Darwin Northern Territory – an Earthquake Hazard

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Abstract

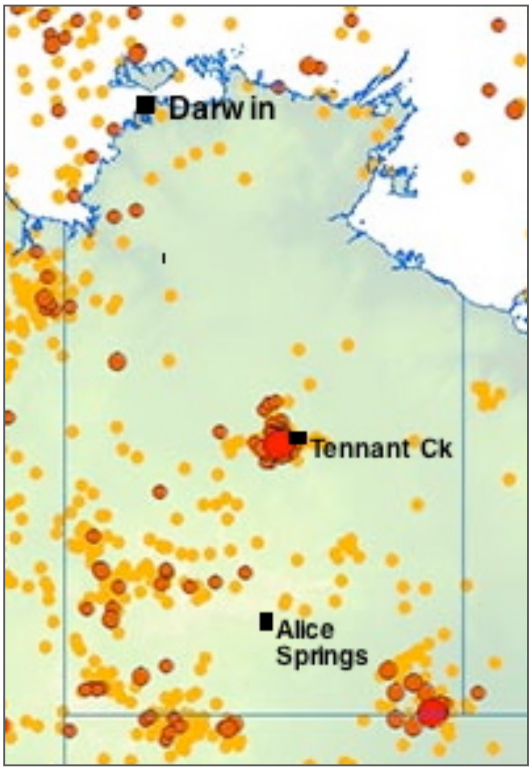
Having filled most of the gaps in catalogued records of Northern Territory earthquakes from 1869, I have used the assigned intensities to reassess the relative earthquake hazard at Darwin, for use in the loading code. On this analysis, Darwinians can expect minor damage every few decades and serious damage once per century with a worst-case earthquake, magnitude 9 on the nearest segment of the plate boundary, 500 km away, expected to cause significant damage. This analysis implies a slightly higher hazard than that in the current code in Australia but is much higher than the assessment by Geoscience Australia dated 2012.

An in-house earthquake hazard appreciation and capacity needs to be developed in the Northern Territory government since it is responsible for public safety, oversighting building construction and infrastructure robustness there.

Keywords: Northern Territory seismicity, earthquake hazard, building code

Introduction

The Northern Territory has two distinct sources of earthquakes; like the other Australian states and territories there are local intraplate earthquakes, but in addition large earthquakes on the nearby plate boundary to the north regularly shake the city. Perhaps this regularity has made the population, insurance companies and government officials complacent. There is no public information or advice about earthquakes for residents of Darwin, no earthquake education for children in schools, and no oversight of engineers or the private certifiers making decisions about earthquake engineering in the territory.



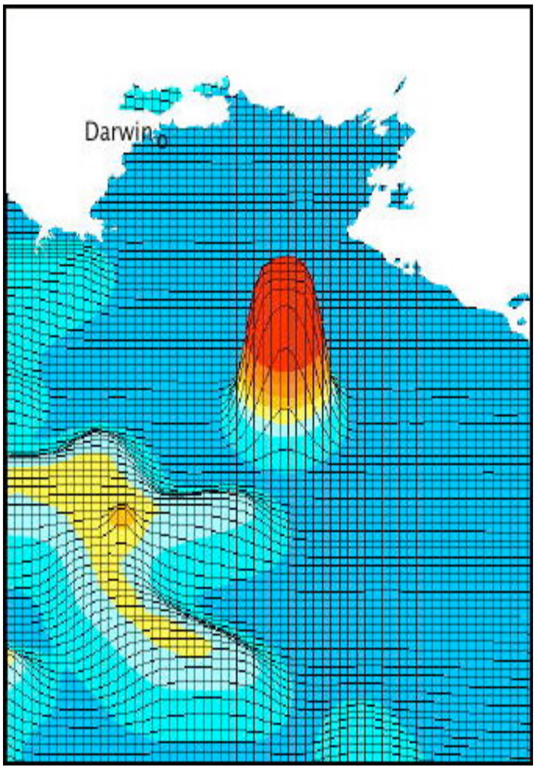


Figure 1. (left) Seismicity of the Northern Territory from the Geoscience Australia earthquake database, epicentres from 1901 to 2011, magnitude ≥3. Note the Simpson Desert epicentres SE of Alice Springs and the distributed earthquakes west and southwest of Alice Springs. The Tennant Ck. hotspot events are all post 1986. (right) Earthquake hazard assessed by Geoscience Australia (Burbidge, 2012), note the negligible hazard in the Simpson Desert.

Since 1869 city buildings have suffered minor damage in nine separate earthquakes. Even Government House has twice suffered damage. The worst case was in 1963 when an airport hangar and modern tall buildings in the city were damaged, occasioning an inspection by engineers employed by the then Commonwealth Department of Works (unpbl. report by CommWorks).

A megathrust magnitude 9+ earthquake on the plate boundary 500 km north of Darwin is a plausible threat and would cause significant damage. Such megathrust earthquakes occurred offshore Sumatra and Honshu Japan in the last decade where none were known to have occurred previously despite a long historical record. The rate of plate collision north of Darwin is between the rates at Sumatra and northern Japan, and the Sunda Arc plate boundary (~3000km long) is quite capable of accommodating such a great earthquake.

Large intraplate earthquakes, magnitude 6 or more, occurred near the NT/SA border, in 1941 and 1986, near the NT/WA border in 1970 and at Tennant Creek in 1988 and such earthquakes pose a hazard to the Territories' built infrastructure, buildings and lifelines. Other smaller intraplate earthquakes near Alice Springs and Katherine have been 're-discovered' and tabulated though the location and size uncertainties are large (see McCue, 2013 - member contributions on the AEES website www.aees.org.au).

The current Loading Code AS1170.4 rates Darwin's Z factor as 0.09, only slightly lower than Adelaide and Newcastle however a recently published assessment by Geoscience Australia has Darwin rated an equivalent value of 0.02. Both can't be right! This paper investigates an alternative approach to assessing which of these two estimates is in the ballpark.

