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CONCEPTUAL MODELS OF HEAT TRANSPORT IN THE TAUPO VOLCANIC ZONE, NEW ZEALAND

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SUMMARY - Six published conceptual models of the TVZ (Taupo Volcanic Zone) are reviewed, and compared against fourteen known or inferred physical properties of the TVZ. A model of three layers, each with constant density, is assumed to eventually develop above a depth of 25 km. A constant rate of eruption of material was assumed, which eventually implies a constant rate of spreading, and a constant rate of volumetric creation in all three layers. Heat flow calculations are performed, by assuming conductive heat transport below 8 km and above Layer 3, and intrusive heat sources below Layer 1 and above 8 km. Some examples are provided which match the present total heat output from the TVZ of about 4200 MW, but these either have spreading rates greater than the low values of about 8 ± 4 mm/a being reported from GPS measurements, or else consider extension rates in the TVZ to have varied over time.

1 Introduction

The Taupo Volcanic Zone (TVZ) is (see Fig. 1) in the **North** Island of New Zealand, extending in an approximately northeast-southwest direction (Cole, 1990), and opening in the north to be about *60* km in east-west extent (Grindley, 1965). The geological, geochemical and geophysical properties of the TVZ have recently been summarised in a Special Issue of Journal of Volcanology and Geothermal Research (Simmons and Weaver, 1995) on the TVZ. Hochstein (1995) has emphasised that the long term eruption rate of rhyolites from the TVZ is the highest on earth for a volcanic arc setting, and also that the total crustal heat transfer is arguably the highest on earth for an arc setting.

In order to explain the many measured properties of the TVZ, (at least) six published conceptual models of the TVZ have been formulated. To be acceptable, a conceptual model should be capable of describing or accommodating *all* known physical properties of the TVZ. The aim of this section is to briefly discuss all six models, in relation to fourteen fundamental physical properties of the TVZ.

Table 2 shows the performance of the six published conceptual models of the TVZ - spreading, rifting, plasticity, hot-plate, froth and transtensional - and shows how each conceptual model performs against fourteen properties of the TVZ, ranging from location of the TVZ to the uniqueness of the TVZ. A Y, N or blank indicates the corresponding conceptual model satisfies, does not satisfy, or may satisfy the corresponding property of the TVZ.

Since each column contains an N, none of the present conceptual models is yet fully acceptable. There are three possible ways forward : either some of the properties of the TVZ are interpreted incorrectly, and need to be altered; or a new conceptual model needs to be formulated in such a way to avoid an N; or both the properties and conceptual models need to be altered. This section proceeds by discussing the fourteen properties and the six models in Table 1, and finishes by discussing some of the difficulties of these models.

1.1 TVZ Properties

The fourteen properties discussed in this subsection are not complete, but are included to provide a balanced framework for an initial discussion of models of the TVZ.

Location refers to the geographic and arc setting of the TVZ, which runs parallel to the andesitic arc, (see Fig. 1) and is nowhere further than 100 km from the line of the arc volcanoes.

Property	Spreading	Rifting	Plasticity	Hot-plate	Froth	Transtension
Location	Y	Y	Y		N	Y
Size	Y	Y				
Deformation	N	Y				Y
Heat flow	Y	N	Y	Y	Y	Y
Chemistry	Y	N	N		Y	Y
volcanology	Y	N			Y	Y
Gravity	Y	N			Y	Y
Magnetism	Y	N			Y	Y
Seismic velocity	N	Y	N	N	N	Y
Petrogenesis						
1.6Ma activity						
Rhyolite/andesite						
Westerly rhyolites						
Uniqueness	N	N	Y	Y	N	N

Table 1: Performance of six published models of the TVZ.

Size refers to the length (between about 160-200 km) and width (less than 100 km) of the TVZ. The total area of the TVZ is between about 6000-8000 km^2. The area of 6000 km^2 can be imagined (see the heavy solid rectangle in Fig. 2) as approximately 150 km long, from the south of Lake Taupo to the Bay of Plenty coast, and about 40 km wide, which includes all of the presently active geothermal fields.

