MID-CRUSTAL EPISODIC GRANULAR VORTICES CAN BOOST ANOMALOUS HEAT-RELEASE IN THE TAUPO VOLCANIC ZONE NZ

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ABSTRACT

The Taupo Volcanic Zone (TVZ) in New Zealand is famous for its focussed heat transfer causing massive historic ultra Plinian eruptions, the latest observed in 186 AD in ancient Rome through vivid sunsets. The quantities of heat measured at the surface place the TVZ into an extreme position. Previous explanations have solved the extreme focusing of heat in the upper 5-8km of the crust through fluid convection, along channelized and anomalously high localised heat sources below. However, the question remains, where does the heat come from? Here we show that, by considering the tectonic setting of high speed extension of the crust by 2 cm/yr in a zone of 40km width, solid vortices are triggered that can explain the heat flow anomaly. We found that vortices of approximately 10 km radius with the high extension velocity directly boost the heat transfer into the upper crust. A system that has a vortex lifetime larger than 100k years increases the heat transfer by a factor of 2-5. This rationalises the observed anomalies, and casts a new light on the mechanism causing ultra-Plinian eruptions. Our results demonstrate the role of solid vortices, recently discovered in granular physics, for solving long-standing anomalies of heat transfer in shear zones. Similar observations of heat focussing have been made for the Unzen Graben in Japan and the Himalayan Geothermal belt. The model can equally explain the defocussing of heat measured across the fault following the Chi-Chi earthquake or the heat flow paradox of the San Andreas Fault.

1. INTRODUCTION

The magnitude of the heat released in the Taupo Volcanic Zone (TVZ) has challenged our understanding of how volcanoes operate and why enormous quantities of heat are ejected in particular settings. According to Wilson and Rowland (2016) the four key questions that need an answer are: (i) Why is the heat release so centralised within the TVZ? (ii) Why is there the spatial separation of geothermal systems and volcanism within the central TVZ? (iii) How stable are the geothermal systems in their positions? (iv) What leads to their episodicity? In this paper we present a new mechanism that allows ultra-focused deformation, which can significantly boost the heat release and leads to spatially heterogeneous and hot spot-like episodic geothermal systems.

New Zealand is famous for its geothermal manifestations (geysers, mud volcanoes, boiling springs, sinter terraces, steaming grounds etc.) that appear throughout the TVZ in extremely localised hot spots illustrated by the electrical resistivity map shown in Figure 1. The TVZ is an extensional basin coinciding with the subduction related volcanic arc in the North Island of New Zealand (Stern *et al.*, 2010). Geodetic (Darby *et al.*, 2000), GPS (Holden *et al.*, 2015), differential interferometric synthetic radar DInSAR (Samsonov *et al.*, 2011, Hamling *et al.*, 2015) measurements and plate tectonic considerations (Beavan *et al.*, 2002) have inferred an extension velocity of 7-20 mm/yr (Figure 1). An estimated volume of over 10,000 km^3 of rhyolitic magma has erupted in the last 2 Myr over the larger historic area of the TVZ (Carter *et al.*, 2003) while andesitic, basaltic and dacitic volcanism are minor (Sutton *et al.*, 1995) in volume (< 100 km^3). Age dating and petrological arguments suggest that the lifetimes of the rhyolitic intrusions appear to be extremely short and in the range of thousands of years or less (Wilson & Rowland, 2016).

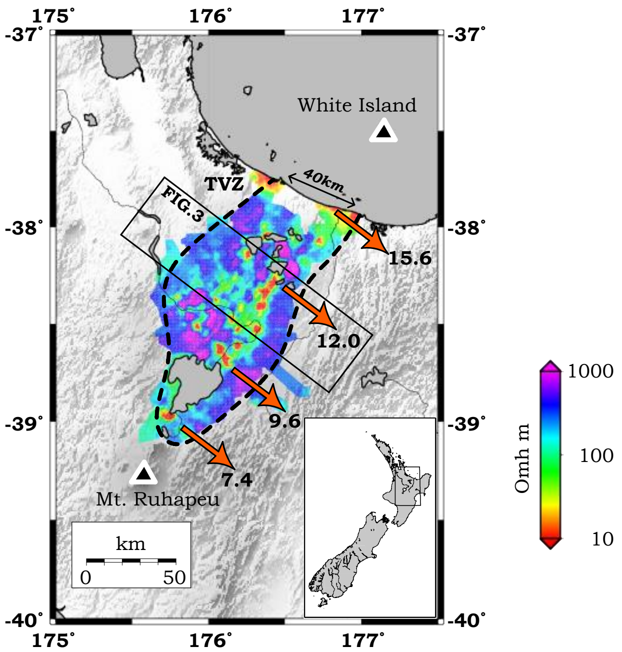

Figure 1: New Zealand hot geothermal systems in the Taupo Volcanic Zone (TVZ).