Analysis of the intensity observations

We are reasonably sure that all felt earthquakes in Darwin above MM intensity 4 have been tabulated since 1869 (McCue, 2013), most of them extracted from newspaper accounts. In the histogram of Figure 2 we have only plotted those since 1904 when the International Seismological Summary (forerunner of the ISC) was established and began publishing a worldwide earthquake catalogue. This enabled targeted searching of newspapers and other sources such as the ISC reports themselves.

Assessing intensity is challenging in a place like Darwin, where the shaking is felt for minutes rather than seconds during distant earthquakes on the plate boundary and where buildings have been designed to resist strong cyclonic winds. Duration of shaking is not a parameter that affects the response spectrum but surely contributes to the cumulative damage once the damage threshold has been reached. Buildings in Darwin can be expected to be more resilient to earthquake loading than in other Australian cities due to the wind strictures on design. At least the roof should be tied to the frame and the frame in turn tied to the foundations providing a known load-transfer path.

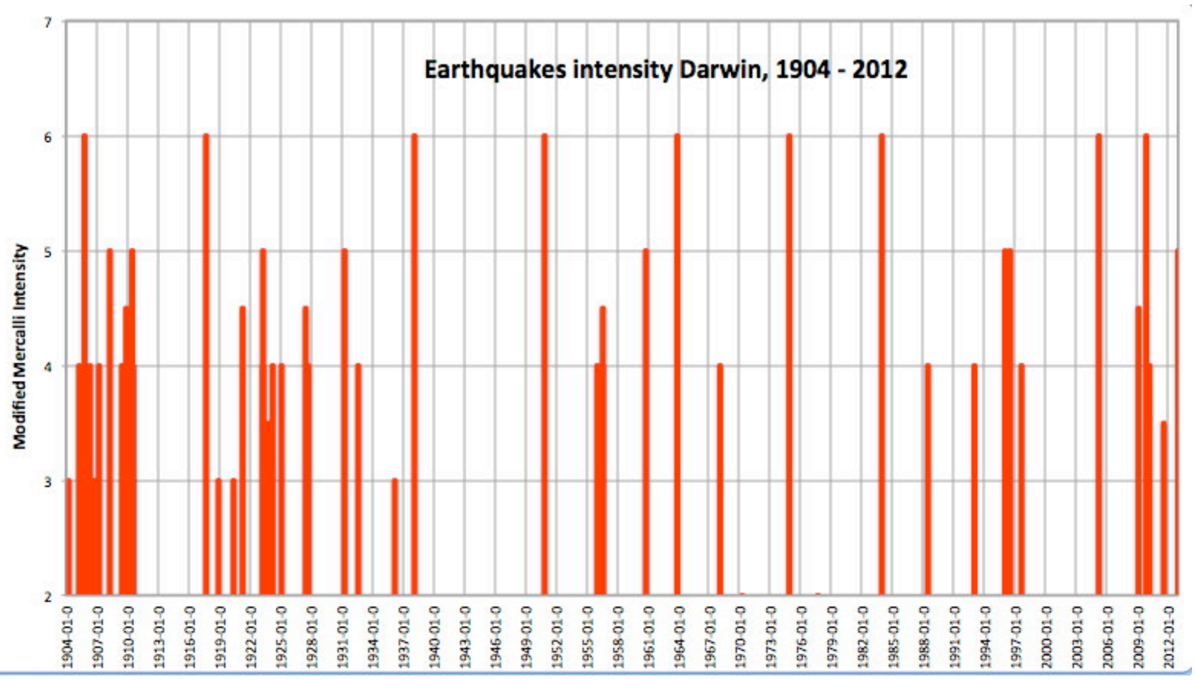


Figure 2 Histogram of intensities observed in Darwin between 1904 and 2012 (from McCue, 2013).

The largest known earthquakes in the Territory were in a remarkable sequence near Tennant Creek that included three large earthquakes of magnitude 6.3, 6.4 and 6.7 in a twelve-hour period on 22nd January 1988. Many thousands of aftershocks have since been recorded, and whilst the rate has decreased it has not yet, 25 years later, returned to its pre-1987 level which was just about zero for the previous 20 years after the Warramunga seismic array was installed there in what was recognised as a 'quiet' site to monitor underground nuclear explosions. A precursory sequence of earthquakes initiated in January 1987 but had apparently all but ceased.

