Earthquake hazard in northeastern Tasmania

Report for KUTh Energy
by
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Introduction

The scope of this study was set out by Dr Fiona Holgate, operations manager KUTh Energy in an exchange of emails with the author in July/August 2010:

1. A review and evaluation of existing work on natural seismic hazard and crustal stress conditions in Tasmania.
2. An appraisal of available legacy earthquake database for Eastern Tasmania.
3. Identification of suitable (or best available) seismic velocity, ground motion & site response models for Eastern Tasmania.
4. An updated (qualitative) assessment of the natural seismic hazard in Eastern Tasmania with specific emphasis on the CL and NF sites.
5. A qualitative appraisal of the potential impact of induced and/or triggered seismic events in the areas around NF & CL by analogy with existing EGS projects & given local population distribution, geology etc.
6. Appraisal of crustal stress conditions in eastern Tasmania including refinement of the Midlands FMS.
7. Recommendations for future data acquisition based on existing data gaps in both seismic and local geological/land use data for both broader Eastern Tasmania & for NF/CL in particular.

1 (i) Review of earthquake hazard

The first published estimate of earthquake hazard in Tasmania was the study by McEwin, Underwood and Denham in 1976. Only two of their zones encroached onto Tasmania itself, one on the Southwest Cape and the other near Burnie based on a very small sample of earthquakes over the period1960-1972. Eastern Tasmania rated below 50mm/sec for the 500yr peak ground velocity and 0.1g for the 50 yr pga, the approximate values below which damage is not expected.

A study by the author (McCue, 1978) using a slightly longer database, 1958 to 1976, also found that the seismicity of Tasmania was low but that the western half of Tasmania and Flinders Island did rate zoning at 50mm/s in 500 year return period. The 50mm/s contour just clipped the northeast coast of Tasmania at the 1500 yr return period.

The earthquake hazard map in the current Australian Building Code from AS1170.4-2007 broadly reflects the geology of Tasmania. It shows the earthquake hazard decreasing evenly from 0.1g on the northwest tip of Tasmania to 0.04g at Schouten Island and then 0.03 g at Hobart. (The code specifies a dimensionless acceleration coefficient because 'g' is included in the weight of the building but I have used units of g for comparison). A probabilistic seismic hazard assessment was not done for the whole island, rather a few

places were investigated and then a committee sat down and drew contours of hazard based on their knowledge of the seismicity.
An interesting feature of such studies worldwide is the propensity for mapped hazard to increase with time as the database grows, as more is known about historical seismicity and paleoseismology, and better models are developed for attenuation and source zones. All these studies agree that the seismicity of the east coast of Tasmania is low but non zero (see Figures 1,2 and 3).

The only known evidence for the occurrence of large (M≥6) onshore Tasmanian earthquakes in the past 50000 years is in south-western Tasmania (Clark and McCue, 2003).

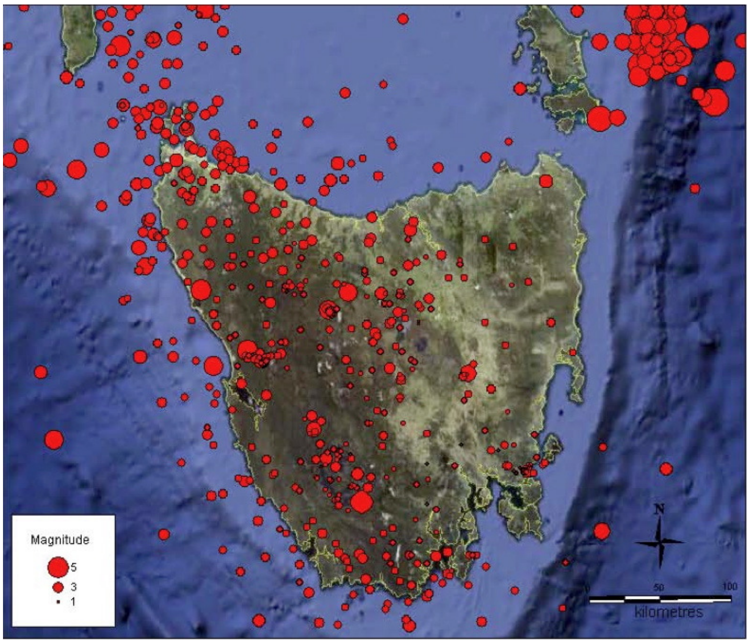

Figure 1 Seismicity of Tasmania, 1880 – 2010 (from Payne and others, 2010)

