

# Seismic Hazard Implications of the Newer Volcanic Province, Australia

T. I. Mote<sup>1</sup> and M. M. L. So<sup>2</sup>

1. Corresponding Author. Associate Principal, Arup, Sydney  
Email: tim.mote@arup.com
2. Seismic Specialist, Arup, Sydney  
Email: minly.so@arup.com

## Abstract

The Newer Volcanic Province (NVP) is formed by edge driven convention (EDC) on the trailing edge of the continental lithosphere. The most recent activity was at Mount Gambier in South Australia, with the youngest eruption there estimated at approximately 4,300 years ago. This paper explores the seismic hazard implications and contribution to seismic hazard from the NVP by using volcanic eruptions as a proxy for historic earthquakes, comparison of the NVP to seismic hazard in analogue volcanic settings, and considers implications to current seismic hazard estimation in the region.

The paucity of observed earthquakes in the NVP suggests that seismic hazard is lower than the surrounding regions. Delineation of the NVP in site specific PSHAs based on seismicity and volcano-tectonic setting is appropriate and could have influence on the hazard calculated for Melbourne. A relationship between the older regions of the NVP with increased spatial density of eruptive centres and the youngest less spatial dense (Mt. Gambier) may suggest future locus of earthquakes. Using the volcanic eruption rate as a proxy for earthquakes shows that if every eruption generated an earthquake greater than ~M6.5 the seismic hazard would be increased. NVP eruption recurrence and the analogue EDC maximum magnitudes have similarity in rate and clustering to the Neotectonic features of Clark (2007).

Potential volcanogenic earthquake sources in the NVP should be incorporated into seismic hazard analyses when assessing higher importance level structures considering 1/2500, 1/5000 or 1/10,000 annual probabilities of exceedance.

**Keywords:** Newer Volcanic Province, Probabilistic Seismic Hazard Analysis, Volcanogenic Earthquakes, Volcanic Hazards, Victoria, Australia

## **INTRODUCTION**

Volcanic hazards are typically associated with eruptive events including lava flows, ballistic projectiles, tephra ash falls, pyroclastic flows, debris avalanches, and lahars. Earthquakes are genetically coincident with volcanic activity and often can generate ground motions large enough to damage structures. Most volcanogenic earthquakes originate within a few kilometres of the surface and result from the movement of magma, the formulation of cracks through which it can move, and gas explosions within the conduit (Blong, 1984). Other volcanogenic earthquakes result from the distribution of the load of the volcano and from caldera subsidence. There is an invariable spatial and temporal link between seismicity and volcanic activity.

Accounts of historic damaging volcanogenic earthquakes include:

- 64 A.D. Naples, Italy - While Vesuvio was erupting, a theatre collapsed soon after a performance by Nero (Blong 1984)
- 1868 Kilauea M7.9 (Klein and Wright, 2008)
- 1914 Sakura-jima - Japan M6.7
- 1957 Azores - MMI of X.
- 1975 Yellowstone - ML6.1
- 1975 Kilauea, Hawaii - M7.2
- 2006 Kiholo Bay, Hawaii - M6.7

The Pliocene-Holocene aged Newer Volcanic Province (NVP) in western Victoria, southeast Australia, is a monogenic volcanic field of the most recent volcanic activity of Australia. The NVP is considered to be partly formed by edge driven convection on the trailing edge of the continental lithosphere (Sutherland et al., 2013).

The most recent activity occurred at Mount Gambier in South Australia, with the youngest eruption dated at approximately 4300 years ago. There are currently no fumaroles, hot springs, or anomalous temperature gradients suggesting activity. Blong (1989) and Joyce (2004) suggest that there is a high volcanic risk in the NVP.

This paper explores the seismic hazard implications and contribution to seismic hazard from the NVP. The study presents the volcano-seismo-tectonic setting, uses volcanic eruptions as a proxy for historic earthquakes, compares the NVP to seismic hazard in analogue volcanic settings, and considers implications to current seismic hazard estimation in the region.

## **NEWER VOLCANIC PROVINCE**

### **Volcanic Setting**

The NVP is “volcanic field” characterised by small volume, short-lived, monogenetic eruptions (i.e. single eruptions) often associated with intraplate tectonic settings. The NVP constitutes a well preserved example of intraplate continental basalt plain province with the morphological characteristic of a volcanic field.

Covering an area of 15,000 km<sup>2</sup> and extends for 400km west of Melbourne, the NVP lava plains range in age from 4.5 Ma to 10ka and are covered by generally younger monogenic volcanism. Landsat mapping by Lesti et al. (2008) identified a total of 683

eruption points. Joyce (2004) identify over 200 cinder cones, 40 maars, tuff cones and tuff rings, 200 small shield volcanoes and valley-fill lava flows. The highest volcano is Mt Elephant rising 240m above the plains to an elevation of 393m above sea level. The most recent activity was at Mount Gambier in South Australia, with the youngest eruption there being dated to approximately 4300 years ago.