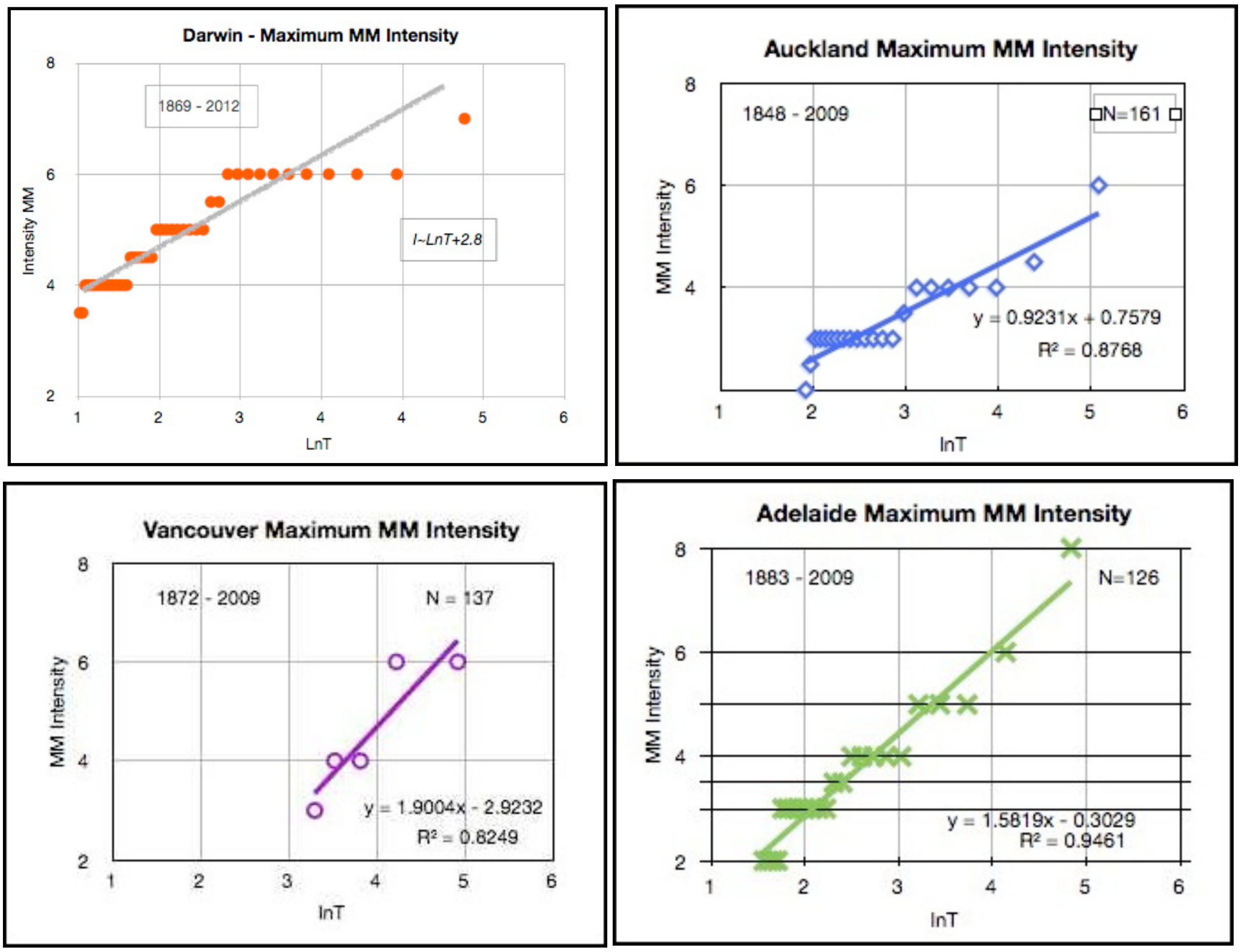


Figure 3 Type-1 extreme-value distribution of MM intensities observed in Darwin Northern Territory, Auckland New Zealand and Vancouver, Canada. The period of observations is shown. Obviously Darwin is at higher risk than either of the other two cities that are similarly located 300km or more from the nearest plate boundary. Values on lnT of 0, 2.3 and 4.6 correspond to return periods 'T' of 1, 10 and 100 years where ln is the natural log.

The big difference between the three near-plate boundary regions is obviously the attenuation. Several major earthquakes in the Banda Arc, including those of 1963 and 1977 shook tall buildings in Adelaide and Perth enough for the occupants to evacuate the buildings, several thousand kilometres from the source. Thick, cold continental crust of the Australian Plate is now colliding with oceanic crust of the Eurasian Plate, or a subplate of that plate, at the subduction zone. In Canada and New Zealand, thin, warm oceanic crust is on either side of the plate boundary. Crustal attenuation is high and plate velocities lower off the east coast of NZ and west coast of Canada than offshore Darwin so that few earthquakes have been felt let alone caused damage as far as Auckland or Vancouver.

A similar study for Adelaide shows that the earthquake hazard there is slightly lower than that in

Darwin, fewer earthquakes are felt in Adelaide though the source regions couldn't be more different. That is not to say that there are no nearfield earthquakes to Darwin (see Figure 1). There is a low, but not negligible, risk of a Simpson Desert, Lake McKay or Tennant Ck earthquake sequence occurring nearby.

Using magnitude to determine recurrence relations in a standard PSHA analysis limits the database to the post-1917 sample (or post-1965 in the GA study). Using the record of past intensities we have the complete known record all the way back to 1869 without unnecessary assumptions about the location, focal depth or magnitude of the causative earthquake, or having to arbitrarily choose an attenuation relationship developed elsewhere, from the myriad on offer.

A standard Type-1 extreme-value analysis lends itself to this extensive dataset, even though multiple events in a year are condensed to the largest one, a bit like excluding aftershocks (the majority of events in the Northern Territory) in a standard recurrence relationship. It is clear that intensities below MM4 are rarely reported and at the other end of the scale the difficulty of assessing intensity at the strong shaking end, in an environment where buildings are better designed and built due to the risk of cyclones, becomes apparent. This is compounded by the lack of published reports such as that produced but unpublished by CommWorks after the 1963 earthquake.