The high hazard rating east of Flinders Island reflects the series of large earthquakes there between 1887 and 1892 and again in 1946, the latter the only one accurately located. We assume that such earthquakes could occur anywhere in continental crust within the Australian Plate. There is no explanation as to why or when they occurred.

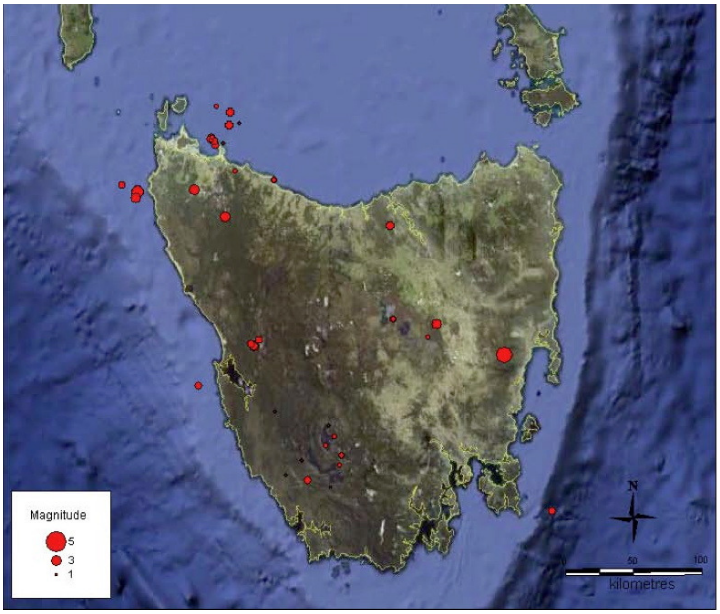

Figure 2 Seismicity of Tasmania, 2009 (from Payne and others, 2010)

