Probabilistic approaches in EGS seismic hazard assessment

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ABSTRACT

We discuss the growing interest in probabilistic based approaches for seismic hazard assessment in EGS (Engineered Geothermal Systems), in which they are used both for estimating the likely maximum event size and also as the basis of real-time adaptive “traffic light” systems. Probabilistic approaches are also of practical interest to EGS developers because they do not demand a detailed knowledge of fault parameters, hydro-mechanical interaction within the reservoir or the seismic rupture process.

However probabilistic approaches not only require an *apriori* statistical sample, but also confidence that large events are not somehow “anomalies” or “special” events, but are part of a continuous statistical and scalable seismicity distribution. This argument is made difficult by the frequent distinction between “induced” and “triggered” seismicity. The implication being that the former are part of some continuous statistical distribution, whereas the latter are anomalous seismicity related to some specific, and sometimes unknown, large-scale structure.

To illustrate this latter point we then consider a specific example of apparently “anomalous” seismicity from the UK Hot Dry Rock EGS Project (Rosemanowes) in the 1980’s. The largest event was M_L 2 and was felt locally. At the time the largest events appeared distinct in terms of both magnitude and focal mechanism compared to the 5000+ other “induced” events. Consequently there was ongoing uncertainty as to whether the larger events were in fact anomalies or a statistically probable consequence of the long-term injection operations.

A present-day implication of this uncertainty is whether it is appropriate to adopt probabilistic based approaches for EGS development currently planned in the area, or whether a purely mechanistic approach is required that takes into account local geological and tectonic conditions, with its high associated exploration demands.

Recent re-analysis of the data suggests that the Rosemanowes events were in fact consistent with a general statistical relationship between seismic energy release and injected fluid volume, and also with the range of focal mechanisms expected from the interaction of injected fluid, stress regime and fracture distribution. We conclude that the large events observed at Rosemanowes should not therefore be considered anomalous, but as a statistical and geomechanical consequence of overall net fluid loss within the subsurface.

This example not only illustrates the care that needs to be taken when distinguishing between induced and triggered seismicity, it also provides some support for the use of probabilistic based hazard assessment approaches and the potential of real-time adaptive “traffic light” systems.

1. INTRODUCTION

As part of the Eden EGS development EGS Energy Ltd has conducted a seismic hazard assessment. The study has investigated the potential for large-scale seismicity (ie felt or larger) resulting from the proposed EGS development and circulation operations. A key component of the study has been the inclusion of the nearby Camborne School of Mines (CSM) Hot Dry Rock (HDR) Project at Rosemanowes as an analogue for the anticipated behaviour at Eden.

This assumption appears reasonable for several reasons: SW England is a region of relatively low tectonic strain; it has low levels of natural seismicity; both sites are within the same uniform granite batholith that extends to surface; available evidence indicates a relatively uniform regional in situ stress regime. Furthermore, even though the Rosemanowes boreholes only extend to around 2.2km depth the EGS seismicity was observed to >3.5km depth, which is similar to the depths anticipated for the Eden EGS project (~4->4.5km).

Although the analogue seems reasonable EGS Energy nonetheless recognise the need to validate this assumption during the early stages of development.

This validation approach also raises a broader question concerning the scalability of probabilistic relationships developed during small volume tests to large fluid volumes, and hence their use as predictive tools.

This paper presents the results of a re-assessment of the seismic behaviour of the Rosemanowes system undertaken as part of the EU FP7 GEISER Project. It has particular relevance for the use of historic EGS seismicity catalogues in probabilistic hazard assessment. In the case of Rosemanowes it addresses the statistical and geomechanical relationship between the few, apparently anomalous, large ($M_L \leq 2$) induced seismic events and the bulk of the microseismic activity.

For many years after the termination of the Rosemanowes project there remained some uncertainty about whether these large events were anomalies, for example "triggered" seismicity on some unknown large-scale structure, or whether they formed part of a continuous distribution of microseismicity and were a statistically quantifiable consequence of the sustained injection operations.

This question is of general importance for EGS seismic hazard assessment. If large-scale induced seismicity is found to represent part of a continuum of induced seismicity then it may be appropriate to consider a probabilistic approach to hazard assessment. However if large-scale events are consistently found to be anomalous in terms of their size, focal mechanism or stress drop, it may be more appropriate to adopt a deterministic approach that takes into account local geological and tectonic conditions, as well as operational parameters.