Table 1 Predicted intensity return period in Darwin

Intensity MM scale	Return Period years
6	15-40
7	40 – 100
8	100-300
9	>300

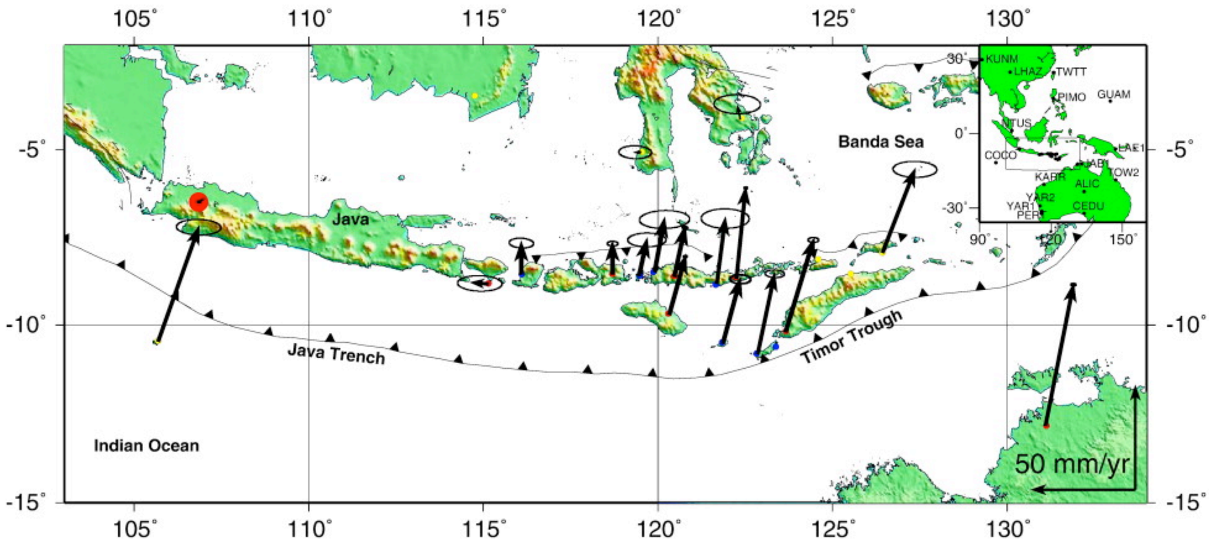


Figure 4 One version of the plate boundary geometry north of Darwin (from Nugrohoa, and others, 2009). The GPS measurements show the direction and relative velocity at selected sites (arrows with uncertainty ellipse). The arrow heads on the trench and trough show the direction of

subduction. The GPS site south of Darwin is in a former GA seismograph vault. The other site on the Australian plate is on Cocos Is.

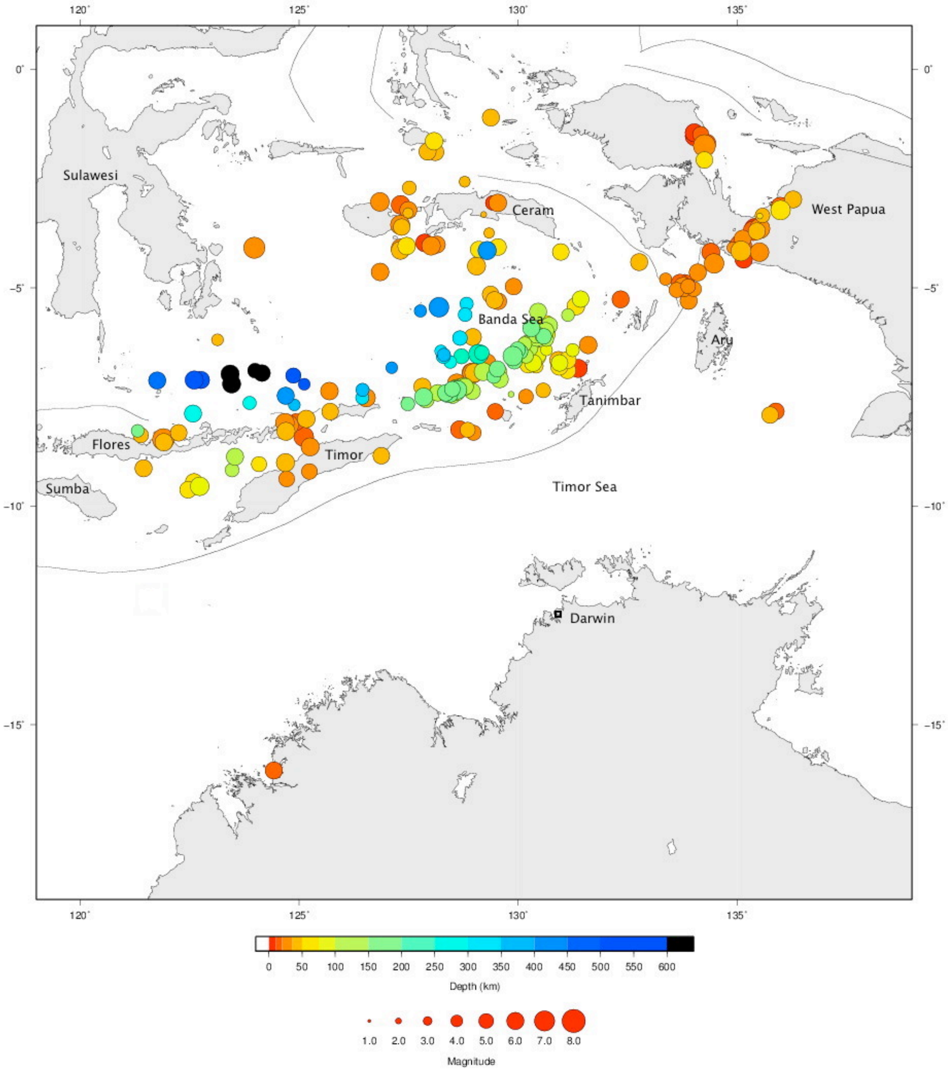


Figure 5 Seismicity of the Sunda Arc within 10° degrees of Darwin, magnitudes greater than 6.2, 1990-2010 (map generated using the ISC online Bulletin Search). In this time window we can assume that the locations are much more reliable than in earlier decades.