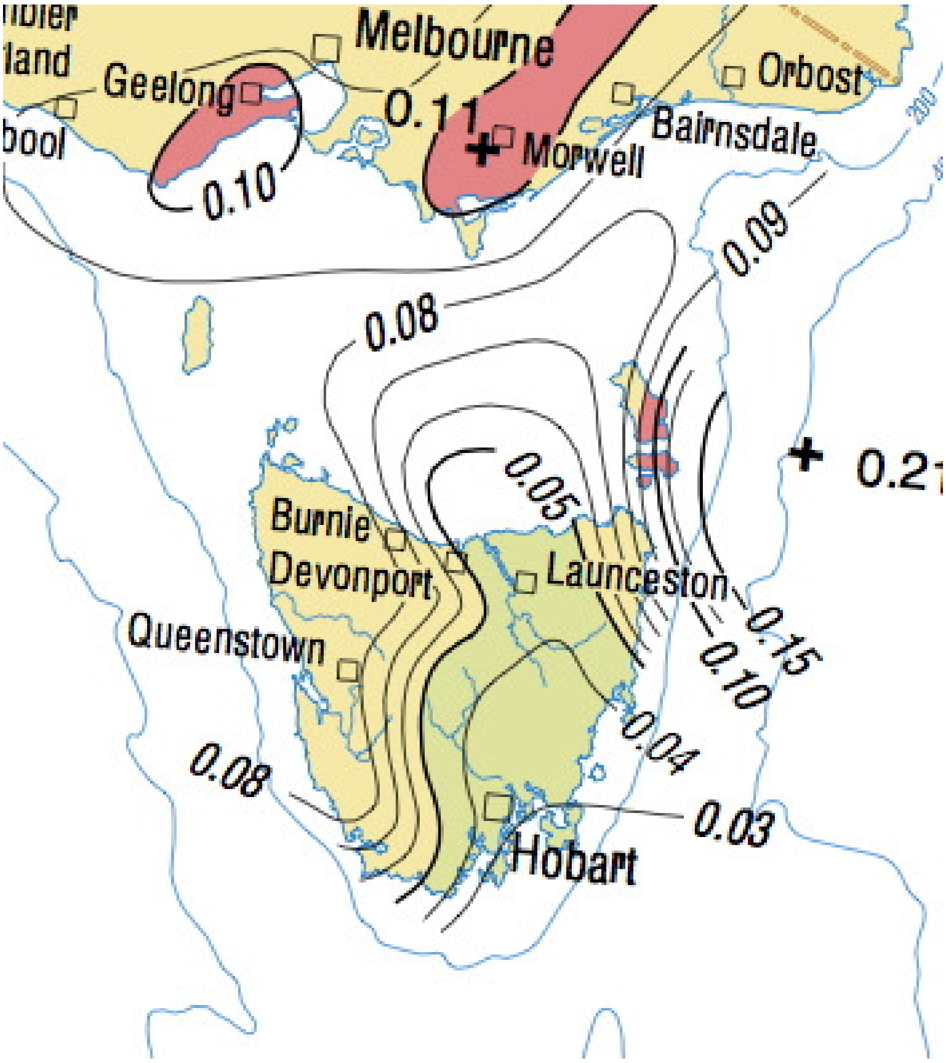

Figure 3. Earthquake hazard map of Tasmania (AS1170.4 – 2007)

One of the interesting and least understood features of the seismicity of Australia is the occurrence of earthquake swarms, hundreds or even thousands of small earthquakes concentrated in a small volume of the shallow crust. Such swarms are akin to earthquakes induced by hydrofracturing of the crust to create reservoirs for geothermal energy production or even to those induced by reservoir filling. Swarms are thought to be caused by natural changes in pore fluid pressures in the shallow crust. One such swarm occurred near Bream Creek in eastern Tasmania in 1987. but there is not enough quality data to examine the focal mechanisms. Roger Lewis commented that : *I was involved in local fieldwork on this swarm. We put out field stations and walked the countryside but saw nothing at the surface. It was very localized, virtually all the events being beneath a single farm paddock. The repeated events were producing structural damage in some houses. According to the farmer who owned and lived beside the said paddock there had been an earlier swarm there in the 1940's. It was apparent while operating the seismic net from UTAS that there were several other swarms over the years at remote locations. Also a concentration of events, possibly on the Lake Edgar Fault during the filling of Lake Gordon*.

1 (ii) Review of crustal stress in Tasmania

Extensive crustal stress measurements were made by and for the Tasmanian Hydro Electric Authority (now TasHydro) during the dam and power station construction phase of the hydro project in the 1960s. Some of the results are publicly available (see Hoek and Brown, 2003) but more are in the TasHydro archives. No Tasmanian data seems to have been used by modellers such as Cloetingh and Wortel (1986) and Sandiford and Egholm (2008), their inferred principal stress directions are at odds with the measurements (see Figure 4).