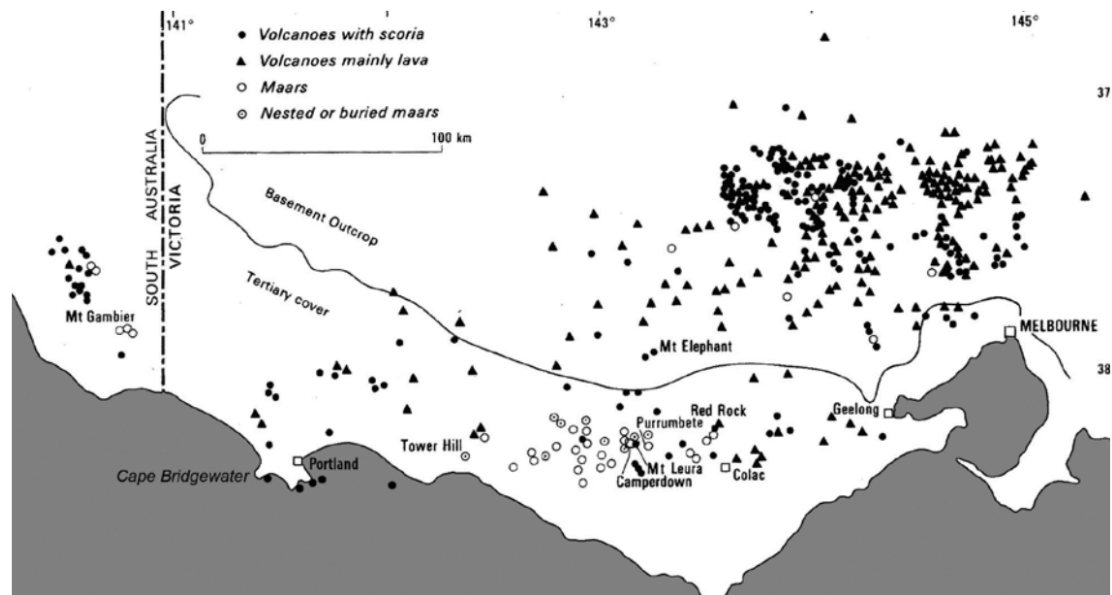


Figure 1 Eruption points of the NVP (Joyce 2004)

Three subprovinces have been identified in the NVP: the Central Highlands subprovince, north of Melbourne, the Western Plains subprovince, and the Mt. Gambier subprovince to the west (Figure 1). Mt. Gambier is separated by 50km from the nearest volcanoes of the western plain are the young volcanoes of Mt. Gambier and Mt. Schank.

Phreatomagmatic eruptions are almost exclusive of the Western Plains and Mt. Gambier subprovinces attributed to the presence of groundwater bodies in the Cretaceous-Pliocene Otway Basin sedimentary sequence which underlie the two subprovinces and which does not occur in the Central Highlands subprovince (Joyce 1975).

### Tectonic Controls

The eruption vents are strongly aligned and controlled by fracture zones, mainly along the NW-SE extensional structures, and to a lesser extent, along N-S reactivated Palaeozoic discontinuities. This setting is in agreement with the known NW-SE, recent horizontal orientation of the maximum stress.

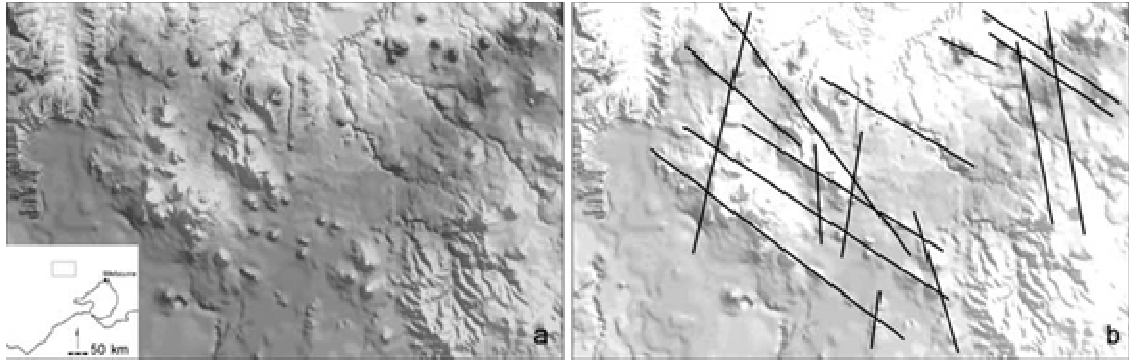


Figure 2 Spatial alignment of eruption points. (Lesti et al., 2008)

The total volume erupted in the time span of the NVP activity is fairly small and indicates low eruption rates the absence of substantial differentiation stages and crustal contamination during this implies that the mobilisation of magma from subcrustal reservoirs to the surface relates to tectonic triggers able to induce sudden and short-lived decompression on the mantle source withdrawing small batches of magma (Lesti et al., 2008). Takada (1994) suggested that plains basalt monogenetic fields relate to low magma supply rate and/or high strain rate which do not favour the interconnectivity of conduits and therefore the formation of crustal magma chambers and polygenetic volcanoes.

Without the tectonics stress reactivating weakness in the crust it is probable that the small quantity of magma would not be able to reach the surface.

## EDGE DRIVEN CONVECTION

The intraplate signature and the localization on the northern side of the Southern Ocean have been used in the past to ascribe the volcanic activity either to the presence of a mantle hot spot or to thermal anomalies inherited from the seafloor spreading that separated Australia from Antarctica during the Gondwana breakup.

Not every hotspot is related to a deep-mantle plume and there a number of examples of intraplate volcanoes that have never been suggested to be related to a mantle plume. The mechanism of these intraplate events is poorly understood; however small-scale convection triggered at the edge of a continent or craton is a proposed mechanism (King, 2007). Edge driven convection (EDC) is where a small-scale convective instability (induced by local variations in lithospheric thickness) displaces hot mantle material upward, provides an alternative hypothesis for such volcanism. Figure 2 shows the global deep mantle plume (black) and edge drive convection hot spots (white).