Vancouver Canada

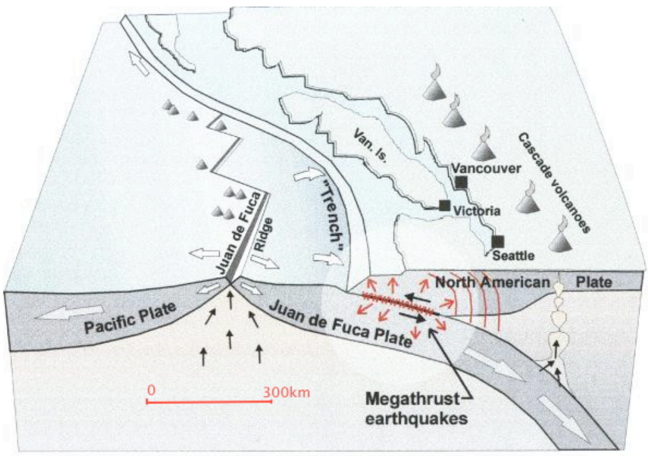


Figure 6 Plate geometry near Vancouver Canada. http://www.earthquakescanada.nrcan.gc.ca/zones/westcan-eng.php

There are not many places on Earth that face a similar hazard scenario to continental Darwin; ~400 km from the trench marking the edge of the nearest plate boundary, a subduction zone and island arc in oceanic crust fronting a continent. The Australian plate is moving at about 50mm/yr with respect to the Sunda Arc. Similar but different scenarios that come to mind are Vancouver Canada and Auckland NZ.

The Juan de Fuca sub-plate is being created at the Juan de Fuca Ridge to the west and subducted to the east under south-western Canada at the Cascadia Subduction zone at the rate of 25 mm/yr. The trench is about 300 km west of Vancouver. The main difference is in the polarity of subduction, in northwest Australia the slab dips away from Darwin whereas in southwest Canada it dips towards Vancouver though being relatively recent the slab is short, not extending far into the mantle, despite the cartoon.

Huge subduction earthquakes are thought to have occurred every 300-800 years along the Cascadia subduction zone based on geological evidence. This rate of megathrust earthquakes is comparable to the rate derived above for the Sunda Arc even though the plate velocity north of Darwin is about twice as fast as it is off Canada's Vancouver Island. That doesn't make sense unless the stress drops at the plate interfaces are very different. More likely the large uncertainty in recurrence intervals masks the true average rates of great earthquakes.

Auckland New Zealand

Figure 7 The city of Auckland is built on the Australian Plate about 300km west of the plate boundary (red dots) off the east coast of the North Island of New Zealand, where the Pacific Plate subducts beneath the Australian Plate.

I have taken all the felt reports available e.g. Downes, 1995) and Bulletins of the NZ Society for Earthquake Engineering to compile the hazard curve for Auckland in Figure 3. Surprisingly few earthquakes are felt in Auckland and the highest rated intensity is MM6, only minor damage observed.

Attenuation

A sense of the attenuation of seismic waves travelling between the Banda Sea and Darwin can be gained from the following intensity plot of Figure 5 where the data in Table 4 of McCue (2013) are plotted in the various magnitude bins shown of half-width 0.25 magnitude units.

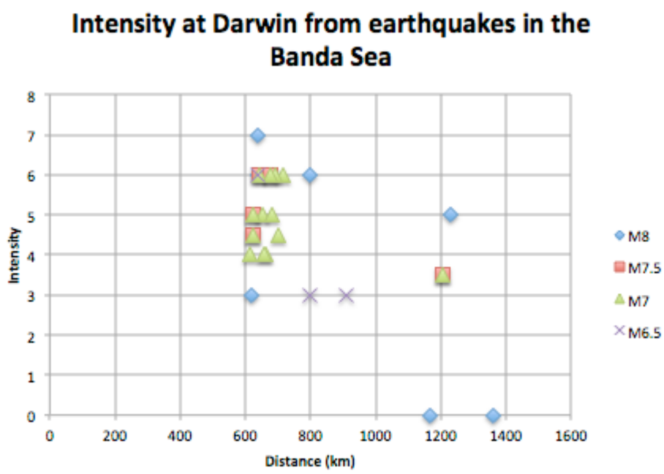


Figure 8 Intensity at Darwin vs focal distance for events in 0.5 magnitude bins centred on the magnitude shown. The blue diamonds are for a magnitude range 7.8 – 8.3. There is one outlier, the 1918 earthquake, which points to either a poor location (~1000km out), or a poor assessment of intensity (4 units), given the GUTE magnitude assessment is correct. Note that no allowance has been made for focal depth, there was not enough data for that.

The 1918 earthquake in the Banda Sea

Checks were made of felt reports and the ISS location:

The *Northern Territory Times and Gazette* Saturday 23 November 1918, reports:

(page 18) There was a most distinct shock of earthquake felt in Darwin at about ten minutes past four o'clock on Tuesday morning.

BROCKS CREEK NOTES

Our Brock's Creek correspondent

(page 15) writes, under date 20.11.18: "We had a slight earthquake shock at a quarter past 4 on Tuesday morning. I heard it coming a long way off, travelling from west to east. The tremor lasted just two minutes. The whole house trembled and shook, everything was rattling and shaking —gives one an uncanny feeling.

An Adelaide newspaper mentions that the earthquake was also felt at Brocks Ck, River Katherine and Daly Waters. The Riverview Bulletin states that it was felt in Timor and the Aroe Is.

These are hardly accounts of severe or damaging shaking but four days had passed between the earthquake and publication of the newspaper. Perhaps the intensity could be better rated an intensity of MM4 to 5 rather than MM3 but even so the location has to be a problem.

The second smaller earthquake was also felt:

Another earthquake was registered by the seismograph at the Adelaide Observatory on November 24. The record shows that the centre of the disturbance was some 1,900 miles distant. A previous shock which occurred on the 19th inst. was centred in the Arafura Sea, and it is probable that this one also originated there. It was felt at Darwin, whence the following report was received: — 'Earthshock at 8.30 a.m., commencing with low rumbling sound like distant thunder in the south; vibration at first light, latter part very strong, dying away in northerly direction; duration two to three minutes.' The data of the Adelaide record are as follow: — First preliminary. 8h. 33.8 min. a.m.; second preliminary, 8h. 38.3 min.; maximum phase, 8h. 44 min.; maximum amplitude, 12.8; duration, lh. 33 min.