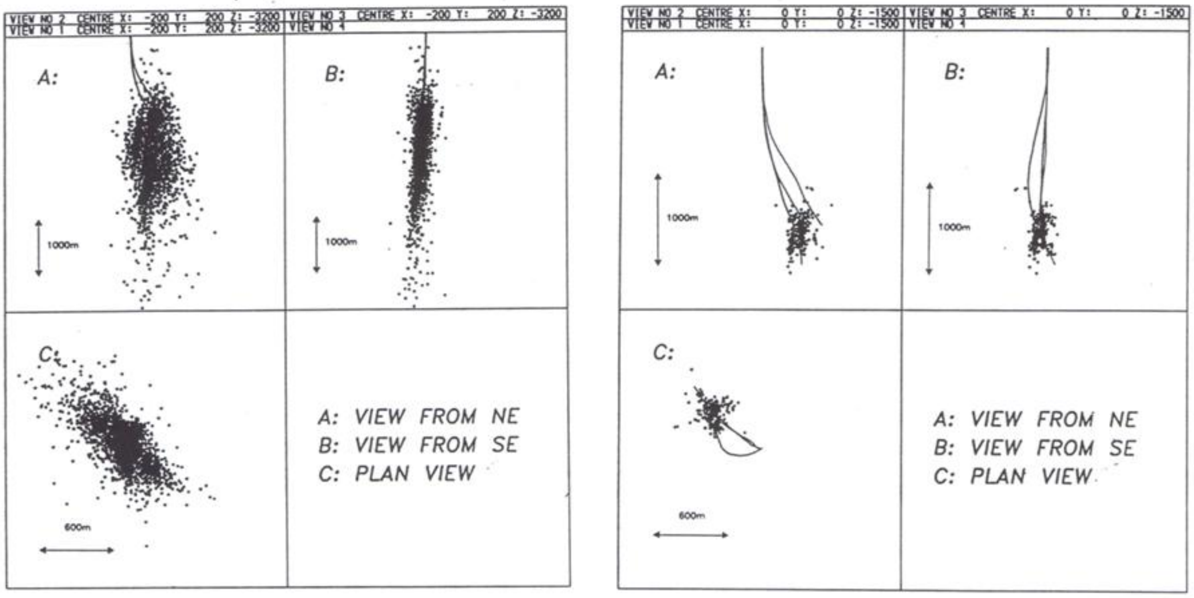

Figure 1: Side and map views of the boreholes and seismicity during Phase 2A and 2B of the Rosemanowes geothermal experimentation. A) Left - Phase 2A seismicity and RH11/RH12 boreholes, B) Right - Phase 2B seismicity showing additional borehole RH15.

2. SEISMICITY AT THE CSM ROSEMANOWES PROJECT

Large-scale EGS experimentation was undertaken at the CSM HDR Project between 1980 and 1991. There were 3 main Phases, with a series of sub-phases. Briefly:

- *Phase 1:* Experiments at shallow depth (300 m) to assess the feasibility of enhancing the permeability of the rock
- *Phase 2:* Studies at intermediate depth (2500 m) to determine the feasibility of creating a viable HDR subsurface heat exchanger. This was the main experimental phase at Rosemanowes and is of most relevance to this study
- *Phase 3:* Design and concept testing aimed an HDR prototype at commercial depth (6km)

The first part of Phase 2 (ie Phase 2A) lasted from 1980 to 1983. This involved the drilling of two boreholes deviated from the vertical by *30°* to a depth of 2km (Fig. 1). Hydraulic stimulation was carried out with water from the lower borehole to try to open up the near vertical fractures rising to and intersecting the upper borehole. When circulation started, the system did not behave as predicted: water losses were large (~70%) and the pumping pressures required for circulation were found to be too high.

During Phase 2A approximately 30,000 microseismic events were detected and more than 5,000 were located. The net fluid injection was ~230,000m^3, with an overall net return of ~30%. The largest event reported by the British Geological Survey (BGS 1991) was an M_L=1.0 in 1983.

The microseismic data obtained during the Phase 2A stimulation and circulation indicated that a large microseismic 'cloud' had developed beneath each borehole (Fig. 1). It was believed that the majority of the injected water migrated into this zone below the boreholes and hence was not recovered by the second borehole.

Phases 2B and 2C were undertaken between 1983 and 1988. A third borehole (RH15) (Fig. 1) was drilled at the end of 1984 to a measured depth of 2600m and along a helical path crossing the microseismic 'cloud' obliquely to the vertical plane of the first two boreholes. The aim was to maximize the number of fracture intersections.