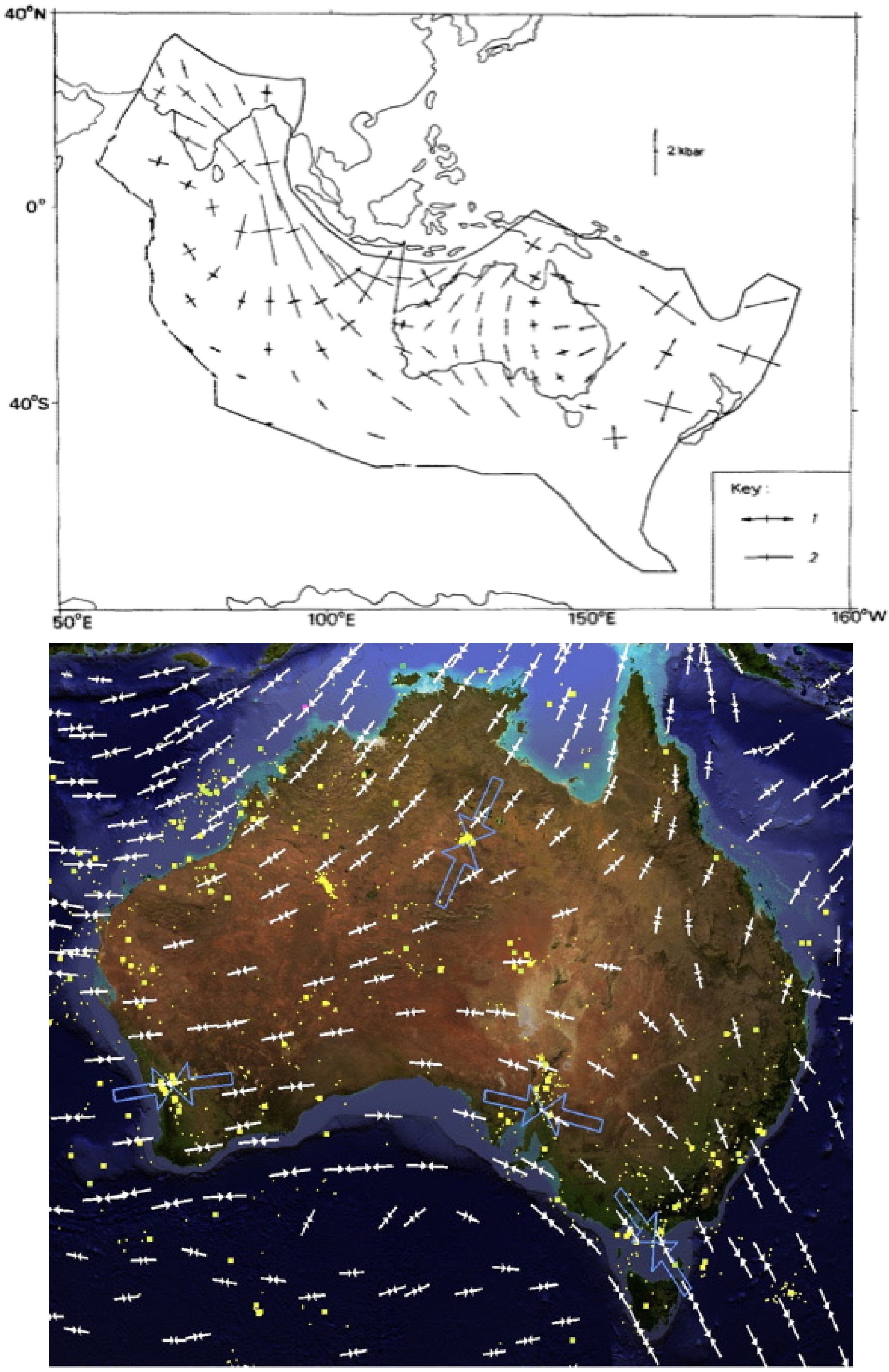

Figure 4. Regional stress field in the Indo-Australian plate Upper map from Cloetingh and Wortel, (1986). Plotted are principal horizontal non-lithostatic stresses averaged over a uniform elastic plate with a reference thickness of 100 km. Symbols 1 and 2 denote tension and compression respectively. The length of

the arrows is a measure for the magnitude of the stresses. Lower map from Sandiford and Egholm (2008).

These maps are not compatible with each other over large areas and focal mechanisms of moderate to large earthquakes eg in northeast NSW and northern SA do not fit the model. The implied principal stress in Tasmania seems to be NW extension in the Cloetingh model and NW compression in the Sandiford model whereas our recent analysis suggests EW compression.

Most measurements of crustal stress are made within a few hundred metres of the surface and often in mines where the stress may have been perturbed by mining. The results tabled below for Hellyer Mine (Walton, 1993) located about 50 km west of Mole Creek show that measurements of the bearing of σ_1 vary dramatically from roughly WSW (samples 1,2 and 3) to about SSE (all other samples). In 1987, tests were conducted ~295m below surface. In 1993, tests 1 to 3 were conducted ~ 440m below surface and tests 4 to 6 at ~195m below surface. The results from the tests are presented below but note a comment in the report *'the orientation of the stresses is more difficult to predict, and they are likely to be influenced by the major structural features'*.