The ISS Location

The ISS and GUTE solutions are published on the ISC Bulletin available on line and shown in the table below. Under the new ISC-GEM project, (www.isc.ac.uk/iscgem/) this event was relocated recently, but being deep they did not re-compute the magnitude due to a lack of data. The ADE and RIV seismographs for example were saturated by the ground vibration, the seismometers hitting the stops. As a result this event is not listed in the main ISC-GEM catalogue but in an Appendix.

Table 2 Banda Sea Events of November 1918 located by various agencies, both felt in Darwin

Date	Time	Latitude °S	Longitude °E	Depth	Ms PAS	Author
1918/11/18	18:41:45	-8.0	127.5	223.0		ISS
	18:41:55	-7.0	129.0	190.0	7.8	GUTE
	18:42:06.3	-6.76	129.64	225		ISC-GEM
	18:41:55	-10	130	-		Pigot
	18:41:45.5	-7.08	129.73	225		ASC
1918/11/23	22:57:45	-8.0	127.5	223.0		ISS
	22:57:55	-7.0	129.0	190.0	7.2	GUTE

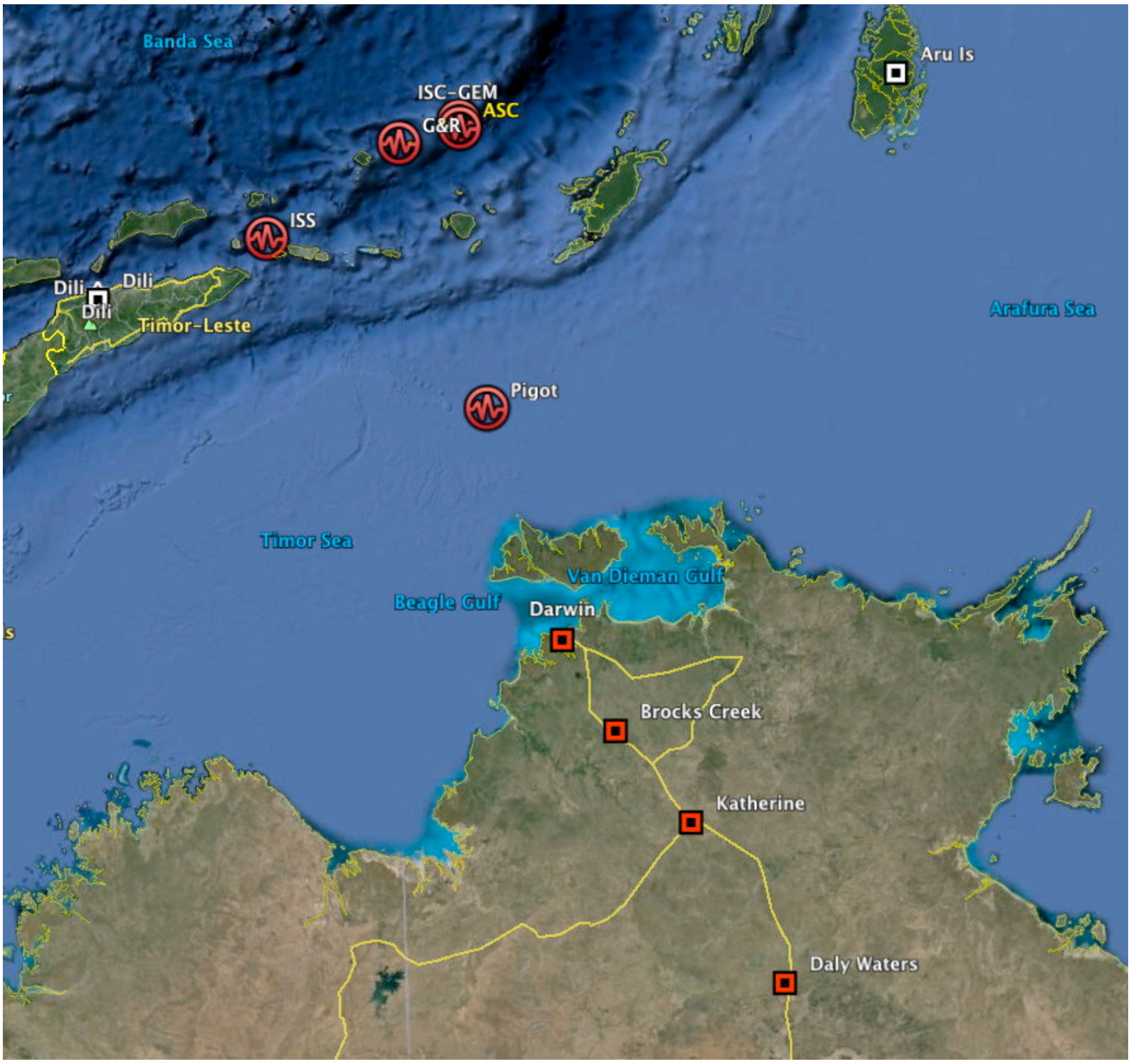


Figure 9 The various estimates of the epicenter of the 18 November 1918 earthquake as listed in Table 2 above. Pigot's estimate is remarkable given it was a single station calculation made within days of the event. The earthquake was reported felt at the places marked with a small square (Darwin, Dili, Aru Is, etc).

(ISS comments "Direct comparison of the records of these earthquakes suggests that they have the same origin. A focal depth 0.030 below normal has therefore been assumed, as also for the same epicentre on Nov 23 at 22h., though the evidence of the anticentric stations is not clear. The residuals suggest that the epicentre is further east, say at 8.0°S 129.0°E, but the material is not quite good enough to give a secure determination.)"

Phase arrivals were reported to the ISS and provided by the ISC, some were published in contemporary Australian newspapers and the Riverview Bulletin that has recently been scanned by Geoscience Australia.

