

In response to this peer review I have addressed the comments as follows (in italics):

Firstly a thank you letter should be addressed to S. Baisch in recognition of the thoroughness of his review and generosity in providing detailed and very useful comments.

He writes:

Thank you for sending me the HDR hazard evaluation study. I think it is a very interesting and important study towards defining general regulations for developing/operating geothermal systems. From my perspective I would like to make a few comments on those sections which are directly related to our work (basically section 4 and section 6).

Data from the Habanero reservoir:

- The magnitude frequency relation (Gutenberg-Richter) on page 35 (figure 7) is heavily biased by data clipping (see associated discussion on page 2243 of attached BSSA paper). Event magnitudes larger than say 1.7 could not be determined with the local recording system and to me it looks like they are simply missing in this figure. I do not know to what extent the magnitude data enters into the stress-transfer calculations (section 5), but it should be kept in mind that a significant portion of the most important data (a few hundred events with $M > 1.7$) might be missing.

Generally the Gutenberg-Richter relationship has been discussed throughout the text in terms of the seismic event recurrence relationship or the b-value, the b-value has not been calculated completely for the Habanero Geodynamics project – as Dr Baisch points out. We are aware that the probability of event recurrence has increased in this region of Australia, this is discussed as follows: the region is determined to experience a peak round of acceleration of 0.05g with a 10% chance of this being exceeded in 50 years. Thus the presence of the geothermal reservoir has increased the “recurrence” component of this region. Despite this the hazard map is unaffected because the Habanero events are not treated independently. Usually when creating a hazard map earthquake aftershocks and foreshocks are not included in the calculations; only the main event is assessed for the probability predictions. As part of this study the Habanero events are treated as one main event as they are so closely spaced in time, this means the risk map will not change, this is a reasonable approach due to the nature of the events in space and time. This has been assessed as a reasonable treatment by the seismological community, but further work on the seismicity of each site should be undertaken to study “recurrence” in more detail to justify this assumption further in particular relation to the geomechanical behaviour of the reservoir.

The seismic event recurrence relationships for any new projects should be published and made available for discussion in terms of seismic hazard.

On page 35 (figure 7) shows a relationship published for the Habanero project, but as Dr. Baisch describes this is biased due to data clipping; whereby the higher magnitude events are not included, these higher magnitudes events are given in Table 4.2. Background b-values in this region are low and it is clear that any activity above background will increase the b-value, it is hence clear that the Habanero activity has increased the recurrence relationship, the particular level of increase is not important as this does not come into further calculations in section 5. It is proposed that the actual values may be calculated by the Geodynamics team and published, also at a later date any further EGS projects should be required to report number of events against event magnitude. This will be useful in comparing company activity and generally of use for the scientific community in understanding reservoir development.

This proposal has been incorporated in the executive summary.

- On several occasions, the dominating signal frequency of induced seismicity is assumed to be > 100 Hz (e.g. page 30). This strongly contradicts my experience from various geothermal sites and certainly does not apply to the Habanero seismicity where seismic signal frequencies are well below 100 Hz.

Most references to frequency in this report relate to the frequencies observed in basement granites at the UK geothermal energy project. Dr Baisch emphasizes that these may not be wholly representative of observations at other projects citing his own experience. Therefore a review of frequency ranges should be made. Initial work has been done and the frequency ranges from the Habanero project have been incorporated.

Frequency spectra for the Habanero project seismic events have subsequently been provided and ranges have been incorporated in the text, at page 30.

- Hypocenter locations shown in figure 6 (page 34) and figure 2 (page 40) are based on results from preliminary data analysis (compare the discussion on page 2250 of attached BSSA paper). Since there have been significant modifications I suggest exchanging the hypocenter plots by figure 6 of attached BSSA paper. Note, that modifications concerning the hypocenter locations will also affect the vertical extension of the numerical model shown in figure 4 (page 42).

The degree of adjustment/resolution observed in terms of newly evaluated event location given in the BSSA paper (Baisch et al., 2006) are too minor to affect the geomechanical model developed which already has an approximate spatial distribution representing a sub-horizontal structure with a lateral extension of 2kmx1.5km and a thickness of 200m, this is the same as estimated in the recent BSSA paper. The newly developed hypocenter location map has now been added to the report and is included as Figure 4.6b.

