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LETTERS

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The role of exhumation in metamorphic dehydration and fluid production

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When mountain belts form, crustal rocks undergo metamorphism, resulting in the breakdown of volatile-bearing minerals and the release of water-rich fluids. As these fluids move towards the Earth's surface, they can cause generation of ore deposits, enhance deformation of the crust and change rock composition[1]. Generation of such fluids has long been considered to occur dominantly during heating associated with burial of rocks. In contrast, the exhumation of rocks that follows heating has not been expected to generate large amounts of fluid[1–3]. Here we use mineral-equilibria modelling to show that the erosion-induced exhumation of greywacke—a common rock type in mountain-forming regions—generates a continual supply of new fluid. Fluid formation is particularly pronounced at temperatures below about 500 °C. Such fluids can explain the pairing of seismic and electrical conductivity anomalies observed in the Southern Alps in New Zealand, as well as the formation of vein-infilled backshears there.

The common simplifying assumption that metamorphic devolatilization results solely from heating[1–3] has not been properly assessed, and although it is usual to assume that fluids present during exhumation have an external source[4,5], this may not be the case. Metamorphic devolatilization depends strongly on both rock chemistry and on the shape of the metamorphic pressure–temperature (P–T) path[6]. Devolatilization can continue, and the amount of fluid being generated has the potential to surge, depending on which minerals are breaking down, up to the metamorphic peak, where devolatilization ceases. The key to this Letter is the observation that, depending on the shape of the P–T path, and the slope of the water content contours, dehydration can continue through a significant proportion of the exhumation history, with the metamorphic peak being reached at relatively low pressure.

In active orogenic belts, rapid exhumation, by processes such as normal faulting in extensional settings or erosion in collisional belts[7], can cause nearly isothermal decompression. Here, we examine metamorphic dehydration during such decompression. The Southern Alps of New Zealand (Fig. 1a,b) is ideal for considering this. The Southern Alps are a geodynamically and lithologically simple modern orogen in which paired seismic and resistivity anomalies are interpreted to document the presence of conductive aqueous fluid below the seismogenic zone, at a position in the orogen where compositionally monotonous Alpine schist (metamorphosed accretionary prism greywacke rock) undergoes nearly isothermal decompression accompanying its rapid uplift and erosional exhumation[8–13] (Fig. 1b,c). The Southern Alps have been forming since ~6 million years ago by the oblique continent–continent collision of the Pacific plate against the Australian plate, at the Alpine fault. Movement of the Pacific plate west-southwest at ~37 mm yr^{-1} relative to the Australian plate brings Pacific plate rocks into the orogen, where they are uptilted, brought to the surface by dextral-reverse slip on the southeast-dipping Alpine fault and erosionally exhumed. Uplift rates (up to ~10 mm yr^{-1}) are some of the highest in the world[8,9,13], resulting in P–T paths for a significant part of the exhumation history that are characterized by isothermal decompression[14,15]. The orogen is too cold throughout to melt, and is overwhelmingly composed of a single rock type (metamorphosed greywacke), the metamorphism of which has been examined in some detail using the same THERMOCALC mineral-equilibria modelling methods that we apply in our present study[16]. Fluid calculations, done for one representative greywacke composition, have the potential to provide meaningful insights into whether metamorphic dehydration can generate significant new fluid during exhumation. The geophysical results that show where metamorphic fluid exists today under the Southern Alps orogen are important because they can serve as independent validation of the results of our petrological calculations, by showing where effects attributable to the existence of significant amounts of conductive aqueous fluid are recognizable.

