Vol 446 | 26 April 2007 | doi:10.1038/nature05743

The role of fluids in lower-crustal earthquakes near continental rifts

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The occurrence of earthquakes in the lower crust near continental rifts has long been puzzling, as the lower crust is generally thought to be too hot for brittle failure to occur[1,2]. Such anomalous events have usually been explained in terms of the lower crust being cooler than normal[3,4]. But if the lower crust is indeed cold enough to produce earthquakes, then the uppermost mantle beneath it should also be cold enough[2], and yet uppermost mantle earthquakes are not observed[5]. Numerous lower-crustal earthquakes occur near the southwestern termination of the Taupo Volcanic Zone (TVZ), an active continental rift in New Zealand[6]. Here we present three-dimensional tomographic imaging of seismic velocities and seismic attenuation in this region using data from a dense seismograph deployment[7]. We find that crustal earthquakes accurately relocated with our three-dimensional seismic velocity model form a continuous band along the rift, deepening from mostly less than 10 km in the central TVZ to depths of 30–40 km in the lower crust, 30 km southwest of the termination of the volcanic zone. These earthquakes often occur in swarms, suggesting fluid movement in critically loaded fault zones[8]. Seismic velocities within the band are also consistent with the presence of fluids, and the deepening seismicity parallels the boundary between high seismic attenuation (interpreted as partial melt) within the central TVZ and low seismic attenuation in the crust to the southwest. This linking of upper and lower-crustal seismicity and crustal structure allows us to propose a common explanation for all the seismicity, involving the weakening of faults on the periphery of an otherwise dry, mafic crust by hot fluids, including those exsolved from underlying melt. Such fluids may generally be an important driver of lower-crustal seismicity near continental rifts.

The TVZ is an active continental rift in the central part of North Island, New Zealand (Fig. 1). It is the product of back-arc spreading within the Hikurangi subduction zone, with the top of the subducted Pacific plate being about 85 km deep beneath the TVZ. The modern central TVZ is the most frequently active and productive silicic volcanic system on Earth, erupting rhyolite at ~0.28 $m^3 s^{-1}$ for at least the past 0.34 million years (ref. 9). The average heat flux from the central 6,000 km^2 of the TVZ is very high at 700 mW m^{-2} (ref. 10). Also, the southern limit of the TVZ has been migrating southwestwards with time, as indicated by the timing of both recent volcanism and associated surface faulting in the southern TVZ[11].

A recent six-month dense deployment of portable seismographs in central North Island with a station spacing of 15–20 km has provided an opportunity to study the relationship between the TVZ and the lower-crustal seismicity near its southwestern termination. This deployment has allowed detailed three-dimensional tomographic imaging of seismic velocities (compressional P-wave velocity v_P; and the ratio of v_P to the shear S-wave velocity v_P/v_S) throughout the crust and upper mantle[7]. Here we additionally model the three-dimensional seismic attenuation structure, by determining the quality factor of P-waves Q_P (which is inversely related to attenuation), using the t^* inversion technique of ref. 12. We have included a limited frequency dependence for Q_P, with Q_P being frequency-independent above f_0, and having a frequency dependence of $(f/f_0)^{0.5}$ below f_0. We have taken f_0 to be 10 Hz, so the Q_P determined is equivalent to a Q_P at ~10 Hz.

This three-dimensional imaging has revealed that in the central TVZ the crust is ~35 km thick, with the lower crust greatly modified through intrusion and underplating. This crustal structure is similar to that deduced from two-dimensional modelling of explosive and earthquake sources[13]. Southwest of the termination of the TVZ at Mt Ruapehu the crust thickens by ~10 km, and is interpreted to be composed of Cretaceous schist and remnant oceanic crust[12]. In the mantle wedge, v_P is lowest (7.4 km s^{-1}) and v_P/v_S is highest (1.87) at 65 km depth, immediately west of the Taupo caldera. This region is