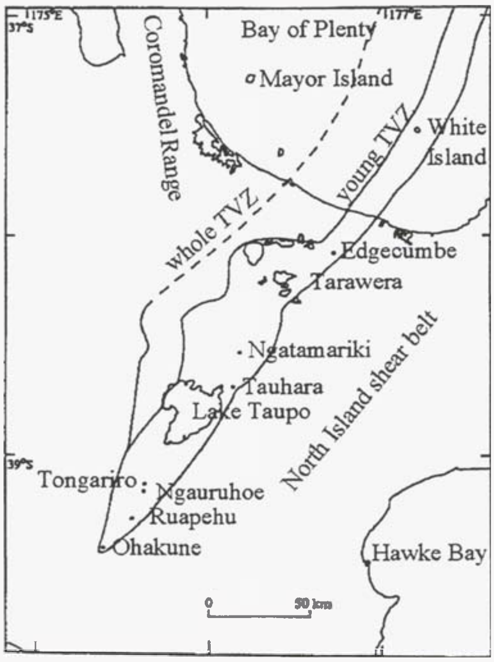

Figure 1: Location of the TVZ

However, an area of about half of this (McNabb, 1975) is obtained if areas are drawn around the downflow areas for the active geothermal fields in the TVZ. There are about 20 active fields, with individual hot upflow areas of about 15 km^2, an outer downflow areas of about 150 km^2, giving a total of about 3000 km^2. Twenty three geothermal fields are listed in Fig. 2, together with the boundaries of the old and young TVZ, as also shown in Fig. 1. Numerical calculations (Kissling, 1996) show that rising geothermal plumes tend to contract on ascent, supporting the idea that the area of geothermal activity may be considerably smaller than the source area of volcanism.

Alternatively, an area of about 8400 km^2 (= 20,000 km^3 divided by about 2.5 km) follows from Fig. 3 by taking a rectangular area about 88 km long and 54 km wide plus an approximately triangular area about 120 km opening to 60 km wide (Fig. 2, Wilson et al., 1995). The rectangle and triangle are shown as heavy broken lines in Fig. 2. The area of 8400 km^2 is larger than the 6000 km^2 number because the former describes the vent positions over the last 1.6 Ma, whereas the latter figure describes the location of the presently active geothermal fields. There are fossil geothermal fields in the region uncommon to each. All calculations in this paper assume an area of 6000 km^2, a length of 200 km and a width of 30 km for the TVZ. This rectangle is not shown in Fig. 2 because it runs through the geothermal fields.

Deformation (Sisson, 1979) is occurring in the TVZ. The best available estimate of the present opening rate of the TVZ (Darby and Merteens, 1995) over the last 5 years (K. Hodgkinson, personal communication) from GPS measurements is 8 ± 4 m d a, which is very close to the estimates from land based geodetic methods. Darby and Williams (1991) estimated the extension rate north of Lake Taupo is 18 ± 5 mm/a, but these measurements have now been rejected, as being contaminated by subsidence of the nearby Wairakei geothermal field.

Heat flow from the TVZ is estimated as 4200 ± 400 MW by Bibby et al. (1995), and as about 5200 MW by Hochstein (1995).

The **chemistry** of the TVZ waters is characterised by bi-modal compositions. Most waters from the west (east) have low (high) CO_2 contents, low (high) ^{18}O **shifts,** and high (low) Chloride to Heat ratios (Giggenbach, 1995). The ratio of many chemical components are close to those occurring in adjacent magmatic rocks (Ellis and Mahon, 1964,1967). Total chloride flow from the TVZ is about 3 kg/s.

Volcanology is characterised by large extrusions (about 0.3 m^3/s, Wilson et al., (1995)) of rhyolite, to give a total of about 15,000 - 20,000 km^3 of mostly rhyolitic infill on the top 2.5 km of the TVZ. It is suggested that a constant rate of erupted volcanic volume is all that can be supported by the data at present, since the recent eruptive rate (in the last 0.1 Ma) is equal to the average eruptive rate over the last 1.6 Ma.

Figure **2:** Area estimates for the TVZ. The shaded and labelled areas are the geothermal fields: 1. Taheke, 2. Rotorua, 3. East Rotorua, 4. Rotoiti, 5. Rotoma, 6. Kawerau, 7. Horohoro, 8. Waimangu, 9. Waiotapu-Waikite, 10. Mangakino, 11. Ongaroto, 12. Atiamuri, 13. Te Kopia, **14.** Reporoa, 15. Mokai, 16. Orakeikorako, 17. Ngatamariki, 18. Ohaaki, 19. Wairakei, 20. Rotokawa, 21. Tauhara, 22. Lake Taupo, **23.** Tokaanu.