Results of quantitative mineral-equilibria modelling are used to investigate the amounts of new fluid that are generated progressively during isothermal decompression of a typical sample of Alpine schist. The composition of the sample studied is representative of the rocks that make up >95% of this major mountain range, so the results presented here should pertain to processes in the orogen as a whole[16]. The results show that significant dehydration occurs as the rocks are exhumed, so long as the rocks have not travelled a comparable or hotter P–T path previously. This dehydration occurs mainly at temperatures less than or near 500 °C, as the P–T paths of the rocks cross into or through the shaded reaction zone in Fig. 2. It is sufficient to consider exhumation paths to be, as a first approximation, isothermal. The uplift rates mean that exhumation is likely to be essentially adiabatic, and given that heat consumption by these dehydration reactions is small, exhumation is nearly isothermal (Supplementary Discussion, Fig. S2). The effect of dehydration across the zone in Fig. 2 is apparent in Fig. 3, which shows the calculated amount of new fluid (moles H_2O/mole of rock) that is progressively generated during isothermal decompression, for a series of temperatures. As rock passes up through the orogen, the onset of increased new metamorphic fluid generation begins. This process is a previously unrecognized way for significant amounts of new fluid to be generated as rocks undergo uplift towards the surface at near peak metamorphic temperatures.

Rocks that preserve biotite and garnet zone assemblages indicative of temperatures of ~500 °C or less crop out approximately midway between the Alpine fault and the main divide of the

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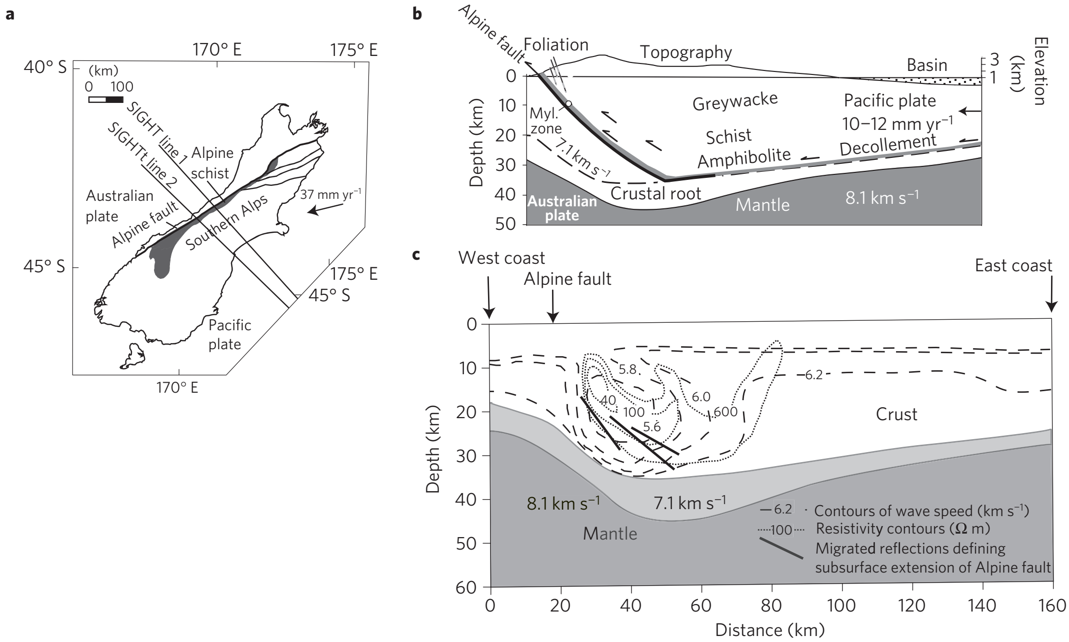

Figure 1 | The active plate boundary, South Island, New Zealand. a, Oblique continental plate convergence of the Pacific plate against the Australian plate is forming the Southern Alps on the Pacific plate side of the Alpine fault, and exposing the Alpine schist (grey; refs 8, 9). **b**, Schematic interpretation of crustal structure across the South Island in the vicinity of the two SIGHT lines. Myl. zone refers to the 1–2-km-thick mylonite zone of the Alpine fault. **c**, Location of paired seismic and magnetotelluric anomalies under the Southern Alps. Seismic wave speeds are mainly from SIGHT line 2 (refs 10, 11), and the low resistivity zone[12,13] was documented using data from SIGHT line 1.

