Provocation and Reaction: A study into the influence of slow slip earthquakes and volcanic activity in the southern Taupo Volcanic Zone, New Zealand

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ABSTRACT

Slow slip events (SSEs) occur regularly on the Hikurangi subduction zone along the East coast of the North Island. These SSEs sometimes trigger small local earthquakes, usually offshore. To study the general influence SSEs have on seismicity rates in New Zealand, we did a statistical analysis of earthquake rates comparing times when SSEs were occurring to all other times. We found that although seismicity rates remain relatively low, for most regions there is a significant increase in the number of earthquakes that occur during SSEs. This shows that while the changes associated with SSEs are too small and too slow to be felt, they are large enough to influence tectonic processes and earthquake rates. Future New Zealand hazard models that take into account time variations could incorporate this information. Given the connection to earthquake rates, we have investigated whether these SSEs affect the timing of volcanic activity at Taupo caldera beneath Lake Taupo. In 2008 a small SSE was accompanied by a large increase in seismicity and gas release at Taupo caldera. Despite other similar and larger SSEs in the area, no other accompanying volcanic unrest has been observed at Taupo in association with these events. By calculating strain from GPS instruments around Lake Taupo we have shown that the 2008 SSE was unique in that it produced dilational strain, which acted to stretch out the caldera. All other SSEs examined appear to have the opposite affect, pushing the caldera together. We also looked for changes in seismic velocity associated with these SSEs, but have not found any links. The seismic velocity does vary with time and some of these changes may be seasonal. We suggest that the 2008 SSE pulled apart the caldera enough to allow existing gases to rise to the surface and be released. In the future increases in extension at the caldera should trigger increased monitoring and scrutiny of other volcanic parameters.

OBJECTIVES/RESEARCH OUTCOMES

Overall we are happy to have achieved the proposed research.

1) For target slow slip events, we will:

a. Analyse changes in areal strain and strain rate

The geodetic observations from the three target slow slip events (SSEs) were all analysed with SSPX software to create areal strain maps for the Taupo region.

b. Model theoretical changes in strain and strain rate

A finite element mesh was created and used to apply the published slip distributions for the three SSEs. This produced both theoretical displacements (equivalent to raw geodetic data), and strain (equivalent to processed SSPX results).

c. Compare observed and model (local crustal deformation)

The modelled strain was analysed in two ways. First by using the model displacements to run identical processing in SSPX for direct comparison to the observed strain. Secondly to compare the observed strain calculated on a grid to the more continuous strain picture available from the finite element model. There was relatively little difference between the broad strain directions directly from the model and the calculated strain observations. This similarity shows that due to the large station spacing the Taupo GPS network is relatively insensitive to grid size of the strain calculations. The minor differences that were observed could be useful in identifying locations for additional stations in the network.

2) **Analyse earthquake rates and seismic properties at the time of strain changes of interest**
We followed on from work started during my PhD (funded by EQC 1352) and completed a statistical analysis looking at how earthquake rates change during SSEs in New Zealand. The work, which was published in the New Zealand Journal of Geology and Geophysics, showed that many regions in New Zealand have significantly higher rates of seismicity during SSEs.

By analysing a long time period of seismic data we were able to identify the seismicity associated with the 2008 SSE as the strongest increase in seismicity in the Taupo caldera in the last decade. This allowed us to show that it was truly a unique event. We have also determined that separating out the seismicity inside and outside the caldera is important to looking for seismicity most likely to be associated with volcanic processes.

The ambient noise (seismic properties) analysis has not shown temporal changes around the SSEs as we hypothesized. We think that this may be due to data quality and long inter-station paths. The small number of permanent seismometers, and the large area of the lake means very few station pairs have paths that are similar enough that they can be stacked. Small changes in seismic velocity may be occurring below our current detection level. The detection level could be improved by deploying small clusters of stations, and also potentially by further processing of the data.

3) **Use strain modelling and seismic analyses to determine whether thresholds of preconditions exist for triggering of seismic or volcanic activity.**
The starkest contrast between the 2008 SSE that was associated with volcanic unrest, and the other analysed SSEs without observed unrest was its large dilational strain. Contractional strain at similar magnitudes does not seem to produce a response. While we were not able to analyse strain rate directly, initial processing of ambient noise data around the Kaikoura earthquake suggests that strain rate may be important in provoking a change in seismic velocity.

4) **Identify geodetic and seismic methods that may be used as tools to monitor the relevant changes in the TVZ**
As dilational areal strain correlates most strongly with volcanic unrest, we suggest monitoring of baseline length changes between stations across the caldera. Baseline length changes between continuous GPS stations are an easy proxy for dilational strain. A baseline length increase suggest that dilational strain is occurring somewhere along the path between stations. This is an important point to note, as the newer geodetic processing and daily solutions provided by GeoNet have moved away from simple relative positions, and instead each individual station is normalized based on the average position. This normalization does not allow simple baseline length changes to be calculated unless the

averages are known. I suggest the GAMIT/GLOBK daily solutions not be normalized and be presented similar to the older processing. Normalization is easy to do from the relative position data, but relative position data and information about changes between two stations cannot be backed out from the normalized data without the averages.