The Phase 2B programme began with a medium-viscosity gel stimulation to try to open up the volume between this new borehole and the deeper of the original boreholes. The injected volume during the stimulation was around $6000m^3$. During Phase 2B overall the total net injection volume was around $120,000m^3$, with an overall net recovery of over 70%. Approximately 1300 microseismic events were detected and more than 500 located (Figure 1). The largest event in Phase 2B was M_w ~0.0 (CSM 1986).

The main phase of reservoir circulation at Rosemanowes was Phase 2C. During the Phase 2C circulation experiments the reservoir was operated at high flowrate and pressure for sustained periods.

Measurements in Phase 2C established that impedance fell as the injection pressure and flow rate increased. However the higher operational pressures resulted in further seismicity, indicating further stimulation of the reservoir and continued growth. Amongst this low magnitude seismicity three larger seismic events occurred, with M_L=2.0, 0.7, and 1.7 (BGS 1987, 1989, 1991). The M_L=2.0 event was felt at the surface by a number of local residents, albeit in extremely quiet environmental conditions. The injection flowrate was subsequently reduced in order to prevent further felt seismicity. The M_L 1.7 event occurred in January 1988 but was not felt at ground surface. No further events of $M_L \geq 1$ occurred in the Phases 2C and 3A experimentation.

As noted earlier an important question remains as to whether these large events should be considered anomalous, or whether they form part of a continuous distribution, or spectrum, of microseismic activity resulting from the EGS experimentation.

This has been investigated by firstly considering the relationships between net fluid injection and seismic energy release, and secondly by examining the focal mechanisms in terms of the expected geomechanical behaviour of the Rosemanowes subsurface.

3. RELATIONSHIP BETWEEN SEISMICITY AND FLUID VOLUME

In this section we consider the relationship between the seismicity observed at the Rosemanowes project and the net injected fluid volumes. Models are developed using the Rosemanowes data from Phases 2A and 2B and then used to make predictions concerning the large events in Phase 2C. The success of these predictions then provides some insight into the nature of the large events.

McGarr (1976) proposed the following relationship between the cumulative seismic moment (ΣM_o) and the injection (or extraction) of a fluid volume $|\Delta V|$.

$$\sum M_o = K\mu|\Delta V| \qquad [1]$$

where μ is the rock mass rigidity and K is a constant which McGarr (1976) estimates to be ~1.0, but depends on the specific site and unit system employed.

In this study we have obtained empirical estimates of the constant K for Phase 2A and 2B, and used these to make predictions about the Phase 2C events. Figure 2 presents an example of a cumulative seismic moment against net injected volume curve for the main stages of Phase 2A. Two curves are shown: one is the original data digitised from plots in the Rosemanowes reports (solid line); the other is calculated from new seismic moment estimates obtained from the historic digital waveform data recovered during the course of the GEISER Project work (dashed line). The curves are very similar indicating successful recovery of both the waveform and hydraulic data.

Similar analyses were performed for all the main stages in Phase 2A and 2B to obtain a distribution of values for the constant K. These values were then used to make a prediction of the expected maximum magnitude for Phase 2C. The conservative assumption is made that all energy is released in a single event.

Figure 3 presents estimates of the maximum expected M_w against net fluid volume for the overall range of K values obtained for Phase 2A and 2B. The M_w for the two largest Phase 2C events are plotted against the net fluid volume corresponding to their occurrence time (CSM 1988). It can be seen that two large events plot well within the bounds of the K value estimates. This indicates that the energy release for these two events is consistent with the general trend estimated from the Phase 2A and 2B data. In other words the large 2C events do not exceed the cumulative energy release predicted by the McGarr (1976) model. Hence we can conclude that at least in terms of the McGarr model the Phase 2C events do not appear anomalous in terms of the cumulative net injected volume.