The same can be said of stress measurements conducted in the walls of a cavity excavated for a power station for example. They would have to be carefully vetted before being used as proxys for free-field crustal stress.

Table 1 Stress measurements, Hellyer Mine

PRINCIPAL STRESSES (MPa)

Test Number	σ_1	Brg.1	Dip1	σ_2	Brg.2	Dip2	σ_3	Brg.3	Dip3
1	12.7	259°	45°	11.2	118°	37°	2.4	11°	21°
2	19.8	249°	55°	12.4	119°	24°	1.5	18°	24°
3	10.6	247°	43°	8.5	128°	28°	1.3	17°	35°
1987	21.1	158°	21°	9.1	324°	68°	3.7	66°	5°
1987	15.9	356°	20°	7.0	133°	64°	2.5	259°	17°
1987	15.8	335°	1°	11.4	68°	75°	2.7	244°	15°
4	9.3	160°	10°	5.2	274°	66°	3.4	66°	21°
5	10.6	156°	9°	7.8	341°	81°	-0.1	67°	0°
6	15.6	163°	2°	8.7	258°	71°	0.6	73°	19°

Brg. = Bearing, east of grid north
Dip = Dip, positive downwards

The most appropriate measures of principal stress orientation in the seismogenic zone, the top ~20 km of the crust, are derived from focal mechanism studies of local earthquakes or paleoseismic studies of Recent faults, and there are only two such examples in Tasmania as mentioned in my previous report. Both show approximately eastwest compression.

2 A best-earthquake database for Tasmania

The earthquake catalogue compiled by Kyen Knight summarised earthquake parameters for Tasmania and the surrounding region using existing catalogues of instrumental recordings of Tasmanian earthquakes. UTas with assistance from TasHydro established the seismographic network in 1957 and ceased their involvement in running the network and maintaining stations for TasHydro in 2000 when that role was taken over by ES&S.

Following solicitations from Gary Gibson, TasHydro have agreed that the epicentre data should be made public and ES&S made available their database for the Tasmanian region for events above magnitude 2.5 up to 2010, a copy of which has been sent to KUTh Energy. This database extends the instrumental record back to include all the historical events derived from macroseismic data by Michael-Leiba, UTas and Kevin McCue (1996) and others prior to the establishment of the Tasmanian Seismographic Network in 1957.

Another small earthquake has been detected and located in the vicinity of the project, on 01 December 2010 at 1539 15.9 UTC, ML 1.8, its epicentre at 41.80°S, 148.57°E at ~20 km depth. I used ES&S and GA station data in the location, even so the nearest seismograph was 102 km away and the gap between stations 245° so the depth is unreliable. It is a great pity the UTas network closed, Kuth should consider installing a small network to monitor the project areas.

3 Crustal model for northeastern Tasmania

In an email exchange with Geoscience Australia's Dr Clive Collins in August 2010, about models of the Tasmanian crust, Dr Collins commented: *the crust is thicker in the centre and north compared to the edges and the southeast. Looking at the models in the plot below, the crustal velocities are similar in the different modern profiles (the ones with velocity gradients) and these are higher than Richardson's old models (the ones with no gradient but constant layer velocities). This is apparently the reason Richardson's Moho is shallow (24-25 km) compared to the others (~27-35 km). The big variations in the crustal thickness (Moho depth) are due to the location of the seismic traverses and also uncertainties in the interpretation. ………. Model PDR13 is a compromise between the thin and thick ones; the velocities are also about 'average' and the interfaces (at ~10 km and ~30 km) agree with most of the others. It is an east coast model so the centre of the island may be thicker.*

The GA model PDR13 which has no low-velocity inversion zones is as follows, compared with VIC5A used for locating the December 2009 local earthquake:

Table 2 Velocity models for NE Tasmania

VIC5A		PDR13	
Depth km	P km/s	Depth km	P km/s
	4.81		2.50
2.15		0.2	
	6.00		5.63
6.72		3.5	
	6.17		5.72
18.76		8.8	
	6.32		5.88
35.18		11.3	
	7.81		6.25
		28.1	
			6.88
		33.1	
			7.92