A low **gravity** anomaly in the TVZ is interpretted as due to the low density infill region of about 2.5 km deep. The density **of** the rocks between about 2.5 and 15 km depth is close to that of greywacke and argillite basement rocks, because there are no long wavelength gravity anomolies (Woodward and Ferry, 1973, 1974) associated with the middle layer. Additional gravity lows are associated with caldera collapse.

The **magnetisation** record indicates (Soengkono, 1995, Fig. 10) the presence of large cooled ($\leq$ 500°C) magnetic bodies under the TVZ of perhaps 4 km thickness extending down to a depth of about 7 km, and of about 20 km in width. However, for depths below about 7 or 8 km, magnetic effects will disappear, as temperatures rise above the Curie Point. Reverse magnetisation occurs to the west of the TVZ, indicating that volcanism **has** moved eastwards with time.

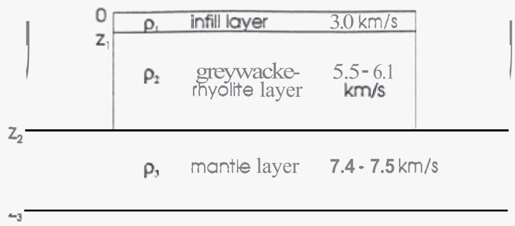

Figure 3: Assumed depth structure in the TVZ.

Analysis of the **seismic velocity** structure under the TVZ indicates a three layer structure (Stem and Davey, 1987). An idealised sketch of these three layers **is** given in Fig. **3.** The upper 2.5 km of about 3.0 km/s material is formed mostly from pyroclastic infill. The region between about 2.5 km to 15**km** depth is occupied by 5.5 - 6.1 km/s material. Adjacent greywacke has a similar seismic velocity. Material between depths of 15 and **25** km has a seismic velocity of 7.4 - 7.5 km/s material. This region appears to be greater in width than the TVZ region above it. Mantle material adjacent to the TVZ has a seismic velocity of about 7.6 km/s.

The Pb, ^{18}O and $^{87}Sr/^{86}Sr$ isotopic compositions of TVZ rhyolites are very similar to those of contemporary TVZ andesites (Graham et al., 1995). Consequently, the **petrogenesis** of the **TVZ** rhyolites can be explained by being formed from mostly andesites similar to those erupting at present, and only a small radiogenic contaminant such as Torlesse meta-greywacke. However, the bimodal nature of rhyolite and basalt eruptions from the same calderas remains unexplained.

The **1.6 Ma activity** relates to recent voluminous rhyolitic activity. If subduction due east of the TVZ began about 5 Ma ago (Ansell and Adams, 1986), then the gap of about 3.4 Ma before rhyolitic volcanism began needs to be explained.

Rhyolites represent about 95% (Graham et al., 1995) of the total eruptives of the TVZ, so that the ratio between rhyolites to andesites is about 20, or greater. This **rhyolite/andesite** ratio needs explanation.

The location of the rhyolites, close to, but to the **west of** the andesitic arc, needs explanation.

Finally, some intrinsic property in a model must explain the **uniqueness** of the **TVZ.** In particular, why does the TVZ have the highest heat output and rhyolitic extrusions on earth for an arc setting.

1.2 TVZ Models

The **spreading** model (Stem, 1987) assumes that the TVZ is spreading apart, and the volume created is occupied by magma. Meteoric water then cools the intruded magma, establishing convective plumes which are the geothermal fields in the TVZ. These ideas are widely accepted, and so will probably be a component in most models of the TVZ.

The **rifting** model (Wilson et al, 1995) assumes that the original greywacke rocks exist at depth, having been stretched by the opening of the TVZ. The volume of greywacke then exists as a continuous unit, below which mantle or other material enters to conserve volume and maintain isostacy.

The **plasticity** model was formulated by Hochstein (1995) in order to produce an additional heat flow over that imagined in the spreading model. The plasticity model assumes that the entire lithosphere beneath the brittle crust is opening, and that the mechanical work performed in this opening is converted into heat, which is then available to fuel the TVZ.