The geothermal activity is mostly located between the Kawerau and Taupo geothermal fields with a characteristic 10 –15 km spacing of geothermal manifestations (Wilson & Rowland, 2016). The present activity, traced in Figure 1 as low electrical resistivity, is located predominantly towards the eastern margin of the graben structure (Bibby, 1988). The figure is based on a 500m Schlumberger array spacing of unpublished apparent resistivity data courtesy of GNS Science, NZ). The minima in the resistivity map (red) co-locate with the sites of strongest geothermal activity. Besides their spatial separation of hot spots, with a ~ 10 km across strike distance, there is no discernible spatial pattern. They seem to appear in a chaotic fashion temporally and spatially. Extension rate (Wallace *et al.*, 2004) of the TVZ are shown by arrows in mm/yr.

In depth, the hydrothermal fields are restricted to the upper 5-8 km of the seismogenic crust presenting highly localised channels of hydrothermal upwelling surrounded by broader zones of downwellings (Kissling *et al.*, 2009). The heat transfer of the geothermal belt averaged over the 40 km width has been estimated (Bibby *et al.*, 1995, Hochstein, 1995) to be around 700 mW/m^2. This value is at least an order of magnitude larger than heat transfer in a normal crustal setting where heat transport to the surface is dominated by conduction.

2. MATERIALS AND METHOD

2.1 Hypotheses

Although the heat transfer processes in the top 5-8 km of the crust are relatively well understood hydrothermal systems, both the highly localised heat source and the efficient heat transfer through the ductile crust below the 8 km mark are yet to be explained. Three different heat sources and heat transfer mechanisms have been suggested (Hochstein, 1995). The heat sources include: (1) a mantle plume, (2) magmatic underplating and (3) local heat generation by shear heating. Heat transfer mechanisms include (1) anomalous magmatic convective or conductive transfer from the base of the crust (20-30 km depth), (2) convective heat transfer via geothermal fluids in the top 8 km and (3) heat transfer by volcanic extrusion or pyroclastics.

As candidates for heat sources, the magmatic underplating as well as the local crustal shear heating hypothesis are both plausible (Hochstein, 1995). It has been shown that the latter can explain an additional local heat source in the ductile crust to generate the anomalous volumes of crustal melts. However, effective heat transfer through convection of fluids only occurs in the upper 5-8 km (Kissling *et al.*, 2009). Efficient heat transfer of *fluid-like convection* through thermally driven magmatic buoyancy of the hot crustal melts alone can be ruled out due to the high viscosity of the silicic melt.

Recently, a mode of heat transfer of granular, *solid-like convection* was discovered in experiments (Miller *et al.*, 2013) (see Figure 2) which can arise in shear zones through correlated motions of velocity and temperature fluctuations as shown by computer simulations (Griffani *et al.*, 2013). In this paper we propose to solve the problem of heat transfer in the ductile crust through accounting for this highly efficient mode of heat transfer.

Classical models for continental extension consider a pure shear environment (McKenzie *et al.*, 2005) where no rotations of the solid crust are expected. A similar depth-integrated model has been used to infer the heat generated by plastic deformation in the TVZ where a local uniform heat source in the crust with a maximum at the brittle-ductile transition was found to generate around 0.8 GW of heat per 100 km volcanic arc length of TVZ (Hochstein *et al.*, 1993). While this model could explain the anomalous generation of crustal melts in Kyushu, Sumatra and the TVZ, the model also predicted a uniform heat distribution across the entire 40 km of opening displacement. This inference is clearly at odds with the observations of localised heating along the eastern graben shoulder of the TVZ.

The classical crustal pure shear extension models (McKenzie *et al.*, 2005, Hochstein *et al.*, 1993) do not consider the natural rheological layering of the crust and mantle, which can introduce vorticity. The most notable layering is the brittle ductile transition in the upper crust (here assumed to be around the 5-8 km depth mark due to the elevated temperatures) and the transition from a quartz dominated creep rheology to a feldspar dominated response at greater depth, followed by an olivine-rich material in the mantle. Simulations of continental extension considering these layers reveal the emergence of detachments at the brittle ductile transition (Regenauer-Lieb *et al.*, 2006) with rotations of upper crustal blocks and vorticity in the layers below owing to the nucleation of ductile shear zones. The TVZ is an extreme end-member of continental crust, where in addition to the natural rheological layering pervasive partial melting in the middle to lower crust is inferred (Deering *et al.*, 2008).

