Short-term increase in earthquake risk at Macquarie Island

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Abstract: Major shallow earthquakes on the Macquarie Ridge in the past 100 years have exposed two seismic gaps, one centred on Macquarie Island. The Macquarie Ridge was created by crustal shortening due to oblique convergence of oceanic crust of the Pacific and Australian Plates. Computed earthquake mechanisms are either strike-slip or thrust. Earthquake hazard estimates for the island, such as the values of the 475 year hazard coefficient in the 2008 Australian Loading Code, do not take account of this gap, based as they are on a purely random distribution of earthquakes. A major gap-filling earthquake could have serious consequences for both the residents and environment of Macquarie Island. The impact of a major (M≥7) close earthquake on the island would be to cause widespread landslides, and water and power supply disruption if not building damage. Damage risk is heightened by the possibility, perhaps 50:50, of a local tsunami being generated, depending only on the mechanism of the earthquake. The risk is heightened for the next few decades, but reverts to the computed long term value at the end of this period of heightened activity. Coping with time varying hazard is a novel but critical problem.

Introduction (http://www.parks.tas.gov.au/macquarie/geology.html)

Macquarie Island straddles the segment of the Pacific/Australian plate boundary from south of New Zealand to about midway between Australia and Antarctica (Figure 1) at the triple junction of these plates with the Antarctic Plate at about 61°S, 162°E, some 650 km south of the island.

Figure 1 Location of Macquarie Island (USGS NEIC)

The Pacific Plate is under-thrusting the Australian Plate at 20 to 30 mm/year currently uplifting the ridge at an estimated 2 mm/year (2 km in the last million years). There are no Recent volcanoes on the island which was formed by uplifting of oceanic crust, not by volcanic activity, although pillow lavas outcrop on the isthmus at the northern end of the island.

Parallel with and 40 km to the east of Macquarie Island is the Macquarie Trench which is between 5000 m and 6000 m deep, separating the ridge from the Campbell Plateau. The geometry of the ridge-trench system divides the plate boundary into three segments: north of the Macquarie Trench, the deep trench (the Puysegur Trench) is on the opposite or western side of the ridge extending to the southwest coast of the South Island of New Zealand, and it again changes polarity 100 kilometres south of Macquarie Island (the Hjort Trench).

Seismicity

Jones and McCue (1988) summarised the seismicity as it was known up to 1986 including discussion of the first report of a felt earthquake on the island on 31 October 1815. Expeditioners wintering on the island since 1957 have reported 2 or 3 felt earthquakes each year. World earthquake databases contain information about the seismicity of the Macquarie Ridge from about 1901 for major $M7^+$ earthquakes and from 1962 for events above about magnitude 5.5. A seismograph has been operational on Macquarie Island since 1960 and provides an invaluable constraint on the epicentral locations. Up to 1986 no great earthquakes were known to have occurred along the ridge, the largest earthquake had a magnitude of 7.8. The study by Jones and McCue showed that the earthquakes originated under the ridge rather than the trench (Figure 2).