The **hot-plate** model considers a plate fragment (perhaps 200 km by 100 km by 10 km) from the Pacific Plate in the Bay of Plenty region to be torn by the back-arc spreading between 5 - 10 Ma ago. Melt from this descending plate fragment then forms magma which rises under the region of Mt Ruapehu, and then moves approximately northward, in a thin sill-like flow, at a depth of about 8 km, yielding heat to the TVZ region, with the magma then descending in the region of about Kawerau. This model (McNabb, 1992, McNabb and McKibbin, 1998) imagines heat to leave the flowing magma conductively. A plate fragment was chosen to provide the high chloride flows typical of the TVZ region.

The froth model (Giggenbach, 1995) imagines a magma and water foam or froth to rise up in the east of the TVZ from the descending Pacific Plate. The lighter more volatile components then rise preferentially to form the gas-rich eastern geothermal fields, while the residual magma flows to the west, to form the chloride-rich, gas-poor western geothermal fields. Heat input is considered to occur from cooling of intrusives by circulating meteoric water, so the froth model has many similarities to the spreading model.

The **transtensional** model (Cole, 1990) assumes that the rapid opening of the TVZ is the sum of back-arc spreading, induced by the NNE Taupo - Hikurangi arc-trench system, together with stresses from a combined NNW North Island Shear Belt and a Mayor Island Fault Belt system. Rhyolitic volcanism is assumed to result from partial melting of andesitic volcanics from the Coromandel Volcanic Zone, assumed to underlie the TVZ region, to produce the predominantly metaluminous rhyolitic and ignimbritic magmas observed in the TVZ, rather than the peraluminous magma which are expected from partial melting of a greywacke-argillite basement. Magma flow is induced by the rapid thinning of the TVZ, and so in this model the TVZ is presumably fuelled by a mantle flow.

2 Transient Heat Flow Model in the Ductile Layer

It is widely accepted that fracture surfaces in rocks with a temperature of over about 400°C tend to creep together (Turcotte and Oxburgh, 1972). Such rocks are called ductile. The removal of fractures in ductile rocks dramatically reduces their permeability, and in this paper, it is assumed that convection of meteoric groundwater is insignificant in ductile rocks. It has been suggested (Bibby et al, 1995, McNabb and McKibbin, 1998) that rocks become ductile in the TVZ at a depth of below about 8 km.

The aim of this section is to calculate the transient development over time and position of temperature in the ductile layer ($z \geq 8$ km) in the TVZ, and to calculate the heat flux from the ductile region into the brittle ($z \leq 8$ km) region of the TVZ. It is assumed that any magma entering the brittle region will be cooled by circulating meteoric water to under 400°C, and the heat transported to the surface.

The equation describing conductive heat transport in the ductile region (where convective heat transport by meteoric water is assumed to be insignificant) in the presence of magmatic intrusions is

$$\rho_2 C \frac{\partial T}{\partial t} = \frac{\partial}{\partial z} K \frac{\partial T}{\partial z} + \frac{1}{V}\frac{dM}{dt}[C(T_m - T) + L] \quad (1)$$

where C is the heat capacity of the rock, T is temperature, t time, K thermal conductivity, T_m the molten temperature of the magma, and L is the latent heat of the magma. In all calculations, K = 2 W/m/C (Clauser and Huenges, 1995).

The mass flow per unit volume term, in the transient calculations, was taken as

$$\frac{1}{V}\frac{dM}{dt} = \frac{\rho_2 v}{w} \quad (2)$$

which corresponds to the TVZ increasing in width at rate v over a fixed height, where ρ_2 is the density of Layer 2, of width w.

Equation (1) is solved subject to an initial temperature distribution which is linear with depth, with a temperature of 400°C at the brittle - ductile surface ($z = 8$ km), and a temperature of T_m at the surface $z = z_2$.