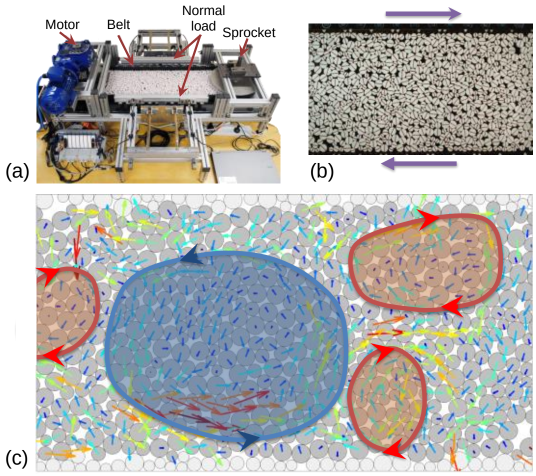

Figure 2: Simple shear experiments with a Stadium Shear Device[20] of 2D granular systems. (a) Experimental setup. (b) Snapshot of the media at random time with boundary conditions highlighted. (c) Velocity fluctuations of grain motion (grain velocity minus mean velocity field established over time). Correlated grain motions are clustered in spatiotemporal episodic vortices identified by coloured arrows (clockwise and counter clockwise vortices are highlighted by red and blue, respectively). Note that the largest (blue) vortex is as large as the minimum system's dimension.

The partially molten crystal mush (Singh *et al.*, 1998) is likely to show a very high degree of complexity with heterogeneous deformation where melt bands segment solids in multiple directions and significant folding and rotations of the mush zone give rise to a complex morphology. These structures imply that the middle to lower crust of partially molten rocks behave fundamentally different to the classical theories.

The interesting aspect for the TVZ is that for such a heterogeneous medium the fluctuations in both temperature and velocities can self-organize at all scales in a new mode of heat and mass transfer. The problem can be looked at as a system of fragmented solid blocks in the mush zone segmented by viscous melt bands and inferred crustal fluids (Reyners *et al.*, 2007) that occasionally have solid-solid collisions. The peculiar deformation patterns in the crystal mush zone can be modelled efficiently by considering these solid interactions, which constrain melt migration. Interactions are known to constrain motions of the solid parts into granular vortex structures (Fig. 2). Similar structures have been observed experimentally in sheared granular media under biaxial loading of disks systems (Richefeu *et al.*, 2012) and triaxial loading of sand (Rechenmacher *et al.*, 2011) and numerically in the work of Radjai and Roux (Radjai & Roux, 2002).

2.1 Heat Vortices

Here, we show that granular vortices of velocity fluctuations can potentially grow to the order of the system size, which makes them crucial for heat transfer. In order to investigate the self-organisation under idealised shear conditions we appeal to the fact that the TVZ is an elongated feature and thus conditions of plane strain may approximately apply in a cross-section perpendicular to the long axis. This 2D shearing condition is reproduced in Figure 2 by an experiment of densely packed PVC cylinders subjected to simple shear using the stadium shear device (Miller *et al.*, 2013). Figure 2c shows the emergence of episodic vortices, which when applied to the TVZ should appear as pulses of self-organisation of the crystal mush into large-scale horizontal axis rolls. When considering thermal gradients, such conditions have been shown to provide extremely efficient heat transfer (Rognon & Einav, 2010). Coupled with heat transfer and local shear heating, the mechanism of granular-like vortices of partially molten crystal mush explains the extreme focussing of deformation into channels which in addition produce heat much more locally than the classical pure shear heating models (Hochstein *et al.*, 1993). This explains questions (ii) to (iv) posed by Wilson and Rowland (2016) (spatial separation, stability, and episodicity of geothermal systems) and can explain the generation of anomalously hot and relatively dry rhyolitic melt (Deering *et al.*, 2008). The solution of the first question (i) of why the deformation is macroscopically localised in the extremely narrow zone of the TVZ depends on the broader scale of the boundary conditions provided by the plate tectonic problem and can be solved by the method of characteristics (Hochstein *et al.*, 1993). This macroscopic localisation phenomenon provides the necessary boundary conditions for the mesoscopic mid-crustal vortices that can boost shear heating and transports heat through the advecting narrow channels (Kissling *et al.*, 2009).