Risk of large magnitude events:

- I think the approach of analyzing the seismic risk in light of (static) stress transfer (caused by previously induced slip) is a good one which is not found very often in the context of geothermal reservoirs. We actually have an observation that seems to support the modelling results from page 43: a large magnitude event occurred long after the end of the stimulation of the Habanero reservoir (see figure 13 of attached BSSA paper). We speculate that this event might reflect stress accumulations at the reservoir boundaries (page 2253 of attached BSSA paper). Interestingly, the location of the event seems to coincide with regions of stress concentrations shown in your numerical models (figure 5 on page 43).

This is a good result and suggests the parameters used for calculating the enhanced static stress region are correct as the stress highs surrounding the reservoir compare well with the large magnitude event occurring after development of the reservoir. This also implies the mechanical model is representing the sub-surface geometry and mechanics well.

- The second approach used to describe the seismic risk is a statistical one based on the magnitude-frequency relation. I am not sure whether I correctly understood the scheme formulated in figure 4 (page 33), but I think the seismicity that occurred during the stimulation of a reservoir should be separated from the seismicity that occurs thereafter. In a tectonically stable region like the Cooper Basin (say with no natural seismicity at all), the induced seismicity during reservoir stimulation is caused by an outer force (highly pressured fluid locally injected) which is acting over a short-period of time only (say 2 weeks). After this, the outer force is completely removed and in the ideal case the system quickly returns to stability again, meaning that background seismicity drops to zero again (which we actually have observed for a number of reservoirs). In this case, the Gutenberg-Richter statistic of a combined data set (stimulation and post-stimulation data) might draw a wrong picture ... The scenario changes once circulation starts in the geothermal system. It is likely that some induced seismicity occurs at this stage, but again, the statistics of the “circulation” seismicity should be isolated from the “stimulation” seismicity to evaluate the seismic hazard associated with the circulation.

Here Dr.Baisch refers to figure 4.4 this has been amended slightly as some spurious comments were included this was an oversight probably cut and pasted from a prior document. Figure 4.4 discusses plan workflow for studies – Stage 1 is complete and the Geoscience Australia risk hazard map has gone unchanged subsequent to recent events at Innamincka- as discussed in Section 6. 3 Uncertainties and proposed future research.

These comments have been incorporated in Section 6.3 Uncertainties and Proposed Future research.

Also comments relating to the proposal of Dr. Baisch to separate the magnitude-frequency relationships analyses into two components one for the “stimulation” phase of the project and one for the “circulation” phase.

- Besides the two approaches mentioned above, the study discusses another mechanism that influences the risk of inducing large magnitude events. This mechanism, which is based on McGarr’s relationship between event magnitudes and injected fluid volume, provides the basis for operational guidelines in the case that induced seismicity becomes too strong (“amber”). I have some concerns with these operational guidelines and the underlying model: (i) We know of a number of data sets which do not support McGarr’s relationship (see discussion on page 604 of attached GRC paper). Volume certainly can have an influence on the induced seismicity, but hydraulic energy might be a better proxy (e.g. you can pump large volumes at very low injection pressure without inducing any seismicity). (ii) There are several data examples where the largest magnitude events occurred actually after the stimulation (see attached GRC paper). We have developed a conceptual model to explain this (attached GRC paper), and, according to this model, reducing injection rates might not be the best thing to do in order to decrease the probability of large magnitude events. Only recently, an M=3.4 earthquake was induced in a geothermal reservoir at Basel (Switzerland). This earthquake occurred right after the project management has stopped the injection because seismic event magnitudes became too large. Here, the largest magnitude event occurred several hours after the injection rate has been reduced to 0 (shut-in). A sudden decrease in seismic activity was only observed after they started flowing back the injection well (thereby removing hydraulic energy from the system). I am not saying that maximum event magnitudes can completely be controlled by the way fluid is injected, but in terms of probability, flowing back a well might be the final measure to limit event magnitudes. Maybe this can be included into the traffic light system: if magnitudes remain high or even keep increasing at reduced injection rates (“amber”) then the well should be flown back. (In this context, some very interesting long-term data are presented by Ake, J. & Mahrer, K. & O’Connell, D. & Block, L., 2005. Deep Injection and Closely-Monitored, Induced Seismicity at Paradox Valley, Colorado. Bull. Seism. Soc. Amer., 95, 664-683.).

This comment is particularly important and was raised briefly in section 6.2 of the report, the proposal to allow the well to flow once reaching the amber stage of the traffic light system is an excellent one – of course this is a logical undertaking - once events of high magnitude occur and the warning stage is reached it is then important to reduce the pressure within the reservoir to prevent further large magnitude events. This is best done by alleviating bottomhole pressure this may not require significant pressure depletion but the safest option is to flow the well at maximum rate to decrease reservoir pressure as much as possible, thus reducing effective reservoir stress. The next phase of development would then be to allow the reservoir to reach stress equilibrium, ie wait until the reservoir is seismically quiet, then review prior events and activities to

understand in detail results obtained. Then attempt to extend the reservoir further under a different more controlled pumping regime.