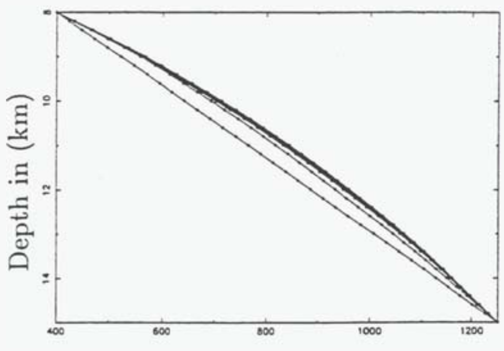

Figure 4: Temperature profiles in the ductile region, as a function of position and times (Ma), for a width of the TVZ of about 30 km.

The corresponding temperature profiles are shown in Fig. 4 for a present width of the TVZ of 30 km and an extension rate of 8 mm/a. These graphs were constructed by solving the heat equation in vertical coordinates of $(z - 8)/(z_2 - 8)$, and then transforming back to Cartesian coordinates. In some calculations, z_2 is fixed at 15 km (where the temperature equals 1250°C), but for the transient spreading and rifting models, z_2 will move upwards in some prescribed manner. The solid lines are for a constant opening rate of 8 mm/a. The nine time scales on Fig. 4 start from 0.0 Ma and increase at 0.2 Ma to a final time of 1.6 Ma. These plots show that the temperature profiles are essentially constant at the brittle-ductile surface at 8 km depth after about 0.2 Ma.

The total surface heat flow (MW) is shown in Fig. 5. The solid lines correspond to a constant opening rate of 8 mm/a, and the broken lines correspond to a variable opening rate with period of 0.1 Ma added to this constant opening rate. Initially, the heat from intrusives is greater, but after some time, conduction is greater, because of the linear increase with time of the area of the TVZ. Closer inspection of the temperature gradients at $z = 8$ km shows an increase up to about 0.4 Ma, after which the temperature gradient decreases slowly. This is the reason for the contribution from conduction not being exactly linear in time. The contribution from intrusives is constant. These values show that conduction (1800 MW) and intrusives (1150 MW) contribute about 3200 MW.

These heat flow calculations show that the variable opening rate (of 0.1 Ma period) does not significantly affect the total heat flows. These calculations have not considered any contribution from andesitic water, which could add about 1000 MW (Weir, 1998) to the total heat flow, if about 300 kg/s of andesitic water enters the TVZ with an enthalpy of about 3 MJ/kg. Adding this to the 3200 MW in Fig. 5 shows that the measured TVZ heat flow measurements of about 4200 MW may be consistent with the measured extension rates of about 8 mm/a at this time.

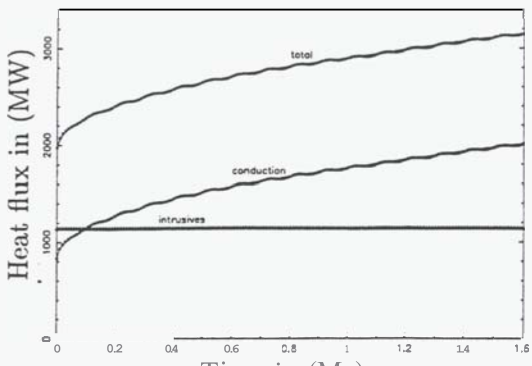

Figure 5: Surface heat fluxes (MW) as functions of time (Ma) for a spreading rate of 8 mm/a for two-stage opening TVZ model.

3 Discussion and Conclusions

This paper began by discussing six conceptual models of the TVZ, and some of the properties that such models should satisfy. A three layer model between the surface and a depth of 25 km was formulated. Material erupts onto the surface, forming Layer 1, to balance the higher density material in Layer 3. The predicted heat output of the model contained a component from intrusions above 8 km which tended to produce a constant heat flow with time of about 1000 MW. Intrusives below 8 km produced an increasing conductive heat flow with time (because of the increasing surface area), which now could be about 2000 MW. Additional to this may be another 1000 MW from andesitic water.

A model valid throughout the 1.6 Ma of the TVZ was not found. If the mechanisms operating in the TVZ are those of spreading, or of rifting, then the simple models considered showed that, to be consistent with the heat flow and seismic records, required spreading rates (13 mm/a) larger than are being currently measured (8 mm/a). The calculations in this paper ignored the early formation of the TVZ, and considered only the latter stage of the TVZ, which was associated with the eastward motion of the NISB. Clearly more research is needed to clarify these issues.

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