ACHIEVEMENTS

- Finite element mesh and model creation. The finite element mesh is purely spatial and it can be used to analyse future slow slip events. The existing mesh could also be used to update stress and strain estimates as the NZ 3D velocity model improves.
- We now have a working hypothesis for why some SSEs trigger volcano unrest, and why other SSEs do not. The hypothesis is that dilation triggers response rather than absolute change in stress or strain.
- Paper published on the rates of earthquakes during Slow Slip events in New Zealand. The rate of earthquakes is shown to be increased during the times of slow slip events, and this work will have implications for future hazard models and on our understanding of how stress is accumulated and released during earthquake cycles.
- We have shown the importance of looking at seismic rates inside and outside the caldera separately. If seismicity all around the Lake Taupo area is used, the large amount of geothermal and fault related activity may mask activity that is more likely to be related to changes in the active magma system and caldera.
- Networking. The presentation of the work at conferences allowed me to connect with Matt Haney who is a well known Ambient Noise expert with an interest in calderas. I talked to him about the observations and challenges at Taupo caldera and this communication will hopefully spawn future work that brings international money and expertise to Taupo and other New Zealand calderas.
- Although the Ambient Noise interferometry results have been inconclusive so far, the general work processing them will help us develop standard techniques that may make it possible to use ambient noise for volcano monitoring.
- Two more papers summarizing these results are in process. One will focus on the finite element modelling and strain results along with the associated volcanic responses (especially 2008). The second paper will present the results of the Ambient Noise analysis and suggest a processing scheme for potential monitoring. The ambient noise paper has been held up by delays in processing and the occurrence of the Kaikoura earthquake. We think that the analysis of the Kaikoura response will add strength to the paper and help us address the topic of strain rate. EQC will be acknowledged in these papers and we will submit copies of the papers once published.

FINDINGS/LEARNINGS

Most Important:

The areal strain direction seems to be the primary control on whether SSEs are a ssociated with volcanic unrest. The deep 2008 SSE is the only event to have associated volcanic response. Inflation of a magma chamber could also produce the observed dilational strain. The finite element model of the 2008 SSE confirms that the observed dilational strain was not purely from a coincidental volcanic source, but that the SSE itself caused local areal dilation within the caldera.

Strain Rate:
The main slow slip events we compared with the Deep 2008 SSE, and the strongest phase of the Manawatu 2010 SSE. These events had similar durations and whle we identified major differences in strain direction, it was hard to estimate the difference in strain rate. Recent preliminary analysis of the response of Taupo caldera to the Kaikoura earthquake suggests strain rate may be an important factor to observing changes in velocity with Ambient Noise interferometry.

Ambient Noise:
Noise cross correlations at Taupo are not very coherent. Therefore, more initial processing must be done before looking for temporal changes. The small number of stations, and long inter-station distances does not allow many station pairs to be stacked which is an important step in detecting small changes. Future studies could augment the existing GeoNet network so that more stacking is possible. The stacking should also help to overcome some issues related to coherency.

Volcano monitoring implications:
Areal dilational strain is more likely to be associated with volcanic unrest. Therefore baseline length changes across the caldera should be monitored. When these begin to increase, other volcanic parameters should be given more scrutiny.

Potential Physical – Volcanic implications:
The finite element models produced strains that were much smaller than the observed strains. Changes in velocity model were not sufficient to account for these differences. Further investigation of the cause of the magnitude difference may lead to improved modelling of volcano responses to applied strain and to the physical properties of the caldera structure.

DISSEMINATION
We have presented this research at two New Zealand Geoscience conferences. With EQC funding support, we were also able to share this work at a specialized international Chapman conference on Slow Slip Phenomena. The work has been presented two other times internationally. Once at the AGU fall meeting last December, and most recently to a volcano specific IAVCEI conference this August. Titles and dates are given below.

GeoSciences NZ 2015 – poster, Far and Wide: Strains induced in the Taupo Volcanic Zone by Slow Slip Events in the Far-Field

Chapman Conference on Slow Slip Phenomena 2016 - poster, Impacts of Slow Slip Events on Volcanic Areas in the Fare-Field: An Example from the Taupo Volcanic Zone, New Zealand.

GeoSciences NZ 2016 – poster, Tracking Volcanic Responses to Far-Field Slow Slip in the Taupo Volcanic Zone, New Zealand

American GeoPhysical Union Fall Meeting 2016 – poster S33A-2821, Power at a Distance, the

Local FORCE(s) Associated with Far-Field Slow Slip in the Taupo Volcanic Zone, New Zealand

International Association of Volcanology and Chemistry of the Earth's Interior 2017 – (oral presentation, abstract attached) – Signatures of Regional Tectonics in Local Volcano Responses in the Taupo Volcanic Zone, New Zealand

In addition to these presentations, we also published a paper on rates of seismicity during slow slip events in the New Zealand Journal of Geology and GeoPhysics –

Jacobs, K.M., Savage, M. K, & Smith, E.C.G. (2016). Quantifying seismicity associated with slow slip events in the Hikurangi margin, New Zealand. *New Zealand Journal of Geology and Geophysics,* 59(a), 58-69. http://dx.doi.org/10.1080/00288306.2015.1127827