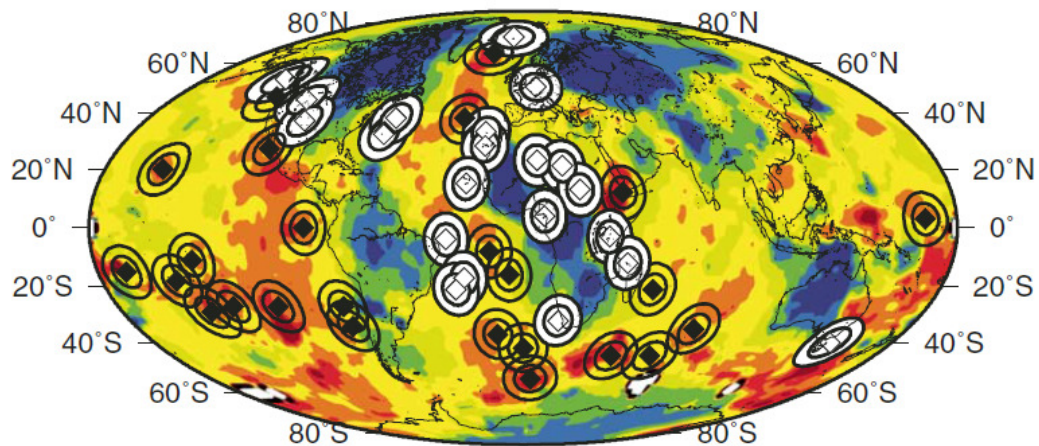


Figure 3 Global hotspots - edge driven convection in white, deep mantle in black (King, 2007)

EDC has been postulated as the trigger for Quaternary intraplate volcanism in Australia, due to the proximity of the craton edge.

To explain why the NVP is contained within a  $400 \times 100$  km region, yet the Precambrian shield region of the Australian continent has a boundary that is at least 10,000 km long, Davies and Rawlinson (2014) show that step changes in lithospheric thickness, which occur along craton edges and at passive margins, produce volcanism only at isolated locations.

Figure 4 shows the slotted and stepped nature of the base of the lithosphere north of the NVP. As the Australian Plate moves northward EDC generates the NVP.

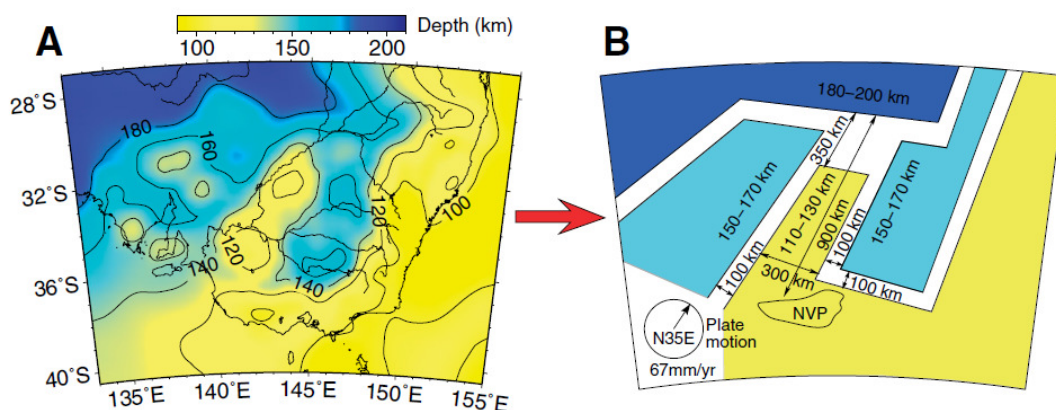


Figure 4 Global Hotspots - edge driven convection in white, deep mantle in black (Davies and Rawlinson, 2014)

## OBSERVED SEISMICITY

Little seismic activity is on record within the NVP over the past ~100 years since the magnitude 5.3 Warrnambool earthquakes of 1903 and the offshore magnitude 6.5 Kingston/Beachport (SA) earthquake of 1897 (Figure 5). Love et al., (2004) has suggested that a number of smaller earthquakes in the NVP may be generically related to the volcanoes in the area due to their depth.

The paucity of earthquakes in the NVP is anomalous to earthquake density that surrounds the NVP (Figure 4). This is clearly shown by the distribution of seismicity in Figure 4 and the termination of seismic along faults at the NVP northern boundary (Gary Gibson personal communication). The Australian Neotectonic features from Clark (2007) are generally not observed in the NVP and inferred to be covered by lava flows.