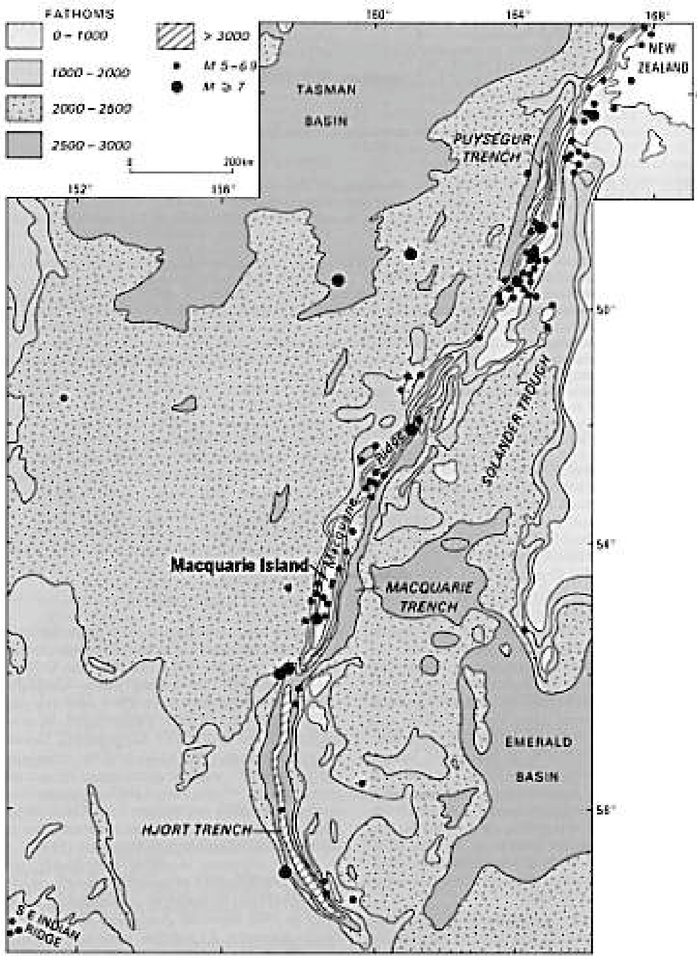

Figure 2 Seismicity of the Macquarie Ridge 1960 – 1986, M≥5.0 (from Jones and McCue, 1988)

The mechanisms of large earthquakes on the Macquarie Ridge up to 1984 were revised, where possible, and tabulated by Jones and McCue who also estimated return periods for earthquakes in different magnitude ranges. They computed a return period of 100 years for a magnitude 8^+ earthquake though none that large had been observed. On 23 May1989, the year after publication of their paper, the first known 'great' $M8^+$ earthquake occurred on the ridge, its epicentre 300 km north of the island. It was the largest earthquake recorded anywhere in the world during the 1980s. Shaking was strong on Macquarie Island, it caused widespread landslides but no serious damage. Shaking was reported as far as Tasmania and southern New Zealand. The mechanism was that of a strike-slip earthquake, yet a small tsunami was recorded in Tasmania and SE Australia.

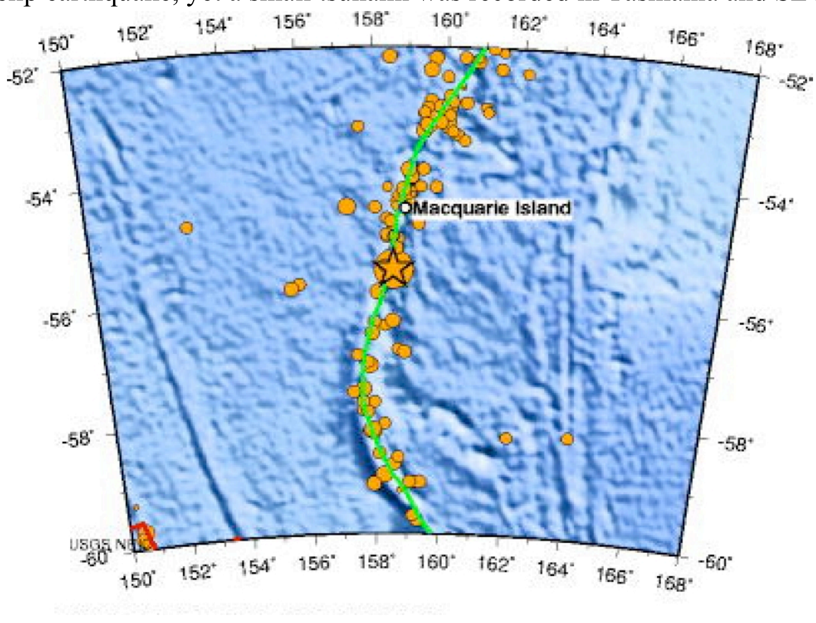

Figure 3 Seismicity of the Macquarie Ridge 1990 – 12 April 2008, M≥5.0 (from USGS NEIC).

Amazingly, not one but two 'great' earthquakes have occurred in the 24 years since the study of Jones and McCue. The second event occurred on Thursday, December 23, 2004 at 14:59 UTC (24 December 2004 at 01:59 am local time) its magnitude M8.1. The epicentre was centred about 400 km W of Auckland Island and 500 km NNE of Macquarie Island and was distant enough that none of the expeditioners on the island felt it, though it was felt throughout Tasmania and in southern New Zealand. This was also a strike-slip event. Expeditioners on the island reported that they had experienced small tremors over the previous few weeks.

Early in 2008 a M7.1 earthquake occurred on the ridge (the star in Figure 3), this time it was south of Macquarie Island and its mechanism was a thrust type. In the epicentral region of this event, the Australian Plate moves north-northeast with respect to the Pacific Plate at a rate of approximately 27 mm/yr. The epicentre of this earthquake on 12 April 2008 was 110 km south of Macquarie Island and 380 km south of the epicentre of the great 1989 earthquake epicentre.