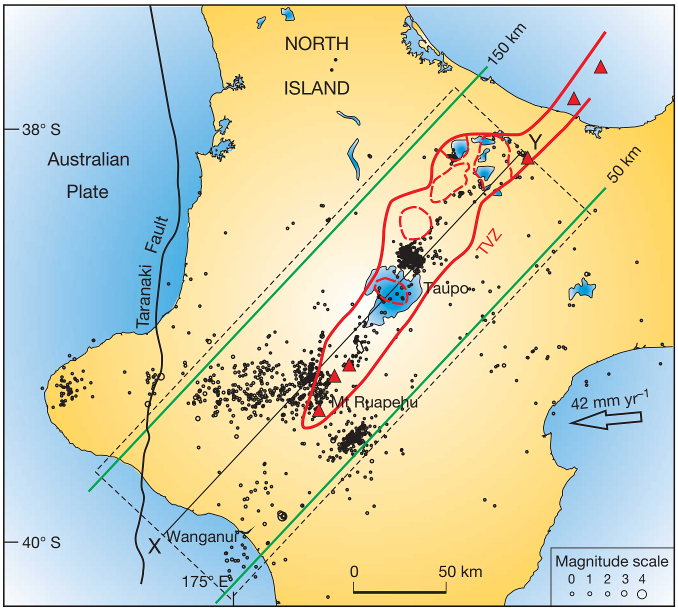

Figure 1 | Tectonic setting of the central North Island of New Zealand. The TVZ is outlined in red, with rhyolite-dominant caldera volcanoes shown dashed and andesite-dominant cone volcanoes shown as triangles[9]. The arrow indicates the velocity of the subducted Pacific plate relative to the overlying Australian plate, and green lines show the depth of the top of the Pacific plate. Circles are earthquakes within the Australian plate relocated using the three-dimensional seismic velocity model of ref. 7. The dashed rectangle encloses earthquakes included in the depth section XY shown in Fig. 2.

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best interpreted as a significant volume of partial melt, produced by the reaction of fluid released by dehydration of the subducted plate with the convecting mantle wedge. There is no significant low-v_P zone in the mantle wedge southwest of the TVZ, suggesting that the thicker crust there has choked off mantle corner flow[14]. This lack of corner flow is a plausible explanation of the cessation of volcanism to the southwest. The abrupt cessation of corner flow southwest of Mt Ruapehu is likely to promote lateral fluid flow in this region, as suggested by S-wave splitting results[15]. In particular, we would expect the corner flow in the northeast to entrain fluid from the southwest, leading to an anomalous concentration of partial melt, because fluid from a large volume of mantle to the southwest is available to flux melt. This lateral fluid flow is a plausible explanation for the exceptional magmatic productivity of the central TVZ[7].

We have used the three-dimensional seismic velocity model to relocate all earthquakes in the overlying Australian plate during the duration of the seismograph deployment, a total of 1,618 events (Fig. 1). A depth section of those earthquakes within 50 km of the axis of the TVZ is shown in Fig. 2. These events have median standard errors of 0.5 km in both epicentre and depth. Within the TVZ, the earthquakes are mostly less than 10 km deep. At the southwest termination of the TVZ at Mt Ruapehu, the earthquakes form a continuous ~10-km-thick band which dips to the southwest before flattening out in the 30–40 km depth range. The relationship of this seismicity distribution to seismic properties in the crust and uppermost mantle is illustrated in Fig. 3.