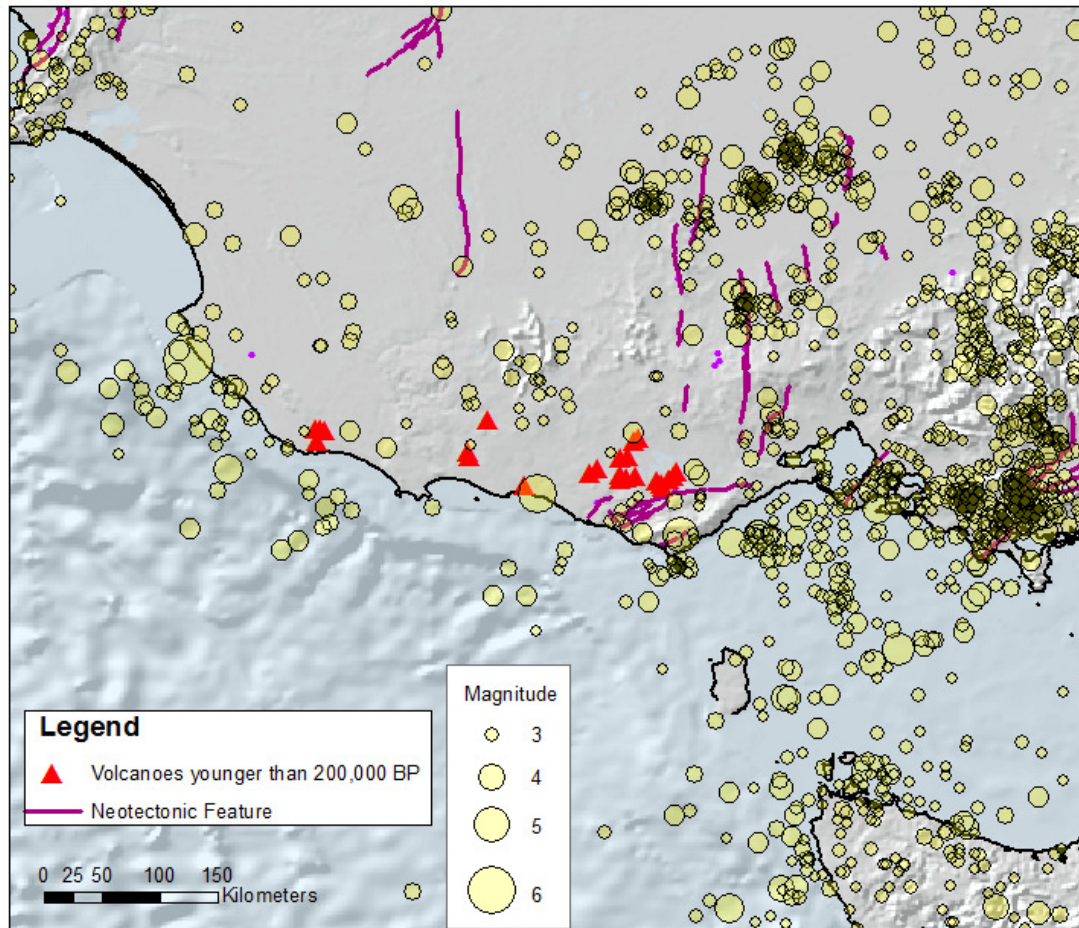


Figure 4 Volcano-Seismo-Tectonic Setting

## EDGE DRIVEN CONVECTION ANALOGUES

### Canary Islands

Edge driven convection analogues to the NVP include the Canary Islands, which has seen active volcanism since Miocene times. The group of volcanic islands is localised on the Eastern Atlantic passive margin, on the ideal Western projection of the South Atlas Fold Belt. The Canary Islands were subjected to a M5.2 earthquake in 1992 and palaeoseismicity studies suggest that a historic M6.8 earthquake occurred based on the liquefaction of beach deposits.

### Yellowstone

The Yellowstone volcanic area is an example of intraplate edge driven convection. The earthquake hazard in the Teton-Yellowstone area is the highest in the US Intermountain region (Peterson et al., 2008).

It is influenced by the active Basin-Range Province 700km west and the Yellowstone volcanic sources. The effects of the Yellowstone hotspot have a profound effect on seismicity in Yellowstone and on the surrounding fault zones (White et al., 2009). Seismicity in the Yellowstone caldera is characterised by clusters of mainly shallow earthquakes (< 5km). Notable seismicity includes a 1975 ML6.1 event. Focal depths show a shallowing across the caldera explained by a lowering of the brittle-ductile transition layer due to elevated temperatures in the magma chamber.

## **NVP SEISMIC HAZARD IMPLICATIONS**

Australian volcanologists state that further eruption in the NVP is possible and well may be overdue (Blong, 1989) with a future eruption would not be the renewal of activity at an existing volcano, but the initiation of a new volcano (Joyce, 2004).

In this review of published research on the NVP, although volcanic risk is suggested, there was no quantitative assessment of the likelihood or location of future events.

### **Seismicity Considerations**

The lack of observed seismicity in the last 100 years across the NVP would support a reduction in seismic hazard based on traditional PSHA earthquake areal source zone delineation and earthquake recurrence calculation.

The Geoscience Australia (GA) National Seismic Hazard Map PSHA source zones (Leonard et al., 2014) that covers the NVP can be used to exemplify the potential implications to seismic hazard on a site-specific scale.

Figure 5 shows the spatial density of earthquakes in the GA model and the areal source zones used in the PSHA. Zone 9 covers both the low earthquake density of the NVP and increased density east of Melbourne. If a single earthquake activity rate is used for this zone it will increase the hazard for sites in the NVP and decrease the hazard for sites east of Melbourne.

Site specific PSHAs in the region should delineate the NVP as separate areal source zone as there is an observed decrease in seismicity and plausible seismotectonic reason why this occurs.