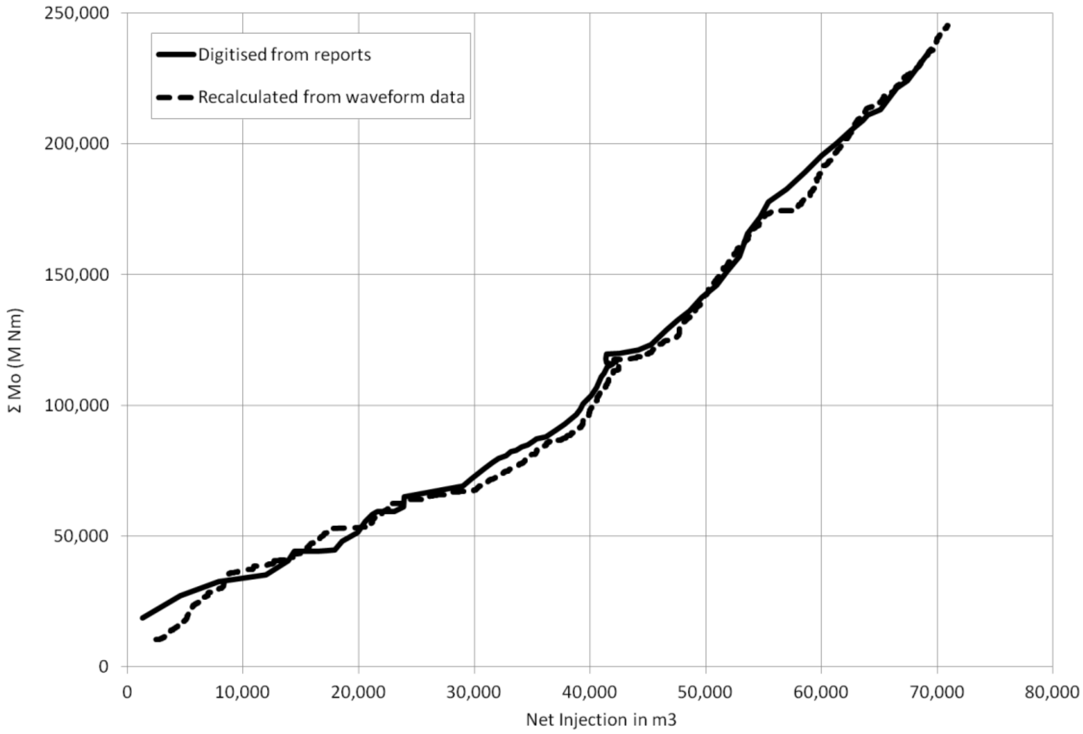

Figure 2: Cumulative seismic moment against net injected volume for Rosemanowes Phase 2A. Solid line digitised from reports, dashed line recalculated from waveform data

A second approach was used in which the distribution of event magnitudes was also taken into account. Dinske (2011) proposed the concept of the seismogenic index (∑). It had been shown that the number of earthquakes having a magnitude larger than a given size increases proportionally with the injected fluid volume, and that this is also affected by the seismotectonic state of the specific site. In order to characterise this state Dinske (2011) introduced the concept of the seismogenic index (∑). This combines several, generally unknown, site-specific properties. However it is relatively simple to evaluate ∑ empirically from microearthquake catalogues using the relationship:

$$\Sigma = \mathrm{Log}_{10}N_{\geq M}(t) - \mathrm{Log}_{10}V_i(t) + bM \qquad [2]$$

where b is the b-value slope obtained from the classic Gutenberg-Richter magnitude frequency distribution, N is the cumulative number of events greater than or equal to a specific magnitude M, and V_i is the net injected fluid volume. Therefore the seismogenic index can be estimated for various values of M by analysing the relationship between injected volume and N. In the case of the main Phase 2A stimulation a b-value was calculated using the maximum-likelihood approach and we then obtained a seismogenic index of approximately -3.65.

This value has been compared to the results obtained by Dinske (2011) for a number of injection projects, including geothermal. It was found that Rosemanowes is on the low side of the seismogenic indices obtained for EGS systems around the world. It is similar to the value obtained for the Soultz shallow reservoir and is consistent with the idea that Rosemanowes was a site of relatively low level seismicity and hazard.

Having estimated the seismogenic index from Phase 2A we can use it to estimate the largest event that might have been expected during Phase 2C. We do this by rearranging the above equation and evaluating M_w for a range of fluid volumes, where N=1. The results of this analysis are shown in Figure 4. This shows the expected maximum event magnitude (N=1 event) plotted against net injected fluid volume. Also shown are 95% error bars. Based on this curve the N=1 event corresponding to the fluid volume injected prior to the M_L 2 event (~158,000m^3) is approximately M_w 1.55. This estimate is close to the BGS observed M_w ~1.7 and indicates that this large event falls well within the 95% confidence limits for the seismogenic index based estimate.

As with the McGarr (1976) approach this indicates that the energy release for the large event is consistent with the general trend estimated from the Phase 2A data. Hence the Rosemanowes Phase 2C large events do not appear anomalous in terms of the cumulative net injected volume.