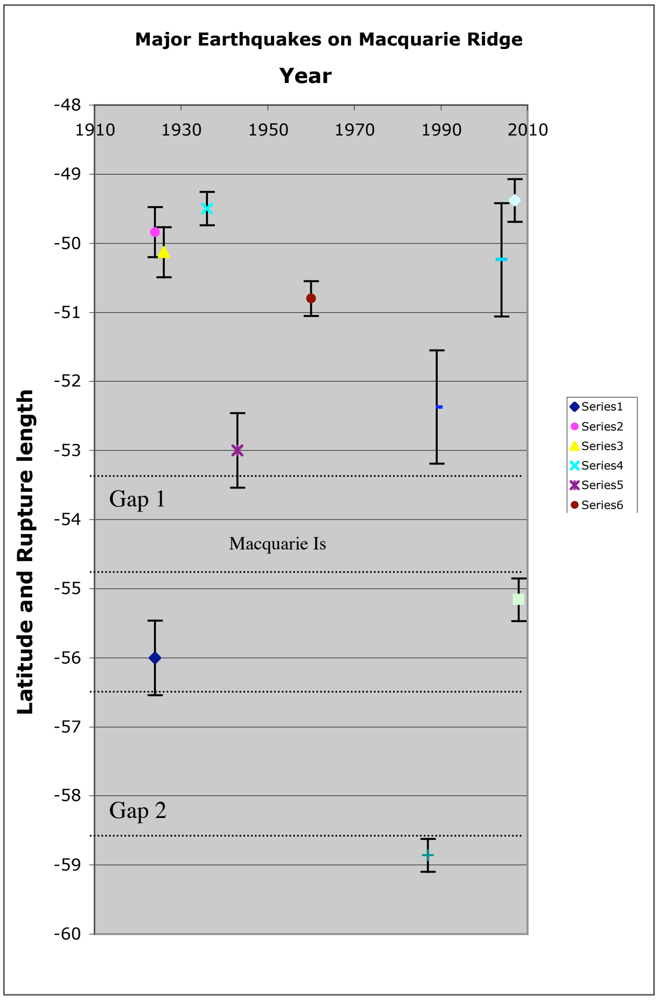

Figure 4 Major earthquakes with postulated associated faulting since about1901. The dashed lines outline the gaps.

Earthquakes since 1924 have ruptured the entire Macquarie Ridge between 49°S and 59°S apart from two gaps, one between the 2008 and 1943 earthquakes straddling the island, the other between the 1924 and 1987 earthquakes 220 km to the south of the island (Figure 4). The exact size of the gaps is uncertain because of the uncertainty in the location of the early earthquakes and the shape of their rupture zones.

We can estimate the size of the gap by making an estimate of earthquake rupture length as a function of magnitude on the Ridge. Das (1993) studied the few small aftershocks of the M8.1, 1989 mainshock, a strike-slip event and found they were distributed along a 220 km section of the plate boundary. She also concluded that slip was bilateral which is useful. Ruff and others (1989) estimated that the fault rupture length of the 1981 M7.7 thrust earthquake on the Ridge north of our study area was 100 km. Worldwide, the rupture length L of a magnitude M6 earthquake is about 10 km.

From these three events, relationships between magnitude M and rupture length L are:
$M = 1.64\log L(\text{km}) + 4.36$ or $\log L(\text{km}) = 0.6M - 2.6$
These are indicative relationships only with insufficient data to estimate errors.

If we assume that all events are bilateral, as indicated by scarce data, that the rupture zone of each earthquake is given by the equation above, and that the relocated early epicentres are good, then the gap near the island is at least 130 km long, sufficient to generate a magnitude 7.9 earthquake, or several magnitude 7+ events. The southern gap, though larger, is too far from the island to be a cause of damage.

Update of recurrence data

Major events on the Macquarie Ridge are listed in table 1. including an additional 20 years of data additional to that used by Jones and McCue. This has been used to revise their recurrence estimates as summarised in figure 5 and table 2.