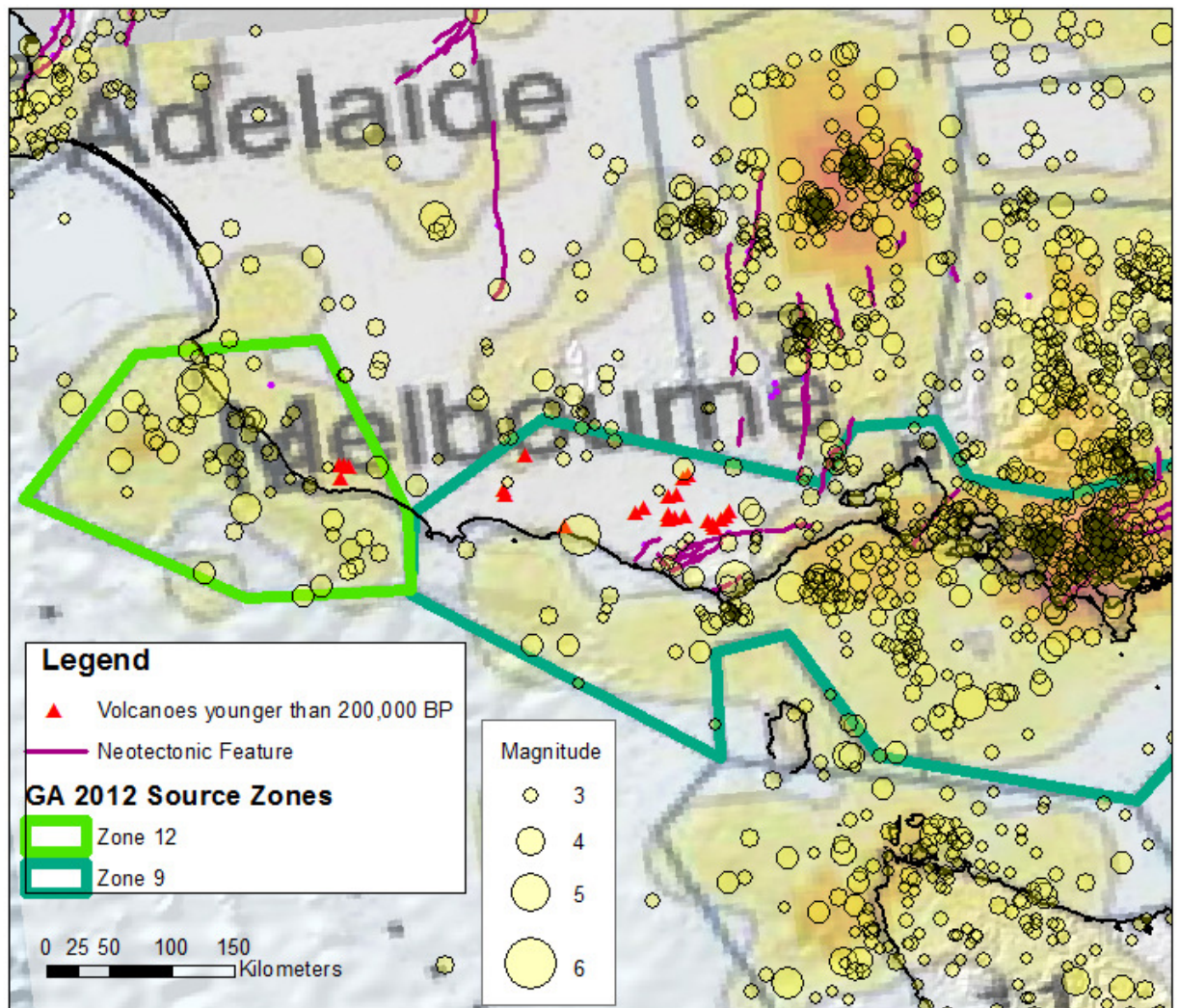


Figure 5 Spatial density of earthquakes and source zones from GA PSHA model (Leonard et. al. 2014) in relation to the NVP.

### Eruption Density

Lesti et al. (2008) completed a spatial density analysis of the eruption centres and noted that the density of the older NVP areas (in the north and west) were relatively equal, but the predominantly younger (e.g. Mt Gambier) areas showed a reduction in spatial density of eruptive centres.

A relationship between the younger (on-going?) activity and lower density of eruptive centres is hypothesised.



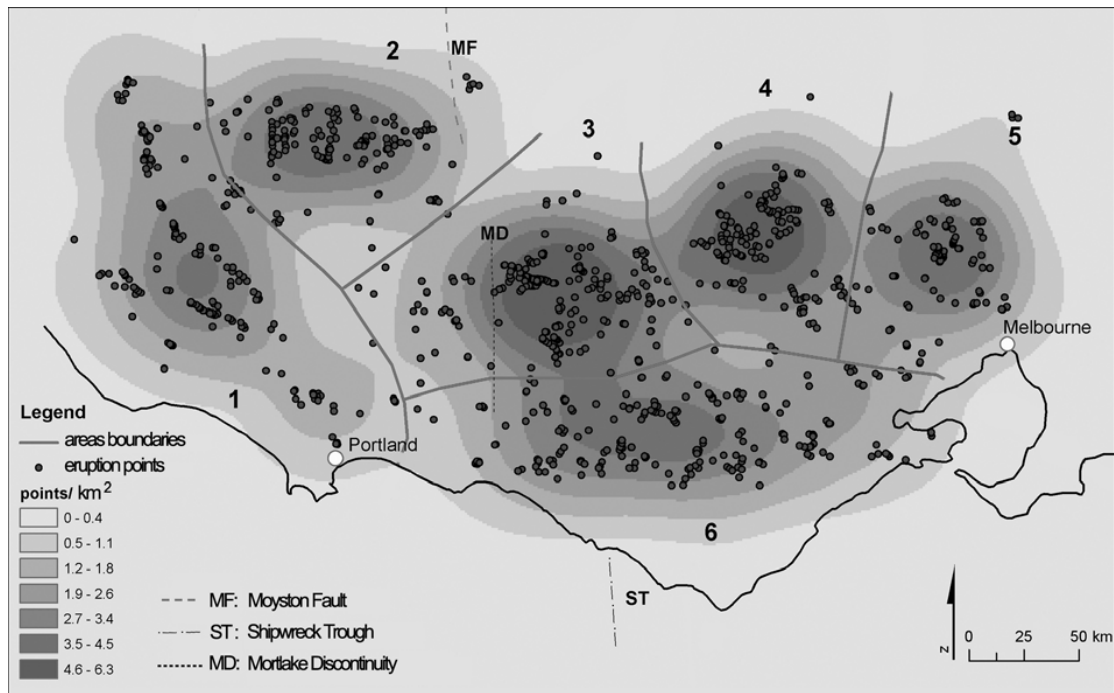


Figure 6 Spatial density of eruptive centres (Lesti et al., 2008)

### Volcanogenic Earthquake Recurrence

An approximate eruption recurrence can be roughly calculated at ~10,000 years based on 400 of eruptions over 4.5Ma from Joyce (2004). This estimate can be revised with the Landsat TM mapping from Lesti et al. (2008) of 683 centres to ~6,000 years. Considering the 25 eruptions younger than 200,000 years, equates to a rate of ~8,000 years and within the same order of magnitude as the 4.5Ma estimates.

Joyce 2004 notes that the volcanic centres are shown to occur in clusters and have a shorter recurrence interval (~2,000 years) between events, but longer quiescence between clusters. This is similar to the fault rupture recurrence of Australian neotectonic features (Clark, 2007) and supports the tectonic-volcanic link. The same stress field and plate motion rate that drives the seismicity in Australia also drive the EDC.