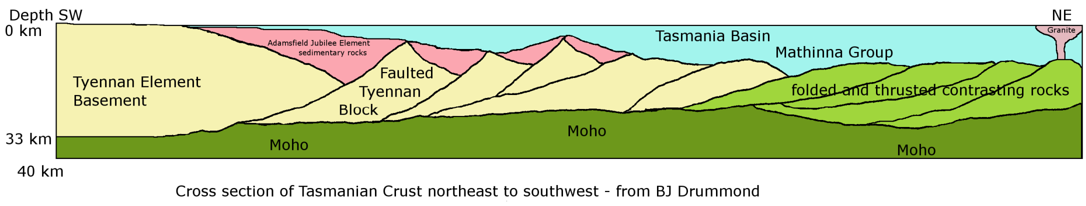

Figure 5. Cross section of the crust and upper mantle of Tasmania, SW to NE

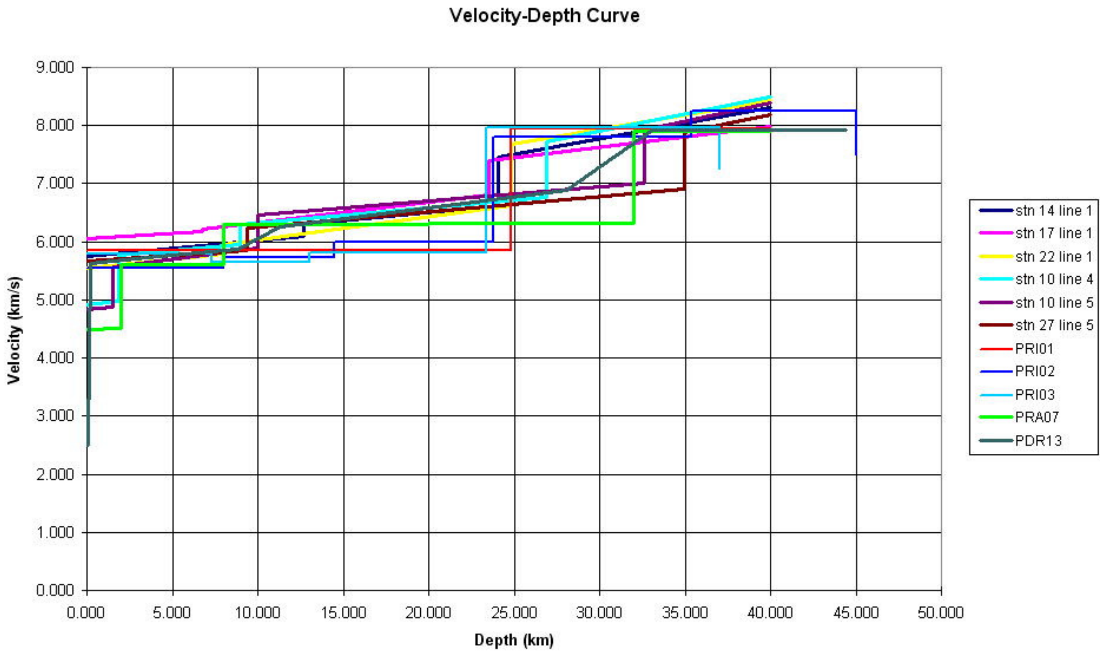

Figure 6. Velocity models of Tasmania, in Drummond et al, 2000.

Table 3 Computed focal coordinates of the 7th December 2009 earthquake

Model	Origin Time UTC	Lat °S	Long °E	Depth km	Variance
PDR13	1330 03.91	42.180	147.720	7.76	0.193
Vic5A	1330 03.92	42.182	147.735	8.64	0.145

4 A qualitative assessment of natural earthquake hazard in north-eastern Tasmania with specific emphasis on the CL and NF sites.