A revision of the epicentre was made by the author using a filtered set of the ISS data, just the 9 nearest stations including PER, ADE and RIV over as wide a range of azimuths as possible (gap 123°), the nearest station DJA was 2530km away (two reporting Taiwan stations were deferred, not included in the location because of large residuals). Pity about the lack of a station at Darwin! The depth was not well constrained, 80km if the S arrivals at DJA and RIV are incorporated but 225km if just the P arrivals were used.

The upshot is that if the intensities were only minor 4 to 5 MM, and the location is about right, then my first assumption is incorrect ie the magnitude is not as large as computed by Gutenberg and Richter, not 7¾ (7.8 for the computer) but perhaps 7¼ (7.3) the same reduction as for the 1906 earthquake off the NW coast of Australia. Abe has apparently rated it MB7.5.

What started off as an investigation of attenuation led to a magnitude correction for the major 1918 Banda Sea earthquake. If this is incorporated into the Intensity/distance plot we obtain Figure 10.

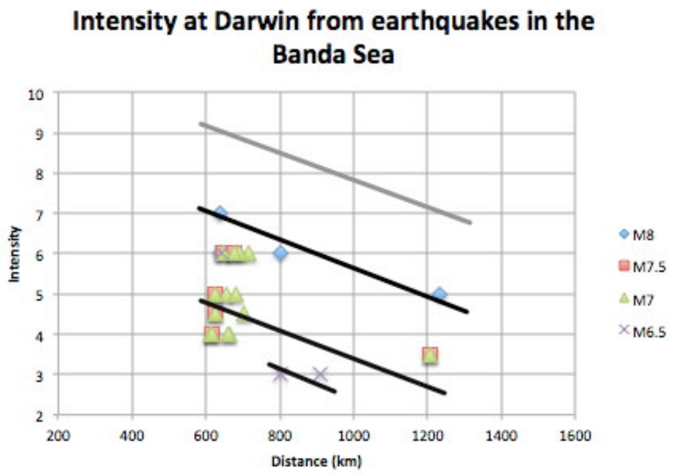


Figure 10 Intensity/Distance plot with corrected 1918 magnitude and attenuation trend lines for M6.5, M7 and M8. The top grey line is a possible intensity/distance plot for a magnitude 9 earthquake extrapolated from the magnitude 7 and magnitude 8 lines.

The figure suggests that the maximum intensity from a mega-thrust earthquake on the nearest part of the plate boundary would generate MM9 levels of ground shaking in Darwin.

Strong Motion Data

A growing database of strong motion records from Darwin, whilst not sufficient to generate site-specific relationships, gives a more useful indication of which relationships may apply in this context. Six accelerograms were obtained in Darwin in the year 2000 alone.

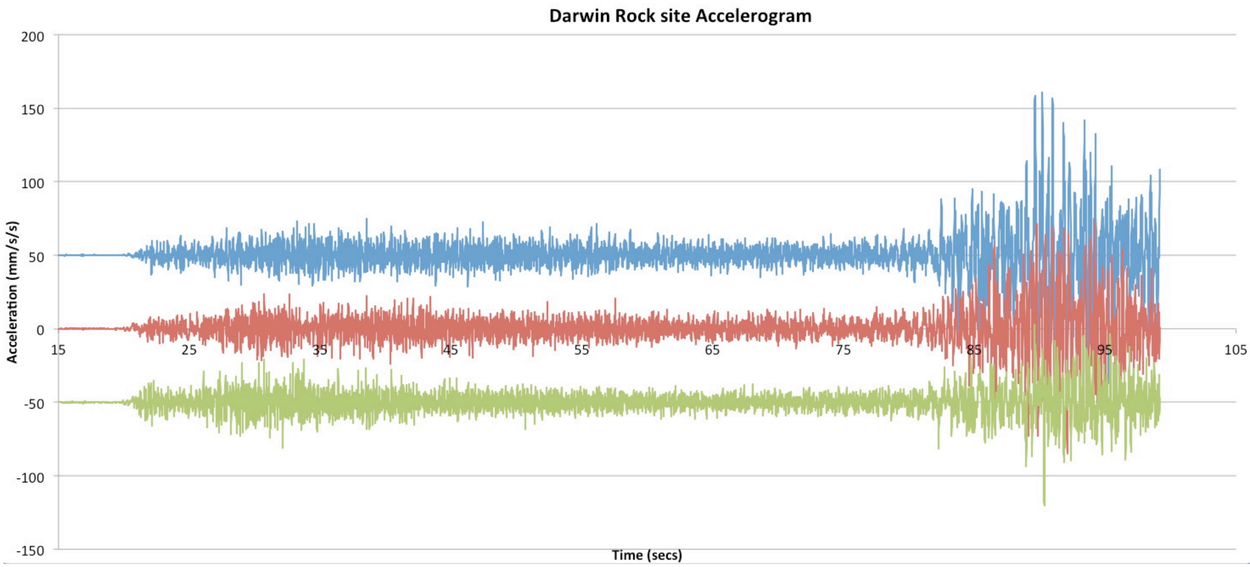


Figure 11 The ground motion East (blue), North (red), Up during the Christmas Day 1995 major earthquake was recorded in Darwin on accelerographs at two sites, Parliament House (soft

foundations DPH) and the Department of Mines and Energy Rock store (rock foundation DRS). Note the lack of surface waves due to the focal depth of 100km. The DRS accelerograph stopped recording after about 100 seconds but captured the main shaking in the 'S' wave. This verifies the early reports suggesting that the shaking was observable for minutes rather than seconds.

1995 12 25 04:43:25 UTC, Banda Sea, magnitude Mw7.1 This major earthquake at (6.94°S, 129.18°E) due north of Darwin, was felt in the Northern Territory and northeast WA. The ISC assigned focal depth was 133 km. Gregson (in McCue and Gregson, 1997) drew up the isoseismal map and rated the intensity in Darwin and on Bathurst Island MM5, at Katherine, Jabiru and near Kununurra MM4. In Indonesia intensities ranged from MM6 at Saumlaki, to 4 at Ambon and Tual and 3 at Sarong and Nabire.