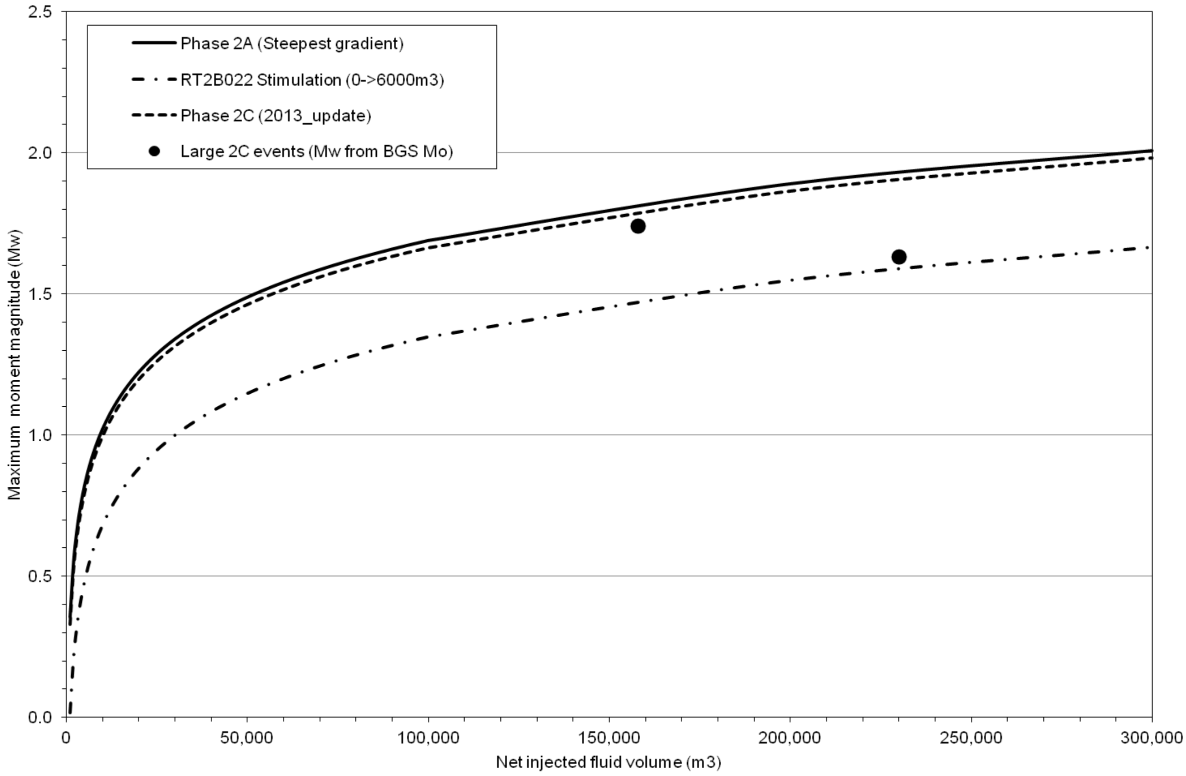

Figure 3: Predicted maximum moment magnitude against net injected fluid volume based on analysis of Phase 2A and Phase 2B Rosemanowes results. Black points are the occurrence of large magnitude events on 12 July 1987 (M_L 2) and 7 January 1988 (M_L 1.7).