These comments have been incorporated in section 6.3 of the report.

I hope you find these comments helpful.

Kind regards,

Stefan Baisch

Comment by L. Rybach on the Hunt and Morelli. Cooper Basin HDR hazard evaluation report.

General Remarks

- 1) *In paragraph 2 – Rybach suggests adding a report section on uncertainties and future research this has been done and is incorporated as section 6.3.*
- 2) *In paragraph 4 – Rybach discusses the shortcomings of the traffic light system this has also been mentioned by another reviewer S.Baisch, both reviewers are concerned with the recent observations made at the Basel – Deep Heat Mining Project. These comments have been addressed both in the executive summary and within the content of the report in section 6.2 and 6.3.*

Specific Remarks

- 1) Title: The title should indicate that it deals with seismic risk.
This has been adjusted in the title of the report.
- 2) The "traffic light" system in light of findings at Basel.
The report has been amended to incorporate recent findings.

3) Module B

3.5 and 3.6 More details should be incorporated to enable later investigators to apply the same or similar procedures.

Additional references are included which provide further details regarding the modelling procedures Morelli and Hunt (2006) and Morelli and Hunt (2007).

In analytical modelling – the slip tendency angle was determined for each fault segment and one general fault friction angle of 37degrees was applied to calculate the factor of safety for all segments.

The faults were digitised and the segments were determined based on the digitised smallest unit, this was the order of 0.5km for each fault segment.

4km was chosen as the mean depth as this was the approximate depth of geothermal energy development projects planned for the region. The habanero Geodynamics project fracture plane lies at 4.2km depth.

Figure 2 the colour scale is the same as figure 3 – this has been added to the figure label.

References to figures 16, 17, 18 and 19 are now given in the text in sections 3.7. 1 and 3.7.2.

4) Module C

Event catalogues: This has been addressed in the last sentence of 4.4.1, this issue was also of concern to review of Baisch – commented upon in his response.

Toro et al (1997) reference has now been added

Event magnitudes $M > 3.0$ are not plotted because the figure used for frequency magnitude relationships comes directly from a published paper it appears these higher magnitude events were clipped. Notes on this issue are given below Baisch also commented on this (his comments are given in red, authors response given in italics)).

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Generally the Gutenberg-Richter relationship has been discussed throughout the text in terms of the seismic event recurrence relationship or the b-value, the b-value has not been presented thoroughly for the Habanero Geodynamics project – as Dr Baisch points out – high magnitude data is missing due to effect of the recording system. We are aware that the probability of event recurrence has increased in this region of Australia, this is discussed as follows: the region is determined to experience a peak round of acceleration of 0.05g with a 10% chance of this being exceeded in 50 years. Thus the presence of the geothermal reservoir has increased the “recurrence” component of this region. Despite this the hazard map is unaffected because the Habanero events are not treated independently. Usually when creating a hazard map earthquake aftershocks and foreshocks are not included in the calculations; only the main event is assessed for the probability predictions. As part of this study the Habanero events are treated as one main event as they are so closely spaced in time, this means the risk map will not change, this is a reasonable approach due to the nature of the events in space and time. This has been assessed as a reasonable treatment by the seismological community, but further work on the seismicity of each site should be undertaken to study “recurrence” in more detail to justify this assumption further in particular relation to the geomechanical behaviour of the reservoir.

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This proposal has been incorporated in the executive summary.

Figure 8: The reason for the elliptic shape of the isolines is simply the plotting algorithm used to plot the circles – a contouring function was used that has distorted the circular nature of the isolines – this is not a subsurface anisotropy effect it is only an artefact of the plotting technique – this will be corrected.

5) Module D

It is expected that the worst case static stress change will be when the reservoir is at its maximum spatial extent. The reservoir is treated as a damaged mass of material that is in a condition of having a lowered capacity to support the rock mass around it hence the static stress change is at its maximum, this is discussed further in Module D.

6) Section 6.

The current authors are unable to answer this question, this would require more detailed examination of the specific data available with relation to pump rates. This can be considered in further research work – this comment has been incorporated in section 6.3 uncertainties and future research.

I would direct the reviewer to speak directly to Geodynamics Pty Ltd for additional data.

The proposal to start monitoring arrangements early is a good one and has been incorporated in section 6.2 and the exec summary.

7) Final

All citations have been added.