Within the TVZ, seismicity in the upper crust is associated with low v_P/v_S (<1.70). Similar low v_P/v_S ratios have been observed beneath active volcanoes in northeastern Japan, and this can be explained by the presence of water[16,17]. The region exhibits vigorous geothermal activity, which is known to be associated with low v_P/v_S (ref. 18). In the lower crust of the TVZ, v_P/v_S increases rapidly and Q_P is low (<300). Using the methodology of ref. 19, Reyners *et al.*[7] have interpreted the low-v_P feature centred near 18 km depth as a region of texturally equilibrated partial melt. This interpretation is consistent with the low Q_P observed in this region. Seismic attenuation is a strong function of temperature[20], with a lower Q_P indicating a higher temperature. Hence the mid- and lower crust of the TVZ can be interpreted as heavily intruded and underplated, largely because of the large flux of melt from mantle corner flow in this region (evident in the high v_P/v_S and low Q_P in the mantle wedge in Fig. 3). We interpret upper-crustal seismicity within the TVZ to be promoted by fluids exsolved from such intrusions, by means of cyclic fluid pore pressure increases which weaken faults[21]. The earthquakes mostly occur in swarms, suggesting fluid movement in critically loaded fault zones[8].While most fluid at shallow depth may be of meteoric origin[10], the high $^3He/^4He$ ratios associated with the TVZ[22] suggest that some fluid has been exsolved from melt.

At the southwestern termination of the TVZ near Mt Ruapehu, the low v_P/v_S associated with shallow seismicity in the central TVZ dips to the southwest in concert with the seismicity, and the dipping seismicity band parallels the boundary between low Q_P (<300) within the central TVZ and high Q_P (>600) in the crust to the southwest (Fig. 3). Earthquakes comprising the dipping band of seismicity often occur in swarms[23], again suggesting the influence of fluids. By analogy with the seismicity and seismic properties in the central TVZ, we also interpret earthquakes in the dipping seismicity band as having been promoted by fluids, including those exsolved from the magmatic intrusions at the southwest margin of the TVZ. The continuation of sporadic earthquake activity in the lower crust further to the southwest under the Wanganui basin (Fig. 2) likewise suggests the influence of fluids. These earthquakes often occur as swarms[24], and the lower crust in which they occur is reflective[25]. Both these observations are consistent with the presence of fluids. A Q_P of 500–600 in the uppermost mantle in this region (Fig. 3) precludes the existence of connected melt. Rather, fluids in the lower crust beneath the Wanganui basin are most probably the result of a well-hydrated mantle wedge, caused by dehydration of the thicker-than-normal subducted crust in this region[7].

How robust is our interpretation of seismicity in the lower crust being triggered by fluids? The strength of the crust is governed by strain rate, temperature and rock composition, as well as pore fluid pressure[26]. Geodetically measured strain rates at the southern termination of the TVZ are $\sim 1 \times 10^{-15}\,s^{-1}$, significantly lower than strain rates within the TVZ itself[27]. The fact that the seismicity continues southwestwards, despite the reduction in strain rate, suggests that regional strain rate is not a major factor in the generation of the seismicity. There are no heat flow measurements in the region of the lower-crustal earthquakes, but on the basis of those nearby, the heat flow is probably about 60 mW m^{-2} (ref. 6). Such a heat flow would suggest that the lower crust would be ductile and hence aseismic. We must thus turn to rock composition to explain the lower-crustal seismicity, and it has previously been proposed that the lower crust is drier and more mafic than usual[6]. The high Q_P (>600) seen in the lower crust to the southwest of the TVZ (Fig. 3) would be consistent with a dry, mafic crust. Yet such a change in rock composition does not appear to be reflected in the seismicity distribution. Seismicity parallels the dipping boundary between low Q_P (<300) within the central TVZ and this high-Q_P (>600) lower crust to the southwest, rather than being restricted only to the high-Q_P lower crust.

High fluid pore pressures thus seem the most plausible explanation of the seismicity distribution. Our preferred model for the seismicity is that it is promoted by hot fluids (including those exsolved from underlying melt) weakening faults at the periphery of an otherwise dry, mafic crust. The volume proportion of these hot fluids is likely to be small, insofar as seismologically determined properties