By using a volcanic eruption as a proxy for an earthquake, the earthquake catalogue could potentially be supplemented out to 200,000 years or 4.5Ma. The size of the earthquake associated with each volcanic eruption or lava flow is unknown.

Figure 6 shows a calculation of recurrence for an areal seismic source zone similar to the GA model Zone 9 (Leonard et al., 2014). The blue bar represents the annual frequency of volcanic eruptions in the NVP. The figure shows that if each eruption is used as a proxy for an earthquake, the magnitude the earthquakes would have to be greater than ~M6.5 to significantly influence the recurrence curve for the region and the subsequent calculation of hazard.

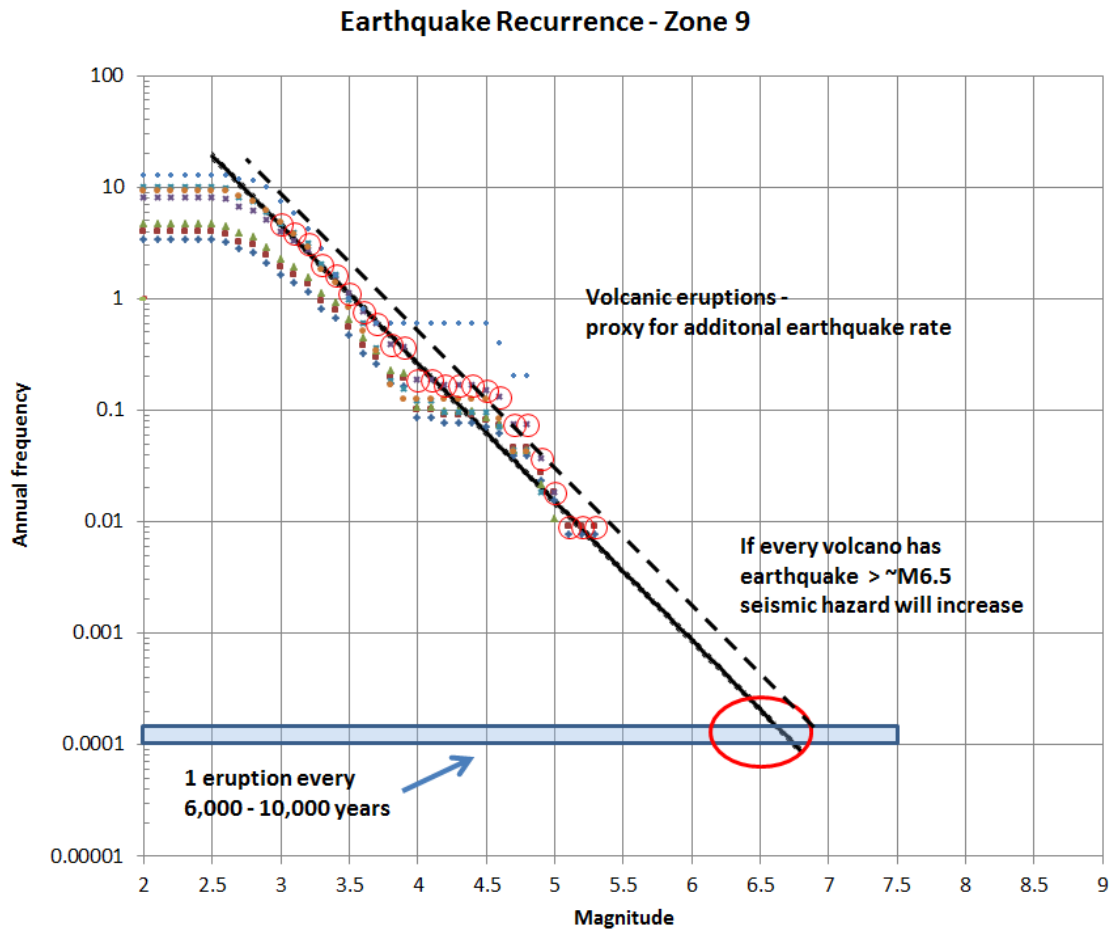


Figure 7 Recurrence curve for the NVP source zone showing the annual frequency of volcanic eruptions

### Analogue Edge Driven Convection Hazard Studies

Seismic hazard from the analogue EDC volcanic provinces are considered for reference. A recent PSHA for the volcanically active Canary Islands by Gonzalez de Vallejo et al. (2006) reports a PGA of 0.06g for a 1/500 annual probability of exceedance. This is less than the AS1170.4 for the NVP at the same annual probability of exceedance.

Scenario planning for a Yellowstone eruption includes earthquake events up to M6.6 (Figure 8) and shows an area (yellow) ~50km across that exceed the Australian 1/500 annual probability of exceedance seismic hazard values.

