75	3	Marble Bar
1911 08 04		31.75	116.85	3	Quellington swarm
1912 02 03	00				Cossack, apparent tsunami waves observed, no known cause
1912 04 25	10:36:30	35.2	118.0	4	Albany
1916 05 03	01:45	33.5	120.0	4	Ravensthorpe, Hopetoun
1917 10 25	21:00				Derby
1919 01 07	21:35	34.0	127.3	5.8	Offshore Eyre, Nullabor Plain
1919 05 01	??	25.0	111.0	>5	Numbers of dead deep-water fish off Sharks Bay. Earthquake recorded at PER. No felt reports.
1920 02 08	05:24:30	35	111	6.2	SW coast, too far offshore to be felt
1923 09 30	08:42	31.9	117.8	3.5	Kwolyin, 33km east of Quairading
1926 07 23	10:10	16.36	122.9	4.6	Cape Leveque, Kings Sound
1927 06 03	07:12:11	7.0	131.0	7.4	Banda Sea, depth 150km
1928 09 08	??	22	115	4.0	Onslow, felt Saturday night
1929 08 16	21:28:25	16.5	121.0	6.2	Offshore Broome GUTE epicentre and magnitude (Ms scale)

“	“	16.1	119.2	6.2	This study (KMc on map)
1931 02 03	13:00	32.0	117.1	3.0	East Beverley. Felt in Balkuling and by neighbours 10 miles away
1931 02 10	06:34:25	5.25	102.5	7.5	Southern Sumatera, felt Cocos Is
1931 03 28	12:38:37	7.0	129.5	7.3	Banda Sea (GUTE soln from the ISC), felt Derby, Wyndham, Broome and Darwin
1931 04 09	12:45	28.9	121.8	4.3	Leonora
1931 09 25	06:00 UTC	5.0	102.75	7.4	Sumatera, Felt Cocos Island
1932 11 01 and 11 02	-	31.6	116.7		Swarm near Northam
1933 02 19	02:05	18.5	121.5	5.8	Felt Broome, recorded PER
1934 07 12	14:00	15	112.5	6.0	Intraplate earthquake offshore Onslow where it was felt
1934 10 18	19:00	31.6	116.7	3.5	Northam
1935 09 01	14:23	22.5	115.2	4.6	Yanrey, south of Onslow, recorded PER
1936 04 29	09:00	22	117.7	5.5	Not listed by ISC, possibly a moderate earthquake east of Onslow
1936 05 04	10:15	32.2	128.5	4.7	Eucla
1939 04 26	06:00	31.6	117.0	3	Meckering, small local
1939 06 23	evening	24.1	116.3	4.3	Bangemall East Gascoyne
1940 01 19	19:30	28.3	114.6	4	Northampton
1940 12 18	21:45	32.2	117.2	4.2	Beverley – widely felt over the Dale country, recorded at Perth Observatory. Location and magnitude from E&T (1971)
1941 04 29*	01 35 41	26.5	116.3	6.8	Meeberrie, largest on-shore earthquake in Australia
1941 08 12	04:40	17.8	122	3.5	Felt Broome
1942 06 16	08:00	35.1	118.0	3.5	Albany
1946 09 17	15:12	32.35	117.0	4.2	Brookton. ML 4.5 according to E&T (1971)
1949 05 02	10:02	31.05	116.25	4.6	New Norcia. PER seismograph boom moved ½ in.
1949 09 29	18:16	29.4	116.3	3.5	Perenjori
1950 11 02	15:27	6.7	129.3	7.5	Felt Derby some awakened, damage Darwin, a major Banda Sea event at intermediate depth.
1950 11 30	23:10	21	115	4.0	50 km north of Onslow
1952 03 11	06:09:00	31.2	116.4	5.2	Bolgart. Damage in Bolgart, rocked tall buildings in Perth and felt in suburbs. Recorded on PER seismograph. Lots of aftershocks.
1952 03 11	20:00	31.3	116.5	3	Bolgart aftershock felt

1952 03 11	20:50	31.3	116.5	3	Bolgart aftershock felt
1952 03 11	22:30	31.3	116.5	3	Bolgart aftershock felt
1952 03 13	18:00	31.3	116.5	3.8	Bolgart aftershock. Large cracks in the Walls of the Anglican Church and new school, hotel and farms.
1952 03 14	04:36	31.1	116.5	3	Bolgart, aftershock felt
1952 04 28	00:15	31.3	116.5	3.8	Bolgart, large aftershock, more cracking of walls and ceilings in houses, 8 aftershocks
1952 05 01	00:25	31.3	116.5	3.8	Bolgart, Further cracking of walls and items thrown off shelves

Appendix 2 Time in Western Australia

(abridged from Wikipedia http://en.wikipedia.org/wiki/Time_in_Australia)

The standardisation of time in Australia became operational in February 1892. Prior to that date meridian time was used when Perth, at longitude 115.9°E, was 7 hours 42min ahead of Greenwich. I have used 8 hours here i.e. 2 hour behind Sydney Time. The Dominions enacted time zone legislation, adopting Greenwich as the standard Meridian, effective from February 1895. The clocks were set ahead of GMT by eight hours in Western Australia; the time zone became known as *Western Standard Time*. UTC replaced GMT as the basis on 01 September 2005.