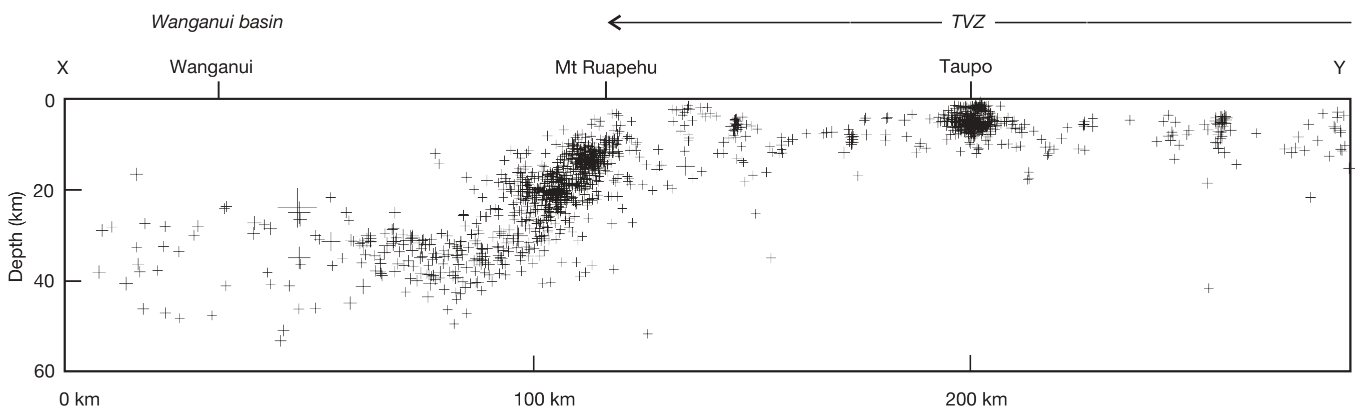

Figure 2 | Depth section of relocated earthquakes in the Australian plate along the axis of the TVZ. Events shown are within 50 km of the line XY shown in Fig. 1. 'Plus' symbol size is scaled to magnitude, with the smallest magnitude 0.9 and the largest magnitude 4.9.

still suggest a dry lower crust. This model is similar to that recently proposed for brittle failure in exhumed lower-crustal rocks, based on petrological and isotopic data[28].

If the lower crust at the southwestern termination of the TVZ is seismic, why are there so few earthquakes in the upper crust? A possible explanation suggested by the high Q_P of the lower crust is that this crust is particularly competent and impervious, restricting fluid flow to a fault-fracture mesh at its periphery. Both Q_P and v_P anisotropy studies[29] suggest that the crust is part of the competent Rakaia/Haast Schist geological terrane. Further south, this rheologically strong terrane is in contact with the subducted Pacific plate, and may contribute to the strong plate coupling in the southern North Island[12]. A competent Sierran block has similarly been suggested as a factor in producing the dipping band of lower-crustal earthquakes beneath the western Sierra Nevada range[30]. The influence of the Rakaia/Haast Schist terrane is further demonstrated by the distribution of lower-crustal earthquakes normal to the TVZ. These extend westwards only as far as the Taranaki fault[6], which marks the western limit of thicker crust associated with this terrane[7]. The ~100 km northwest–southeast extent of the lower-crustal seismicity is much wider than the 30–50 km width of the TVZ. This reflects the wide distribution of low v_P and low Q_P in the uppermost mantle immediately to the northeast[7,29], indicative of elevated temperatures, fluids and melt in this region of active corner flow in the mantle wedge. The TVZ is only the surface expression of an extensive region of mantle corner flow that is progressively eroding the northeastern edge of the Rakaia/Haast Schist terrane. Previous erosion of this terrane further northeast provides an explanation of why lower-crustal earthquakes do not occur along the northwest and southeast edges of the TVZ.

We speculate that the same processes that we observe at the southwestern margin of the TVZ may also apply to lower-crustal earthquakes on the margins of other continental rifts. Earthquake swarm activity in the lower crust has been identified at several rifts, suggesting the possibility of fluid involvement (see Supplementary Information). Our seismicity and tomography results suggest that for these lower-crustal events to occur, not only fluids are needed, but also a rheologically strong lower crust which restricts these fluids to its base.