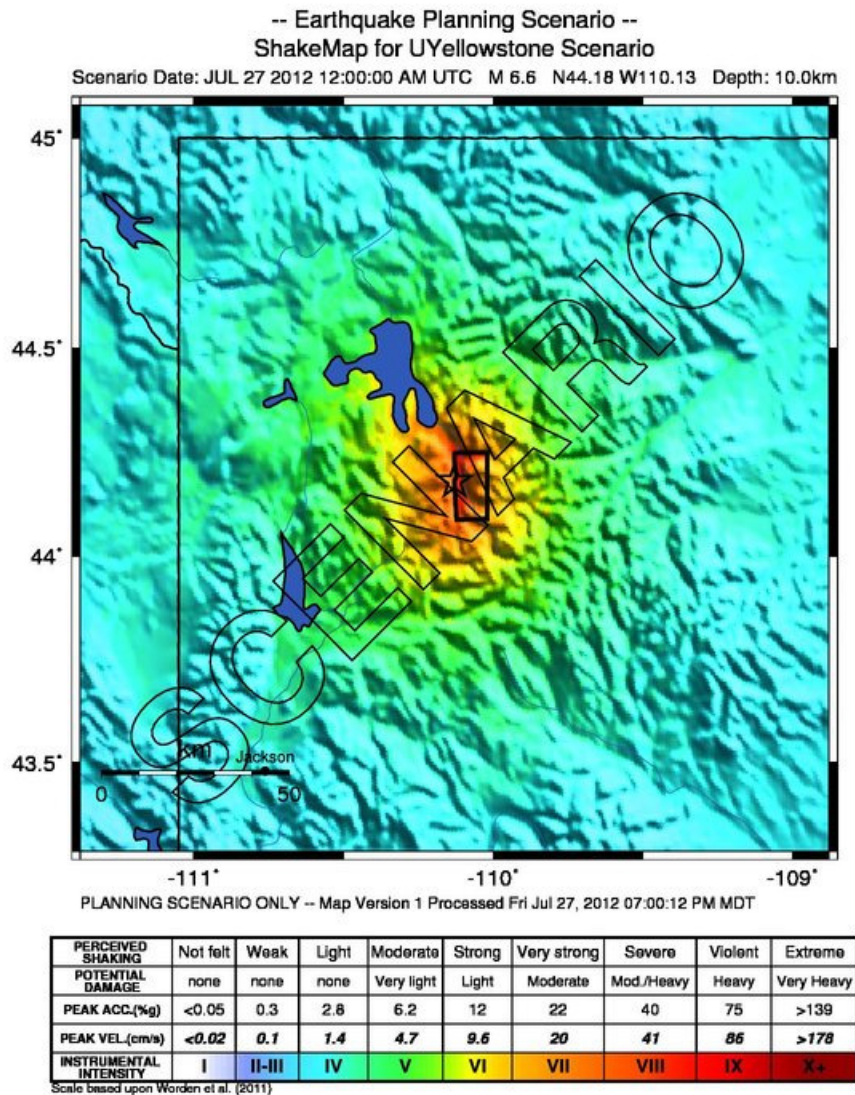


Figure 8 Yellowstone Caldera Earthquake Scenario Shake Map

### Hazard Implications

Figure 9 is the GA National Seismic Map at SA 1.0 second for a 1/10,000 annual probability of exceedance with the young (< 200,000 year) volcano centres and the earthquake catalogue (Leonard et al., 2012). The yellow shading is elevated ground motions. This figure shows that in the Mt. Gambier area the 1/10,000 annual probability of exceedance hazard is lower than the areas associated with recent seismic activity.

In this area, the consideration of large volcanogenic earthquake with a recurrence on the order of 10,000 years would increase the hazard. Somerville & Thio (2011) state active faults having slip rates of 0.1mm/yr or more in intraplate Australia contribute more to hazard at the longer return periods than the distributed earthquake source zones. A 0.1mm/yr slip rate would equate to 1m of slip over 10,000 years or a ~M7.0 earthquake every 10,000 years following Wells and Coppersmith (1994).

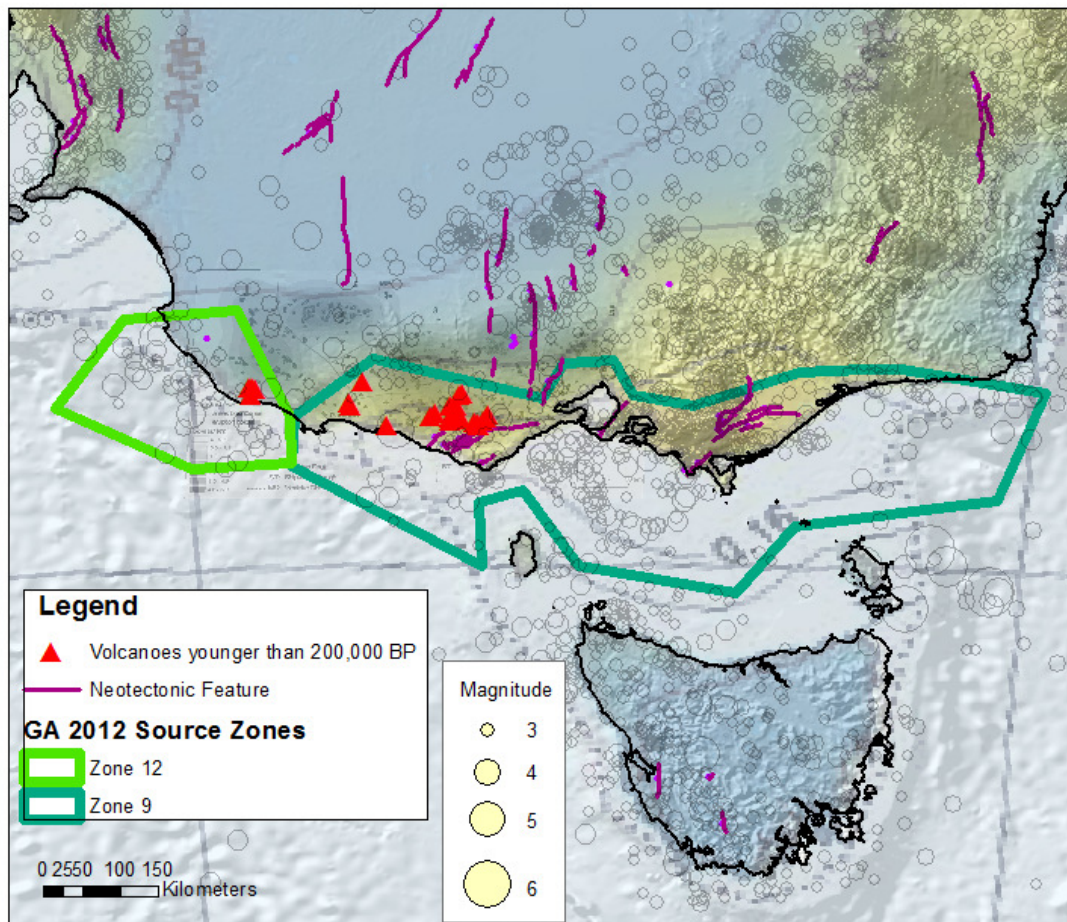


Figure 9 GA 2012 hazard map for SA 1.0s at 10,000 year return period.