For a layer of 20 km thickness we show that the partially molten crystal mush material self-organises into granular-like vortices *R* of ~10 km size. Figure 3 illustrates the corresponding model and indicative dimension of a cross section through the TVZ. We show that for conditions in the TVZ the determinant factor of self-organised vortex size is the smallest system dimension (here assumed to be the thickness). In the following we show that the vortex size in the TVZ is determined by the crustal thickness, **L**. Recent experiments with a sheared granular system shows dependence of the vortex radius **R** on grain size **d** and inertial number **I** through (Rognon *et al.*, 2015):

$$\mathrm{R} \approx \frac{2\mathrm{d}}{\sqrt{\mathrm{I}}} \qquad (1),$$

where $\mathrm{I} \approx \frac{\mathrm{vd}}{\mathrm{L}}\sqrt{\frac{\rho}{\sigma}}$, with v being the extension rate, ρ the bulk density, and $\sigma = \rho g H$ the average lithostatic stress in the TVZ's crust (while g is the gravitational acceleration). In the TVZ $\mathrm{L} \approx \mathrm{H}$.

The above equation is correct, only if it yields a vortex radius value smaller than $\mathrm{L}/2$. Otherwise, the vortex radius is truncated by the boundaries, i.e. it is then given as $\mathrm{R} = \mathrm{L}/2$. It follows that the minimum grain size $\mathrm{d}_{\mathrm{min}}$ required to generate a vortex of $\mathrm{L}/2$ is given by the following formula (taking $\mathrm{L} \approx \mathrm{H}$ for the TVZ):

$$\mathrm{d}_{\mathrm{min}} \approx \frac{\mathrm{v}}{16}\sqrt{\frac{\mathrm{L}}{\mathrm{g}}} \qquad (2).$$

For $\mathrm{v} = 10\ \mathrm{mm/year}$ and $\mathrm{L} = 20\ \mathrm{km}$ corresponding to the TVZ we find $\mathrm{d}_{\mathrm{min}} \approx 10\ \mathrm{nm}$. Since the crystal mush underneath the TVZ has a typical microscopic unit much larger than $10\ \mathrm{nm}$, we conclude that the vortex radius in the TVZ is controlled by the crustal thickness, $\mathrm{R} = 10\ \mathrm{km}$. This is in agreement with the observation of Figure 2 where the largest granular vortex is as big as the width of apparatus.

2.2 Dimensional Analysis

In order to assess the role of the increase in thermal efficiency by such vortices compared to the advection-diffusion process alone, we perform a dimensional analysis of the increased heat transfer. In both numerical and laboratory experiments the vortices can either be episodic structures, which show a linear increase of the heat transfer with respect to the Péclet number, or a quasi-stationary vortex which features a reduced square-root scaling of thermal efficiency versus the Péclet number.

For long lived vortices it has been found by solving the advection-diffusion equation of a vortex rotating as a rigid body in a solid medium (Griffani *et al.*, 2013) that thermal efficiency scales as $\mathrm{Nu} = \mathrm{Q}_{\mathrm{conv}}/\mathrm{Q}_{\mathrm{cond}} \approx \mathrm{Pe}^{0.5}$, where $\mathrm{Q}_{\mathrm{conv}}$ and $\mathrm{Q}_{\mathrm{cond}}$ are the convective/advective and conductive heat transfers and $\mathrm{Pe} = \frac{\mathrm{R}^2\mathrm{f}}{\mathrm{D}_0}$ is the Péclet number, with $\mathrm{R} = \frac{\mathrm{L}}{2}$ is the vortex radius (derived above), and $\mathrm{f} = \frac{\mathrm{v}}{\mathrm{R}}$ is its frequency. Therefore, we estimate an efficiency of quasi-stationary vortices of

$$\mathrm{Nu} \approx \sqrt{\frac{\mathrm{vL}}{2\mathrm{D}_0}} = 1.8 \qquad (3).$$

For short lived vortices, a similar calculation has been made where the centre of the vortices relocates randomly in space every non-dimensional life time **l**, defined as the ratio between the vortex life time to revolution time. It has been found that when $\mathbf{l} < \mathbf{0.5}$ the Nusselt number scales linearly with the Péclet number $\mathbf{Nu} \approx \mathbf{Pe}$. Therefore, in this case of transient vortices corresponding to the TVZ, our estimate suggests:

$$\mathrm{Nu} \approx \frac{\mathrm{vL}}{2\mathrm{D}_0} = 3.3 \qquad (4).$$

3. RESULTS

In order to assess the plausibility of the heat boost through granular convection we use the following representative values not meant to form an exact result but a magnitude estimate. We eliminate from the previously estimated total heat transfer the upper limit of local heat production through shear heating, to obtain the unexplained anomaly. The required solid convective boost is then given by the ratio of this anomaly divided by a conduction flux.