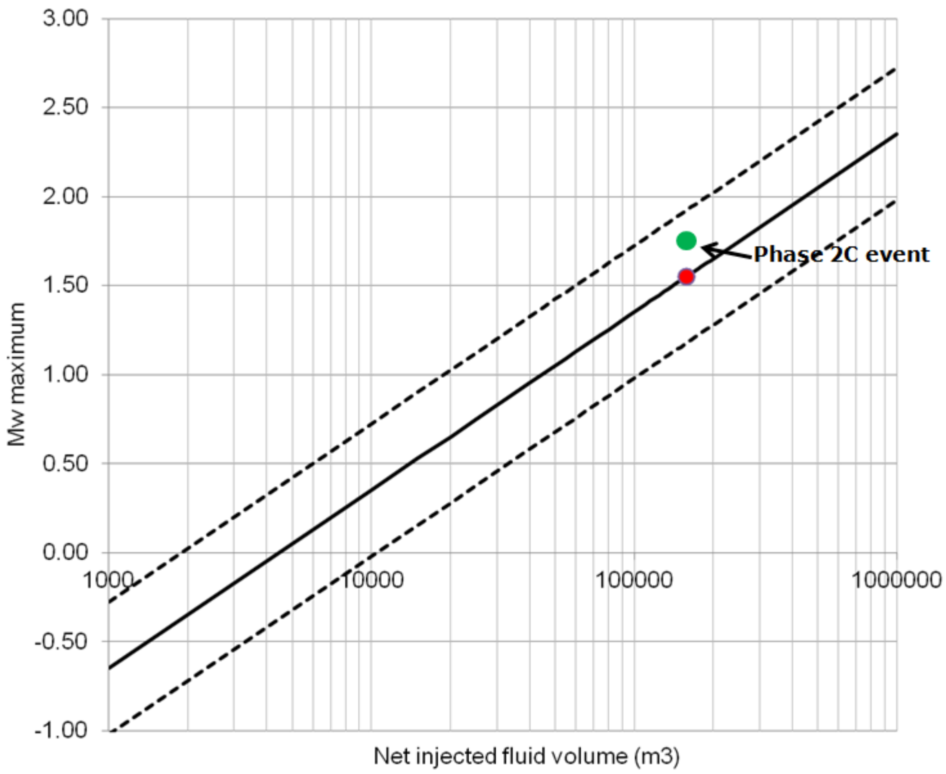

Figure 4: Plot of maximum expected M_w for N=1 probability events using the Rosemanowes RT2A046 derived seismogenic index, compared with the actual occurrence of the 12 July 1987 (M_L 2) event. Dashed lines are 95% confidence limits on seismogenic index.

4. FOCAL MECHANISM ANALYSIS

Analysis of the magnitude-fluid volume relationship suggests that the large events are consistent with the bulk of the Rosemanowes seismicity in terms of the cumulative energy release (ie McGarr 1976) and also the expectations based on the Gutenberg-Richter magnitude-frequency model (ie Dinske 2011).

Therefore unless the Rosemanowes large-events demonstrated some anomalous focal mechanism it would be hard to classify them as anomalies, and not some part of the overall continuous distribution of microseismicity at the Rosemanowes site.

Detailed focal mechanism analysis is difficult with the Rosemanowes data because the sensors were mainly single component (vertical sensors), there is amplitude saturation of large events and also because of the relative sparseness of the array geometry. Nonetheless reanalysis of focal mechanisms data during the GEISER Project has provided some insight into this question.

Figure 5 presents a summary of composite focal mechanisms obtained during this study, and also a focal mechanisms obtained by the BGS for the M_L 2 event BGS (1991). In all cases the projections are upper hemisphere. The top two mechanisms show the BGS solution for the M_L 2 event and a GEISER solution obtained for a nearby smaller (ie non saturated) event. These mechanism are consistent and show a normal faulting component on relatively shallowly dipping failure planes, which strike close the orientation of the maximum principal stress (NW/SE).

These mechanisms were initially considered anomalous by CSM because the vast majority of the solutions obtained at Rosemanowes indicated strike-slip on sub-vertical fractures (left-hand-bottom solution Figure 5). However more detailed analysis suggests that a range of failure mechanisms are present. The vast majority are the pure strike-slip mechanisms, but there are also a much smaller number of mechanisms that include moderate to large normal faulting components. This spectrum of solutions incorporates the BGS obtained solution for the M_L 2 event. Furthermore the frequency of non strike-slip solutions also appears to increase with depth within the reservoir, which is consistent with the location depth of the larger events. Therefore this suggests that the mechanism for the large event is not a complete anomaly, but part of a spectrum of focal mechanisms.

Rosemanowes benefits from quite extensive in situ stress data and it is believed that the stress field is well characterised to at least 2.5km depth and can be reasonably extrapolated for at least another kilometer (CSM 1988). This has allowed us to make some predictions concerning the likely range of focal mechanisms that might be expected during the Rosemanowes injection operations.

A Mohr-Coulomb failure analysis (Fig. 6a) has shown that the minimum fluid pressure required for shear slip occurs for vertical fractures striking approximately 20^o->25^o from the maximum horizontal stress. This is consistent with the bulk of the focal mechanisms observed at Rosemanowes. However there is a fairly broad minimum in the critical pore pressure distribution that extends towards the strike of the maximum horizontal stress for shallower dipping fractures. This exists at both 2.5km and 3.5km depth, but the minima becomes more significant at greater depths. This is because of the divergence of the maximum and minimum horizontal stress with depth at Rosemanowes. Hence we find that shear slip may be possible on fracture planes with shallower dips (~60^o->70^o) and that the frequency of these mechanisms might increase with depth.