Appendix 3 Perth Observatory

The original Perth Observatory was constructed in 1896 and was officially opened in 1900 by John Forrest, the first premier of Western Australia. The observatory was located at Mount Eliza overlooking the city of Perth. Its chief roles were keeping Standard Time for Western Australia and meteorological data collection (from Wikipedia).

William Ernest Cooke was appointed the first Western Australian Government Astronomer in 1896 after a similar posting at the Adelaide Observatory. On arrival in Perth, his first task was to determine the exact latitude and longitude of the colony. He was also able to determine the time of day with greater accuracy. Before his arrival clocks could vary by up to half an hour. The time was announced each day by a cannon still present on the grounds. The design was by the government architect, George Temple-Poole, and features a bold combination of styles (from Wikipedia).

Harold Curlewis succeeded Cooke as Government Astronomer in 1920.

In 1920 and 1921 Curlewis was involved with the Government Astronomer of South Australia, in determinations to fix positions for marking of the Western Australia border on the ground with the South Australian border at Deakin, Western Australia. In 1921 the same group from the Deakin determinations travelled by the State Ship, MV Bambra to Wyndham, where they were guided by Michael Durack to a point near Argyle Downs close to the 129th meridian east longitude (129° east). They used wireless radio time signals, and other methods to fix a position for the Northern Territory border with Western Australia. These early determinations led to the 1968 agreement for the formation of Surveyor Generals Corner. The WA border is not straight, at 26° south, there is an approximately 127 metre east-west offset of the WA/NT border (from Wikipedia).

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Appendix 1 Earthquakes of 1939 from *The West Australian* Saturday 13 January 1940, page 18, by H. B. Curlewis, WA Government Astronomer

EARTHQUAKES OF 1939. Recordings at Perth Observatory.

Concerning earthquake movements in 1939, the Government Astronomer (Mr. H. B. Curlewis) writes: There were only 155 separate recordings of the earthquake-registering instrument, or seismograph, at the Perth Observatory—just on a 100 less than the number recorded for the previous year. Of these movements 49 were classed as tremors only; namely, periods when the continuous vibrations of the earth's crust were somewhat more pronounced than usual. Another 70 were due to distinct earthquake movements, but only of minor intensity; probably in none of these did any serious faulting of the earth's crust occur and in many cases certainly the preliminary and secondary tremors, that travel direct through the earth to the station, did not have sufficient strength to reach Perth. Coming to those in which distinct faulting of the crust took place of a more or less severe nature, 29 could be classed as non-destructive, judging by the appearance of the trace and the lack of reports of any damage having been occasioned, thus leaving only seven that were distinctly severe and destructive, and, even of these, three occurred on the floor of oceans and, as far as is known, caused no loss of life. The most severe of the three occurred on January 30 in the Coral Sea, a truly earth-shaking disturbance. It is interesting to note that in this area of the Pacific some of the most violent earthquakes have been registered by the Perth seismograph. Two or more a year from this part of the Pacific can generally be reckoned on, and they have always caused the boom to swing most strongly. On two occasions it has swung right off the agate cup. Among the others the Chilean disturbance on January 25 caused great loss of life and was accompanied by volcanic eruptions.

On March 21 the liner Orford, when midway between Colombo and Cocos Island, must have been near the epicentre of a severe submarine upheaval, for the vessel shook from stem to stern, just as if she had run into a submerged wreck (Author: GUTE gives 1939/03/21, 0111 09 UTC, 1.5S, 89.5E, Ms 7.2).

The islands of Japan, where probably more earth movements are experienced in the course of a year than anywhere else in the world, were fortunate in having only one very severe disturbance on May 2, when an entire village of the north island was swallowed by the sea, many lives being lost.

On the same date the south Solomon Islands were devastated by a most severe earthquake and tidal wave. Although separated by over 4,000 miles, there was probably a connection between these two major faultings of the earth's crust.