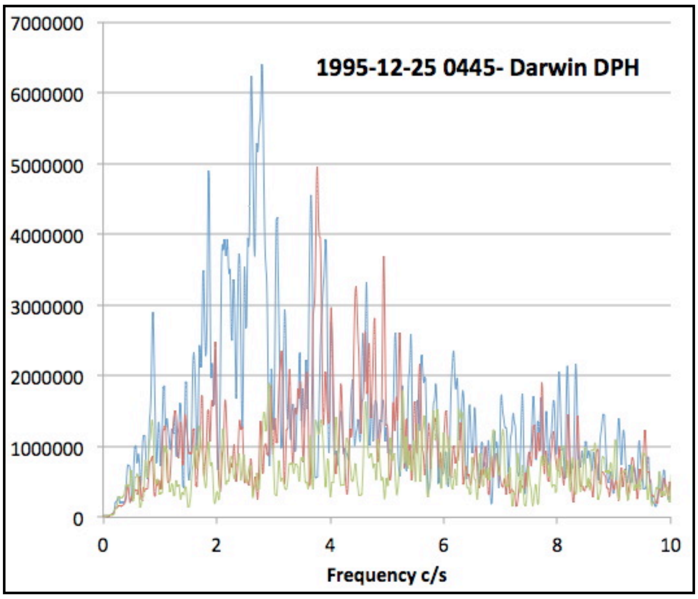


Figure 12 The Fourier spectrum of each of the three components of the Parliament House recording DPH shows that the main energy release was in the 2-4 Hz band in the E-W direction with a corresponding low in the N-S and vertical directions – clearly the 'S' wave. There is also a prominent peak at about 0.8Hz.

A surprising feature of this accelerogram is the strong shaking in the 2 to 4 Hz range, which is the range of natural periods of buildings with 2 to 5 stories. Had this been a shallow earthquake the ground shaking would have been even more severe with an additional substantial longer-period component from surface waves.

Discussion

Interplate earthquakes are the principal but not the only source of risk in the Northern Territory as the recent historical record shows. Known large intraplate earthquakes include the 1937/41 Simpson Desert, the 1970 Lake Mackay, 1986 Marryat Creek and most recently the 1987/88 Tennant Creek earthquake sequences in the region.

We are still struggling to explain intraplate earthquakes in a way that will improve earthquake hazard assessments over the uniform seismicity model and that will educate the public. The oft repeated public statements by public officials such as that in the *Courier-Mail* of Thursday 3 February 1938, page 12 have not helped the public perception of earthquake risk in Australia:

> *We seem to live within a magic circle, for while destructive earthquakes are common enough in the Dutch East Indies, New Guinea, the Solomons, New Zealand, and in other regions just beyond our coasts, not one life has been lost in Australia itself.*
>
> *It seems, too, that this happy state of affairs should continue indefinitely. It may be that from time to time we shall, as yesterday, find ourselves on the fringe of a major disturbance, and, again, from time to time we may expect a minor disturbance of our own, such as those experienced in south eastern Queensland in 1918 and in 1935. But every scrap of seismological evidence yet collected, and every geological argument*

yet advanced, points to Australia as one of the most stable parts of the earth's crust. We are as near as may be earthquake-proof.

The two deaths following the 1902 'Warooka' SA earthquake and the major magnitude 7.2 earthquake in 1906 off the central WA coast seem to have been forgotten or discounted by many, including politicians, journalists and even earth scientists.

I have transcribed the record of felt earthquakes in some detail and in several cases have been able to estimate the location and magnitude of the earthquake that they can now be added to the useable database. More and better estimates of epicentre and magnitude could be obtained with information on their effects in Indonesia and search through early seismograph bulletins.

The May 1909 (McCue, 2013) earthquake is about as close as interplate earthquakes get to Darwin. A great megathrust earthquake on this section of the plate boundary is plausible so special care should be taken for vulnerable or non-standard structures, and more strong motion instruments should be installed in the area. Recent strong motion data recorded in Darwin could be extrapolated to estimate the ground motion in this maximum credible earthquake. The amplitude of ground shaking at Darwin obtained by simple extrapolation of recent strong motion records (e.g. McCue and others, 2001) would result in a pga in excess of 1g at a period of about 0.25s; now that would be destructive.

The possibility of a megathrust earthquake, magnitude 9 or more, on the nearest plate boundary and a large intraplate earthquake should be taken into account by politicians, town planners, emergency planners, engineers and architects in the Territory. Installing more accelerographs now would be a start, to collect more data for modelling both the strong shaking and building response. The data should be archived and made publicly available, the need for a central data repository is clear. Buildings such as hospitals, schools, ambulance and police stations, airport and port facilities etc., should be inspected by governments and strengthened if found vulnerable.

At face value this historical information implies that an earthquake would be felt in Darwin twice in every three years, on average, the city might suffer minor damage every 15 years or so and severe damage every 100 years or so. Another more in-depth risk assessment taking into account the historical seismicity is obviously required.

Note that the frequent earthquakes since 1988 are reminiscent of the pattern before the great 1938 earthquake.

Acknowledgment
Much of this new information has come about thanks to the Australian National Library (ANL) making scanned, searchable newspapers (1803-1954) publicly available on the internet. Earthquake information was obtained from the International Seismological Centre, *On-line Bulletin*, http://www.isc.ac.uk, Internatl. Seis. Cent., Thatcham, United Kingdom, 2011, and from NOAA, National Geophysical Data Center / World Data Service (NGDC/WDS) Significant Earthquake Database, Boulder, CO, USA. (Available at http://www.ngdc.noaa.gov/nndc/struts/form?t=101650&s=1&d=1) as well as from the on-line earthquake database and numerous publications of Geoscience Australia and its predecessors, particularly the annual seismological report series. I thank David Love for his helpful recommendations.

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