Table 1 Major shallow earthquakes on the Macquarie Ridge since 1901

Date	Time	Latitude	Longitude	M
19360222	153154.0	-49.5	164.0	7.2
19870903	64011.82	-58.859	158.476	7.2
19601213	73616.4	-50.8	160.3	7.25
20070930	52335.0	-49.38	164.01	7.4
20080412	3016.0	-55.16	159.04	7.4
19240724	45517.0	-49.84	160.08	7.5
19261003	193801.0	-50.13	159.43	7.5
19240626	13734.0	-56.0	157.5	7.8
19430906	34130.0	-53.0	159.0	7.8
19890523	105446.24	-52.371	160.642	8.1
20041223	145904.0	-50.24	160.13	8.1

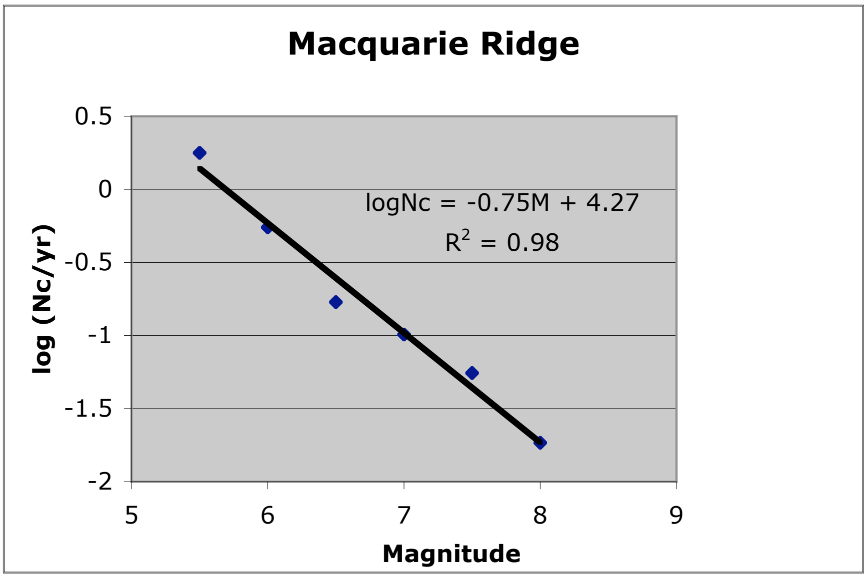

Figure 5 Computed recurrence relation, cumulative number of earthquakes above magnitude M recorded between 1901 and 2008 (Ms/Ww≥7), and 1962 – 2008 (Mb≥5.5).

The slope or 'b' value of the line in Figure 5 of 0.75 is just outside the error range of the average value of 0.97 (±0.2) found by Jones and McCue with the shorter observation time. Despite that, predicted magnitudes for the chosen time periods of 1, 10 and 100 years are similar in the two studies (see table 2 below), the difference within the scatter of magnitude estimates reported for individual events (eg the tabulated magnitude of the great earthquake of 24 December 2004 varied from 8.1 to 8.4 between international seismological agencies). Problems arise using 'b' values when the time period is extrapolated beyond the observed-data range. In this case, despite the very different 'b' values, estimates of magnitude recurrence times within the 100 year observation range are robust.

Table 2 Predicted magnitudes for specific earthquake recurrence times on the Macquarie Ridge

Return Period (years)	1	10	100	
Magnitude	5.7	7.0	8.3	this study
Magnitude	6.2	7.2	8.2	Jones and McCue (1988)

Discussion

Earthquakes do not occur at regular intervals but are clustered in time and space. On plate boundaries there may be coupling between events that determines this behaviour (earthquakes on the North Anatolian Fault since 1934 clearly migrate from east to west along the fault, behaviour that is strongly non-stochastic). Hazard estimates using data such as that in the above table average the time between events over several cycles and neglect the short-term increase in hazard during an earthquake cluster.

On the evidence of earthquake activity since 1989, it is concluded that a seismic gap about 130 km long is centred on Macquarie Island, and that we are at the height of the earthquake cycle. Therefore, there is a heightened risk of a major earthquake occurring near the island in the next few decades.

Such an earthquake would cause severe landslides and threaten vulnerable facilities such as the diesel generator, diesel-tank farm, communications systems and water supply. The living quarters are unlikely to suffer structural damage as they were built to survive strong wind speeds.

In addition, should a major earthquake occur, there is a high risk that consequent events such as a tsunami and damaging aftershocks will follow.

The Australian Government is responsible for the welfare of the expeditioners on this very remote island and for the environmental consequences of a major fuel leak. They should develop a strategic plan to provide a rapid response should a major earthquake occur there.

References

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