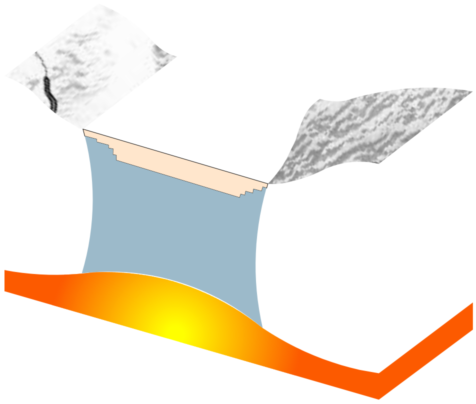

Figure 3: Schematic model of a cross-section through the TVZ highlighting the emergence of crustal scale solid-like vortices of velocity fluctuations. The model also shows the location of anomalous heat and mass transfer feeding the hydrothermal systems observed in the top 5-8 km of the crust. The locations of the resistivity minima are highlighted on the surface in reference to the box shown in Figure 1.

3.1 Solid vortex application

Assuming, for instance, a 20 km thick crust with thermal conductivity of 2.0 W m^{-1} K^{-1} with a top temperature of 100 °C (boiling water) and a bottom temperature of 1300 °C (assuming basaltic underplating), we obtain an approximate value of 100 mW/m^2 of steady state heat transfer by conduction. Assuming a near orthogonal opening direction as indicated in Figure 1 the method of characteristics provides an upper bound of local heat production of around 280 mW/m^2 from internal shearing (Hochstein *et al.*, 1993). The total observed surface heat flow has been reported (Bibby *et al.*, 1995**)** to be on the order of 700 mW/m^2. Therefore, the unexplained anomaly is of the order 320 mW/m^2. This requires a boost through solid convection with a Nusselt number of 3.2, which is close to the theoretical prediction of 3.3 from episodic vortices (see 2.1 Heat Vortices).

4. DISCUSSION AND CONCLUSION

The giant vortex hypothesis can answer questions (ii) to (iv) posed by Wilson and Rowland (2016) (spatial separation, stability, and episodicity of geothermal systems) and offers a plausible explanation for the generation of anomalously hot and relatively dry rhyolitic melt (Deering *et al.*, 2008). The solution of the first question (i) of why the deformation is macroscopically localised in the extremely narrow zone of the TVZ depends on the broader scale of the boundary conditions provided by the plate tectonic problem and can be solved by the method of characteristics (Hochstein *et al.*, 1993). This macroscopic localisation phenomenon provides the necessary boundary conditions for the mesoscopic mid-crustal vortices that can boost shear heating and transports heat through the advecting narrow channels (Kissling *et al.*, 2009).

Our analysis therefore supports the significance of transient, episodic heat pulses through granular-like vortices of partially molten crystallized melt in localised tectonic settings, where high shear deformation rates and partial melts are present. The significance of this mechanism was demonstrated as a possible solution to the heat flow anomaly in the Taupo Volcanic Zone (TVZ). It can explain the observation of extremely short lived crustal magmatic pulses of 100-1000 year duration (Sutton *et al.*, 1995). The vortex mechanism applies for all shear settings, and is particularly powerful for vortices with horizontal axes perpendicular to the vertical thermal gradient such as the discussed extensional TVZ. The significance of granular, episodic, solid vortices is not restricted to the crustal scales discussed here, where the crystal mush zone of the entire middle to lower crust is sporadically mobilised to trigger the supervolcano. They can also be a mechanism to activate the mush zone in a regular-sized volcanic magma chamber. However, for smaller scales a different scaling relation may have to be used. Solid granular vortices may also be observed in other geological structures without the presence of melts such as in shear zones, fault gouges, folds, and boudinage structures. This raises an interesting question as to the role of shear heating and horizontal and vertical axis advection of heat in those smaller scale geometries, which are often associated with much higher shear rates.

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