A long period of quiescence then followed and it was not till December 21 that a submarine disturbance of great violence occurred on the floor of the ocean between Timor and the Celebes and this was followed in six days by the most destructive earthquake of the year, namely, the catastrophe in Asia Minor on December 27 and the following days. About a month beforehand, on November 23, the cables reported a destructive earthquake in Anatolia, and yet the tremors from it only just reached Perth. From the number of lives lost and buildings destroyed, one would have expected to see a very much more decided record. It must be that the district of Asia Minor rests upon very unstable foundations, and, since the terrain is very rough and mountainous, evidently slight earth movements are sufficient to bring great rock masses crashing down in a most indiscriminate and devastating manner. Where the faulting was more severe and widespread, as on December 27, mountains and rock-masses must have come tumbling about the heads of the inhabitants.

Two earthquakes worthy of mention were felt in the Eastern States, one on March 26 when townships along the head of the Bight experienced distinct tremors, which came from severe faulting on the ocean floor about 300 miles to the south, on the northern edge of the Jeffrey's Deep, and the other was felt in Melbourne and suburbs, the tremors being the most severe experienced for 20 years. The visitation happened at 11 p.m. on April 5 and lasted for 30 seconds. Houses shook, windows rattled, crockery was dislodged and pictures fell from the walls, but no major damage occurred.

Notes

- 1: This was indeed a very active year with three earthquakes of magnitude 8 or more, in the Solomon Islands, Sulawesi and Turkey.

- 2: The Head of the Bight earthquake actually occurred near Nilpena in South Australia on 26 March 1939, its magnitude about 5.7.
- 3: The Melbourne earthquake was previously little known but this report triggered a research effort.

Appendix 2. Magnitude

A Milne-Shaw seismometer (installed at Perth Observatory in 1923) has the following characteristics:

Natural period $T_0=12\text{sec}$, Damping ratio $DR = 20:1$, Magnification 250 (some only 150).

The logarithmic decrement λ is given by:

$$\lambda = 2 \pi h / \sqrt{(1-h^2)} \text{ ie } h = \lambda / \sqrt{(4 \pi^2 + \lambda^2)}$$

or $\lambda = 2\ln DR$

h is the damping coefficient which, with $DR = 20$, is 0.69 – i.e. critically damped

Appendix 3 The Safety Of Western Australia

REMARKS BY THE GOVERNMENT GEOLOGIST.

in the *Western Mail*, Saturday 24 November 1906, Page 15.

The occurrence of an earthquake in this State lends special interest to some observations made by the Government Geologist, Mr. Gibb Maitland, in the course of a lecture delivered by him in Perth and Boulder soon after the disastrous earthquake at San Francisco. After describing the various processes involved in the manufacture and transmutation of the older rocks of the State, Mr. Maitland said:

"It is almost impossible that such folding, crushing, and compression as is indicated by the evidence which has been brought before you could have occurred without frequent starts, slips and consequent earthquakes, and while perhaps we may possibly imagine that these movements are at an end, these older rocks are probably not really at rest. It is possible that there may yet be movements which only careful observations carried on over long periods of time could detect. We are apt to regard this portion of the globe upon which we live as having got beyond the stage of inward turmoil and strife; but probably such is far from being the case, and although perhaps any movements may merely suffice to agitate the seismograph at the Observatory, there does not seem to be any geological reason to fear that in this portion of Australia they would be such as to cause a repetition of the disaster which has recently fallen upon San Francisco."

Speaking to a reporter, Mr. Maitland remarked: "This last earthquake has apparently been felt over a considerable area of the State, and generally in a north-easterly and south-westerly direction. This fact is of importance, because from the investigations which have been made, and as may be seen from an inspection of the various geological maps issued by the department, what may be called the fracture system of Western Australia trends generally north-east and south-west. It is probably along these lines that any movement affecting Western Australia would be more immediately felt: Although these fracture lines are more pronounced in the oldest rocks of the State and covering the largest area, it is important to know that in nearly every case the junction between the much newer strata and the older strata is also marked by more or less powerful dislocation. This fact is important, in that it shows that these pronounced movements have continued throughout the length and breadth of the State for pretty well the whole of the geological period. As pointed out in the quotation from my lecture given above, such conditions are likely to prevail in the future. It is, however, to be noted that Western Australia does not lie within what may be called the earthquake line of the globe, and hence there is little to fear that there will be seen in Western Australia any of those extraordinary effects that have been witnessed in Lisbon, San Francisco, and Rio Janeiro."



Figure 20 Original Perth Observatory at Mt Eliza. Astronomers and seismologists included Mr Cooke and Mr Curlewis who are both quoted extensively in this paper and this author for one, is most grateful to them.

Figure 21 Perth Observatory Staff, c.1900. W. Ernest Cooke is seated at left. Cooke's successor Harold Curlewis is standing in the light coloured suit. (Image supplied by Government Astronomer and Director of Perth Observatory, Jamie Biggs).