An alternative strategy to undertaking a probabilistic seismic hazard assessment in which most of the state functions may have to be guessed (source zone geometry, attenuation relation, maximum magnitude, 'b' value), is to look at the history of the sites in terms of observed shaking as measured by intensity, Modified Mercalli intensity. This information is readily available, incorporates all source zones, makes no assumptions about attenuation relationships and identifies sites with unusual foundation response (such as Launceston).

The method requires compilation of a list of inferred felt intensities at the sites since about 1880 (in this case) using existing isoseismal maps published in the 3 volumes of the Australian Isoseismal Atlas supplemented with more recent studies. That's 130 years of historical 'strong-motion' data. The intensities are sorted by size and fitted using an extreme-value distribution (Figure 7). My assumptions are that in NE Tasmania everything over intensity 4 since 1880 and over intensity 2 since 1958 would have been reported.

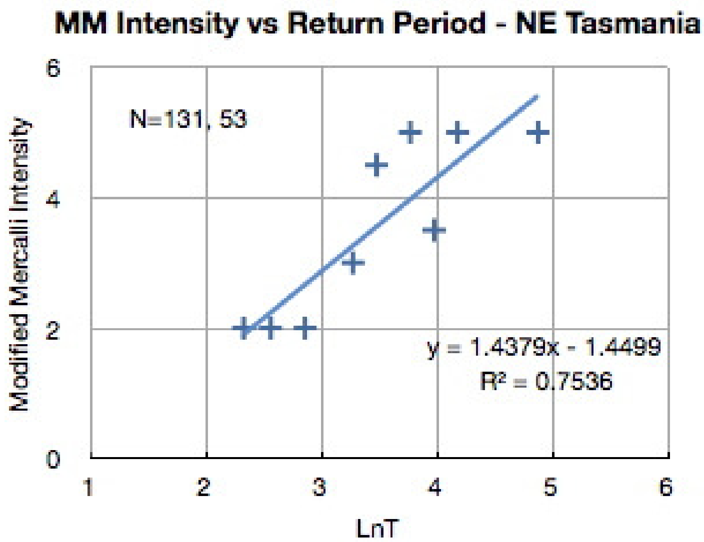

Figure 7 Extreme value distribution of reported intensities

It is doubtful we have missed higher intensity events but likely that lower intensity events have not been picked up which, if included, would flatten the line of best fit and reduce the extrapolated intensity at long return periods. On the 'x' – axis, the natural log of return period T, the 1, 10 and 100 year return periods are at 0, 2.3 and 4.6. Intensity 6, the onset of non-structural damage, has a computed return period of about 200 years using the equation of best fit (the 2nd and following decimal points are superfluous). This corresponds to a peak ground velocity of about 50mm/s or 0.1g, a considerably shorter return period than indicated on AS1170.4.

Large earthquakes in Bass Strait are likely to be be less frequent than we have observed in the last 150 years so my results can be considered to be conservative. Alternatively, this is the hazard level at the northeast tip of Tasmania according to AS1170.4, just 100km from the project sites and source zone boundaries are poorly defined here.

The project partners should decide upon an acceptable level of risk before a hazard study can be interpreted, the AS1170.4 map is for a 10% chance of exceedance in a perceived lifetime of 50 years for a normal building. What is the lifetime of the geothermal project and what is the risk level? Is 10% acceptable? Owners of dams and hazardous buildings take a much smaller level of hazard, 2.5% or even lower in 50 years (ie a 2000yr event as opposed to a 500 yr one). I am not aware of any standards for mining or energy projects but I would suggest that society would probably demand a fairly low level of acceptable risk if they were asked (the example of geothermal prospecting in Switzerland might give some guide to management).

5. Potential impact of induced and/or triggered seismic events

The probability of inducing earthquakes during the fluid injection phase of hot-rock reservoir creation is quite high. Induced earthquakes can be expected to range up to magnitude 3.5 or slightly larger. There is no reason to suspect that they may be different to normal tectonic earthquakes. Both have high frequency seismic content if you get close enough. A magnitude 3.5 earthquake at very shallow depth may cause slight non-structural damage to un-reinforced masonry (URM) structures, particularly those sited on horizontally layered soils overlying bedrock. The repeated small earthquakes may alarm sensitive people not expecting them and there are historical accounts of repeated shakes causing minor non-structural damage (at Bream Creek and South Australia and NSW).