### Attenuation Models

One consideration worth noting, but beyond the scope of this study, is the influence of volcanic specific attenuation relationships or ground motion prediction equations on estimation of ground motions in volcanic zones.

## CONCLUSIONS AND DISCUSSION

The Newer Volcanic Province is a formed by edge driven convention on the trailing edge of the continental lithosphere. The most recent activity was at Mount Gambier in South Australia, with the youngest eruption there estimated at approximately 4300 years ago.

The total volume erupted in the time span of the NVP activity is fairly small and the monogenetic fields relate to a high strain rate. Without the tectonics stress reactivating weakness in the crust it is probable that the small quantity of magma would not be able to reach the surface.

Although there are no fumaroles, hot springs, or anomalous temperature gradients suggesting present activity, there is no reason why the volcanic activity would not continue considering the current plate tectonic regime. An approximate eruption recurrence is on the order of ~10,000 years.

The paucity of observed earthquakes in the NVP suggests that seismic hazard is lower than the surrounding regions. Delineation of the NVP in site specific PSHAs based on seismicity and volcano-tectonic setting is appropriate and could have influence on the hazard calculated for Melbourne.

The older regions of the NVP has increased spatial density of eruptive centres while the youngest (Mt. Gambier) has the least dense. A relationship between the younger (on-going?) activity and lower density of eruptive centres is hypothesised.

Using the volcanic eruption rate as a proxy for earthquakes shows that if every eruption generated an earthquake greater than ~M6.5 the hazard could be increased. Although, the analogue EDC volcanic centres consider M6.6 scenario earthquakes and infer M6.8 events from palaeoseismicity, it seem unlikely that the volcanogenic earthquakes would add to the recurrence calculation unless eruption rates of ~2,000 or less are used. The eruption recurrence, and the analogue EDC maximum magnitudes, have similarity in rate and clustering nature to the Neotectonic features of Clark (2007).

Potential volcanogenic earthquake sources in the NVP should be incorporated into seismic hazard analyses when assessing higher importance level structures considering 1/2500, 1/5000 or 1/10,000 annual probabilities of exceedance.

## REFERENCES

- Blong, R. J. (1984) Volcanic Hazards, A sourcebook on the effects of eruptions. Academic Press.
- Blong R. J. (1989) Intraplate volcanism in Eastern Australia and New Zealand. Cambridge University Press compiled by R. W. Johnson.
- Clark, D. (2007) A seismic source model based on neotectonics data. Proceedings of the Australian Earthquake Engineering Society.
- D. Rhodri Davies and Nicholas Rawlinson (2014) On the origin of recent intraplate volcanism in Australia Geology, first published on October 17, 2014, doi:10.1130/G36093.1
- Gary Gibson (2014) personal communication
- Joyce, B. (2004) The young volcanic regions of southeastern Australia: Early studies, physical volcanology, and eruption risk. Proceedings of the Royal Society of Victoria 116(1):1-13. ISSN 0035-9211.
- King, S. D. (2007) Hotspots and edge-driven convection. Geology 2007;35;223-226
- Klein, F. W. & Wright T. (2008) Exponential decline of aftershocks of the M7.9 1868 great Kilauea earthquake, Hawaii, through the 20th Century. Journal of geophysical research 113 (B9).
- Leonard, M., Burbidge, D. & Edwards, M. (2013) Atlas of Seismic Hazard Maps of Australia. Geoscience Australia Record 2013/2014 GeoCat 77399.



Lesti C.,Giordano G.,Salvini F., and Cas R. (2008) Volcano tectonic setting of the intraplate, Pliocene-Holocene, Newer Volcanic Province (southeast Australia): Role of crustal fracture zones JOURNAL OF GEOPHYSICAL RESEARCH, VOL. 113, B07407, doi:10.1029/2007JB005110, 2008

Love, D., Gibson, G. & McCue, K. (2004) Anomalous tectonism in Southeast South Australia. Proceedings of the Australian Earthquake Engineering Society.

Petersen, Mark D., Frankel, Arthur D., Harmsen, Stephen C., Mueller, Charles S., Haller, Kathleen M., Wheeler, Russell L., Wesson, Robert L., Zeng, Yuehua, Boyd, Oliver S., Perkins, David M., Luco, Nicolas, Field, Edward H., Wills, Chris J., and Rukstales, Kenneth S., (2008), Documentation for the 2008 Update of the United States National Seismic Hazard Maps: U.S. Geological Survey Open-File Report 2008-1128, 61 p.

Somerville, P. & Thio, H. K. (2011) Epistemic Uncertainty in Seismic Hazard Analysis for Australia. Proceedings of the Australian Earthquake Engineering Society.

Sutherland, F.L., Graham, I.T., Hollis, J.D., Meffre, S., Zwingmann, h., Jourdan, F., Pogson, R.E. (2013) Multiple felsic volcanism, Southeast Australia: inputs in appraising proposed magmatic models. Australian journal of Earth Sciences 61, 241-267.

Takada, A. (1994) The influence of regional stress and magmatic input on styles of monogenetic and polygenetic volcanism, J. Geophys. Res., 99(B7), 13,563 – 13,573, doi:10.1029/94JB00494.

White, B. J. P., Smith, R. B., Husen, S., Farrell, J. M. & Wong, I. (2009) Seismicity and earthquake hazard analysis of the Teton-Yellowstone region, Wyoming.

Wells, D. L., and Coppersmith K. J. (1994) New empirical relationships among magnitude, rupture length, rupture width, rupture area, and surface displacement. Bulletin of the Seismological Society of America 84.4: 974-1002.