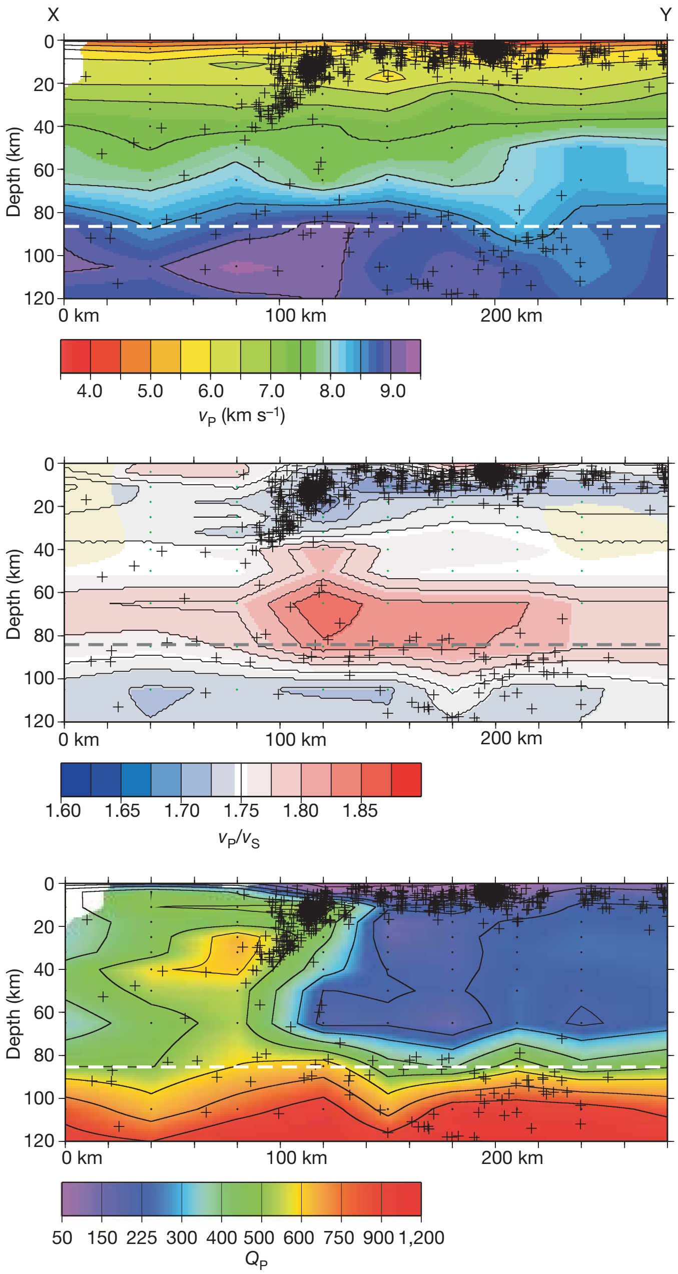

Figure 3 | Depth sections of v_P, v_P/v_S and Q_P (which is inversely related to attenuation) along the axis of the TVZ. Earthquakes ('plus' symbols) in both plates within 20 km of the line XY in Fig. 1 are shown, together with the top surface of the subducted Pacific plate (dashed). Small dots are nodes used in the tomographic inversions. Regions of low resolution are masked but contoured (shown white for v_P and Q_P, and green for v_P/v_S).

Received 13 December 2006; accepted 8 March 2007.

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Supplementary Information is linked to the online version of the paper at www.nature.com/nature.

Acknowledgements We thank R. Robinson and H. Bibby for comments on the manuscript. Our work was supported by the New Zealand Foundation for Research, Science and Technology, the School of Earth and Environment of the University of Leeds, and the Royal Society of London.

Author Contributions M.R. and G.S. planned and undertook the seismograph deployment, M.R. coordinated the data analysis, and D.E.-P. took the lead in the tomographic inversions. All authors contributed to the writing of the paper.

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