As Dr Holgate commented: *felt effects from the (December 2009) Midlands earthquake are a reasonable proxy for the effects that could be expected from an induced event of the same size*. Within a few hundred metres of the epicentre a very shallow induced event may be expected to shake the ground and any overlying structures more strongly. Geodynamics Inc may have some information on the felt effects close to the Habanero injection well, the larger induced events were felt 10 km away at Innaminka. This sort of anecdotal information is very important without any other measurements.

Travel times derived from the crustal model PDR13 were used to revise the location and focal mechanism of the 7th December 2009 earthquake in NE Tasmania discussed by the author in the earlier report. The two models have a similar Moho depth and mid crustal velocities so it is not surprising that the focal coordinates computed using the two models are very similar.

6. Crustal stress in Eastern Tasmania

I checked the azimuth and take off angles for the December 2009 local earthquake to the Tasuni stations using the two crustal models Vic5A and PDR13 and they are within a few degrees of each other so the focal mechanism based on the new model would be almost identical to that in the previous report.

With such sparse focal mechanism data it will be necessary to make some measurements of crustal stress, at least sufficient to see whether major geological structures impact the principal stress directions.

7. Future data acquisition on site

It would be worth doing 6 to 10 surface triaxial measurements in competent bedrock in around the site and in a 100m deep or deeper borehole at top middle and bottom. Other useful measurements might include a velocity log and shear modulus in addition to the rock type and structure.

A seismograph network should be installed before operations begin and maintained for the life of the project. It would have a minimum of 4 six-component instruments (seismometers and accelerometers). This will be of great help in locating focal coordinates accurately enough to investigate any relationship with geological structure. They will help restrain focal mechanisms but at least 12 seismographs would be needed to do a focal mechanism without additional data from other network operators.

An educational program in the region might help to allay fears of anyone living nearby using the Bream Creek swarm as an example. Making the output from the network publicly available on a website, for example, will help with this.

Stress measurements in intact rock should be undertaken widely enough in the site region to determine any influence of structure, particularly faults.

The isoseismal maps I have looked at do show some variation in felt intensities in northeast Tasmania which may reflect enhanced shaking due to foundations on soil compared with those on rock. It would be useful to run a detailed intensity survey in the area when the next felt earthquake occurs and plot it on a soils map to see whether this is a real effect.

A microzonation study to investigate the surface variation of horizontal to vertical spectral ratio of background noise is reasonably quick and indicative of potential problem foundation sites in any future earthquake, whether induced or natural. In particular any areas of saturated silty sands should be mapped. This is necessary where there are buildings or infrastructure at potential risk of damage within the diameter of the expected hydrofracturing and perhaps at fewer sites out to 10 km from the project if there are sensitive or heritage buildings.

Project partners need to discuss and recommend the level of acceptable risk. This might need to involve emergency management officials in local government.

Summary

It is my belief that fluid injection will probably induce small earthquakes at the sites and even if they are of natural origin, like the 1987 Bream Ck swarm, it would be difficult to convince the public otherwise. Some educational material distributed to the public in the vicinity of the projects might help.

After considerable lobbying, I obtained and have provided Kuth with a copy of what I believe is the best earthquake database for Tasmania.

I have searched out a suitable crustal model of NE Tasmania from geoscience Australia, PDR13, and created a model file for the location program EQLOCL. I used this to relocate the December 2009 local earthquake and found that the revised location results in no change to the focal mechanism presented in my previous report. Given only two mid crustal assessments of stress direction, it would be prudent to do some 'undisturbed' surface and downhole stress measurement in the site area.

I have reviewed the earthquake hazard and consider that the AS1170.4 map can be used as the 500yr site pga, though some thought should be given as to whether 500yr is the appropriate design ground motion level at the sites.

KUTh should install a network of seismographs around the sites before any fluid injection starts, preferably long before. The company might also engage a consultant to do a microzonation study at any suspected soft-soil sites where significant ground motion amplification might occur, a detailed survey within the reservoir area and at selected sites up to 10 km away.

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