This analysis can be further expanded to consider the sense of shear slip predicted on planes of any orientation (Fig. 6b). At both 2.5km and 3.5km depth it has been found that there is a transition from strike-slip to normal-faulting mechanisms that corresponds with the shape of the minima in the pore pressure plots. This is also consistent with the observation that the more shallowly dipping fractures striking closer to the maximum horizontal stress will exhibit an increasing normal faulting component.

In summary it appears that the observed focal mechanisms for the large events are entirely consistent with the overall spectrum of focal mechanisms that might be expected based on the measured in situ stress field at the Rosemanowes site. Furthermore the analysis also suggests that the relative frequency of mechanisms with a normal faulting component will increase with depth due to the known divergence of the two horizontal stresses. Therefore the mechanisms for the relatively deep large events appear predictable as part of the overall microseismic event population.

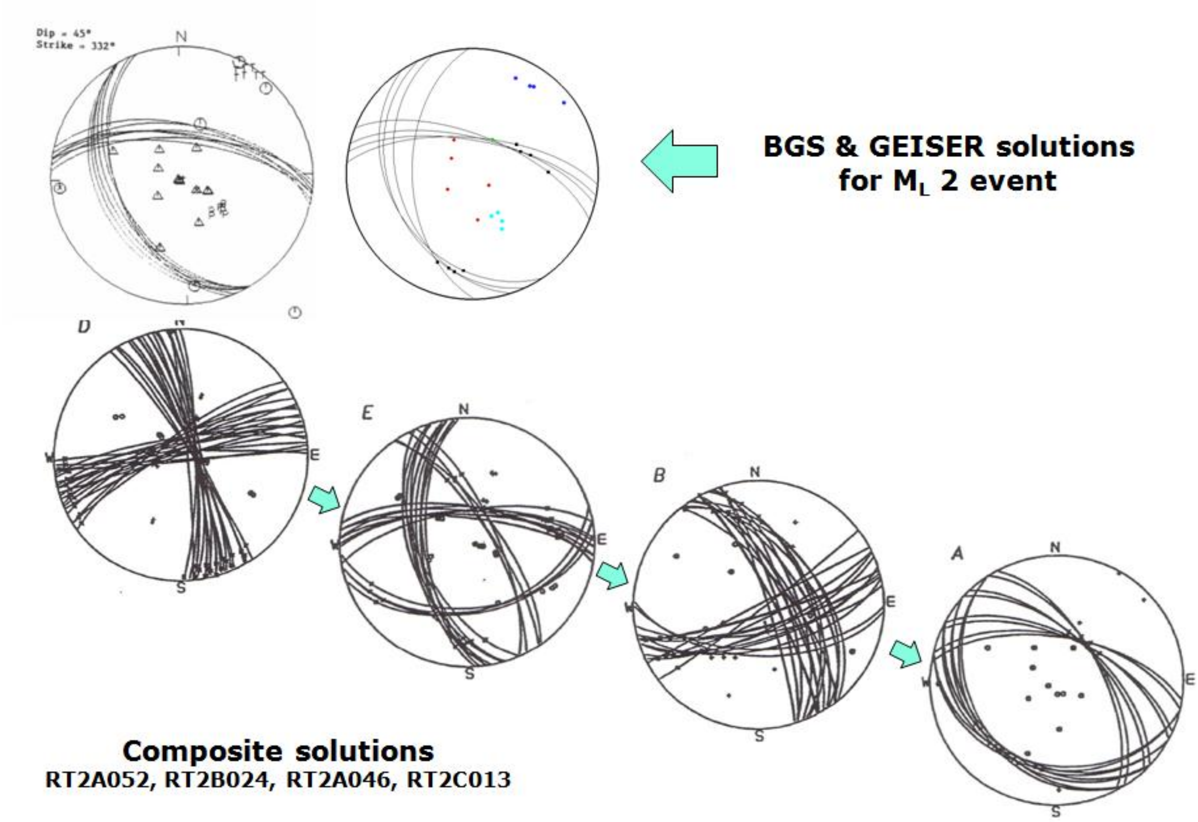

Figure 5: Summary of the range of focal mechanisms observed at Rosemanowes. All mechanisms are shown as upper-hemisphere projections. Top - BGS published mechanisms for the 12 July 1987 (M_L 2) event and GEISER derived solution for a nearby event. Bottom - range of focal mechanisms observed at Rosemanowes with decreasing event frequency to right.

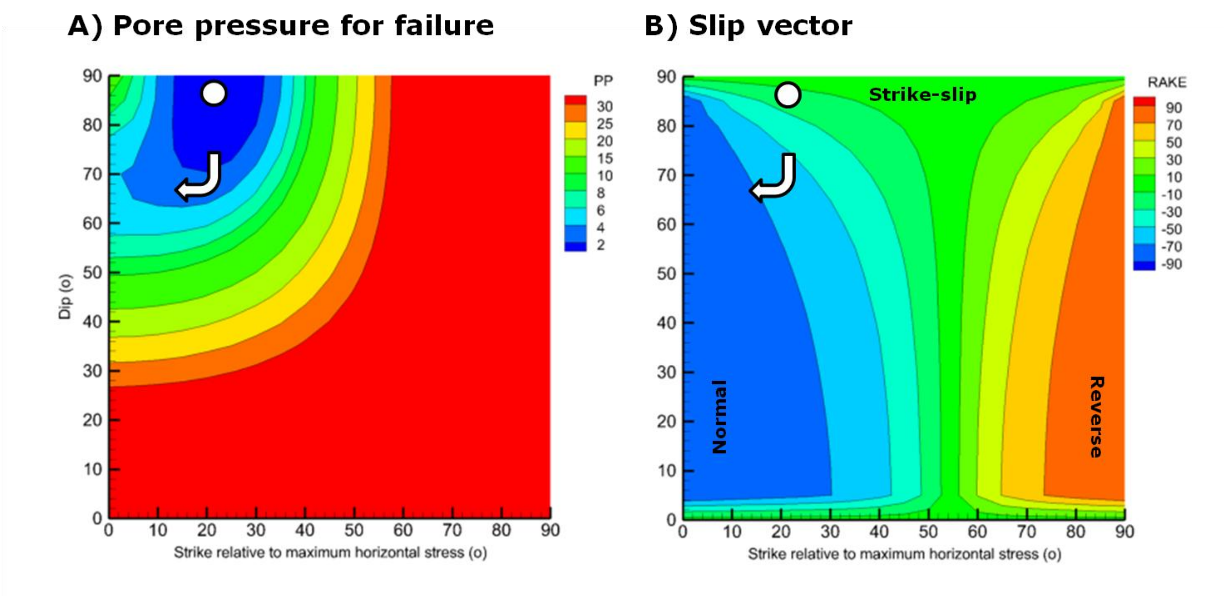

Figure 6: Mohr-Coulomb failure analysis for the large events at Rosemanowes, where the X axis is the fault plane strike in degrees relative to the maximum horizontal stress direction and the Y axis is the dip, where 90^o is vertical and 0^o horizontal. A) Pore pressure increase required for shear failure (MPa), B) Shear slip vector orientation (Rake) where -90^o is normal faulting, 0^o strike-slip and 90^o reverse faulting.

5. RESULTS AND CONCLUSIONS

The main question addressed in this study has been whether the large events observed at Rosemanowes were truly anomalous, or whether they formed part of a continuous distribution of microseismicity.

The significance of this point is that if the large-scale induced seismicity does not form part of a continuum of induced seismicity then it may be inappropriate to adopt a probabilistic hazard assessment approach based on magnitude-frequency statistics. It may necessitate the need for a purely mechanistic approach that would take into account accurate local geological and tectonic conditions, with its associated requirements for exploration.

This is of general importance to EGS hazard assessment, as well as the proposed Eden EGS development where it is assumed that Rosemanowes is a reasonable analogue for the expected behaviour during the Eden EGS development.

The results of the study show that:

- The large events (M_L 2) observed during Phase 2C of the Rosemanowes project appear statistically consistent with the observed magnitude-injected fluid volume relationships observed during previous Phases. This supports the argument that the events are part of a continuous distribution of seismicity, rather than anomalous one-off events.

- The focal mechanisms observed for the large events are also consistent with the predictions of the geomechanical interaction between the injected fluid and the in situ stress field. This suggests the dominance of pure strike-slip on vertical fractures, but also the likelihood of more normal faulting mechanisms on more shallowly dipping fractures. The relative frequency of mechanisms with a normal faulting component is likely to increase with depth, which is also consistent with the occurrence of the larger events

- It appears that the large events observed at Rosemanowes should not be considered anomalous, but are a statistical and geomechanical consequence of net fluid loss within the subsurface at Rosemanowes. This result is significant as it indicates that, at least in this example, a probabilistic hazard assessment approach based on magnitude-frequency statistics may be justifiable.

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