Southern Alps (Supplementary Discussion, Fig. S1). In the central Southern Alps where uplift rates are highest (in the vicinity of South Island GeopHysical Transect (SIGHT) line 2, see Fig. 1), a steep array of vein-infilled backshears occurs in this band of greenschist facies rocks (Supplementary Discussion, Fig. S1). These faults and their infilling veins are interpreted to have formed sequentially, in an escalator-like fashion, at temperatures of ∼450 °C and depths >20 km, accompanying the translation of Pacific plate rocks onto a locally steeper section of the Alpine fault ramp[17]. The estimated P–T conditions of vein formation are consistent with the location of the reaction zone shown in Fig. 2.

There are several important implications of the results of this study. Metamorphic fluids are powerful agents of geological change. Our results offer a direct explanation for the location and origin of the paired low seismic P-wave velocity and low electrical resistivity (high conductivity) anomalies under the Southern Alps (Fig. 1c), and a previously unrecognized source of fluid for post-metamorphic peak orogenic gold mineralization, post-metamorphic peak quartz veins and retrograde alteration. Before this study, all of these features were attributed to the results of devolatilization accompanying increases in P and particularly T, with deeper rocks attaining maximum temperatures later than rocks at shallower levels[5,18]. That mechanism does not explain why geophysical imaging would record an accumulation of fluids at a location that is remote from the orogenic root, especially as fluid should tend to escape rapidly as it is generated.

The geophysical anomalies overlap and are centred in a region where the rocks undergo decompression as they are brought to the surface by motion along the Alpine fault (Fig. 1b,c). The anomalies are attributed to a vertically extensive electrically conducting interconnected network of metamorphic fluid with a salinity possibly approaching that of sea water[10–12]. In an active plate boundary zone such as the Southern Alps orogen, generation of a continuing supply of new fluid during exhumation is likely to enhance any existing fluid connectivity developed through processes including deformation. Although it is conceivable that

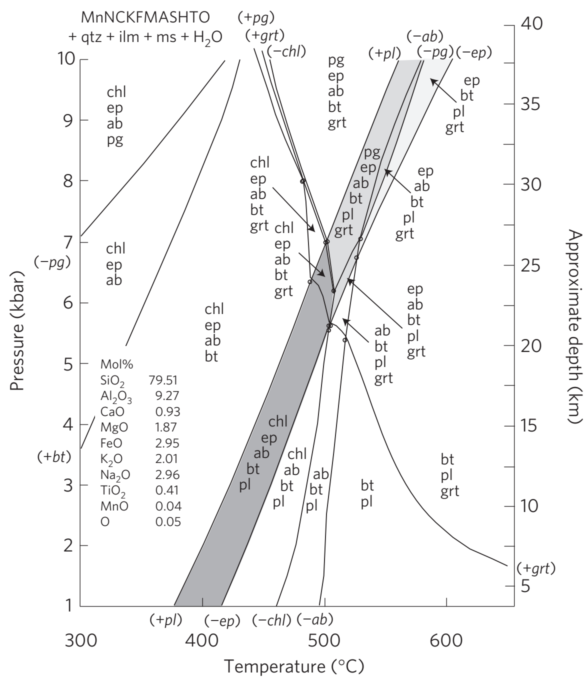

Figure 2 | Enhanced fluid generation during decompression. P–T pseudosection for a typical sample of Alpine schist[16]. Larger amounts of dehydration are indicated by darker shading. Dehydration results from consumption of epidote (ep) accompanying nucleation and growth of plagioclase (pl), and ceases when epidote reacts away. The II-component chemical systems MnO-Na_2O-CaO-K_2O-FeO-MgO-Al_2O_3-SiO_2-H_2O-TiO_2-O (MnNCKFMASHTO) with quartz (qz), ilmenite (ilm), muscovite (ms) and H_2O in excess. Other mineral abbreviations: ab, albite; bt, biotite; chl, chlorite; grt, garnet; pg, paragonite; pl, plagioclase. The italicized labels in parentheses at the ends of lines indicate which phase is gained or lost with increasing temperature.

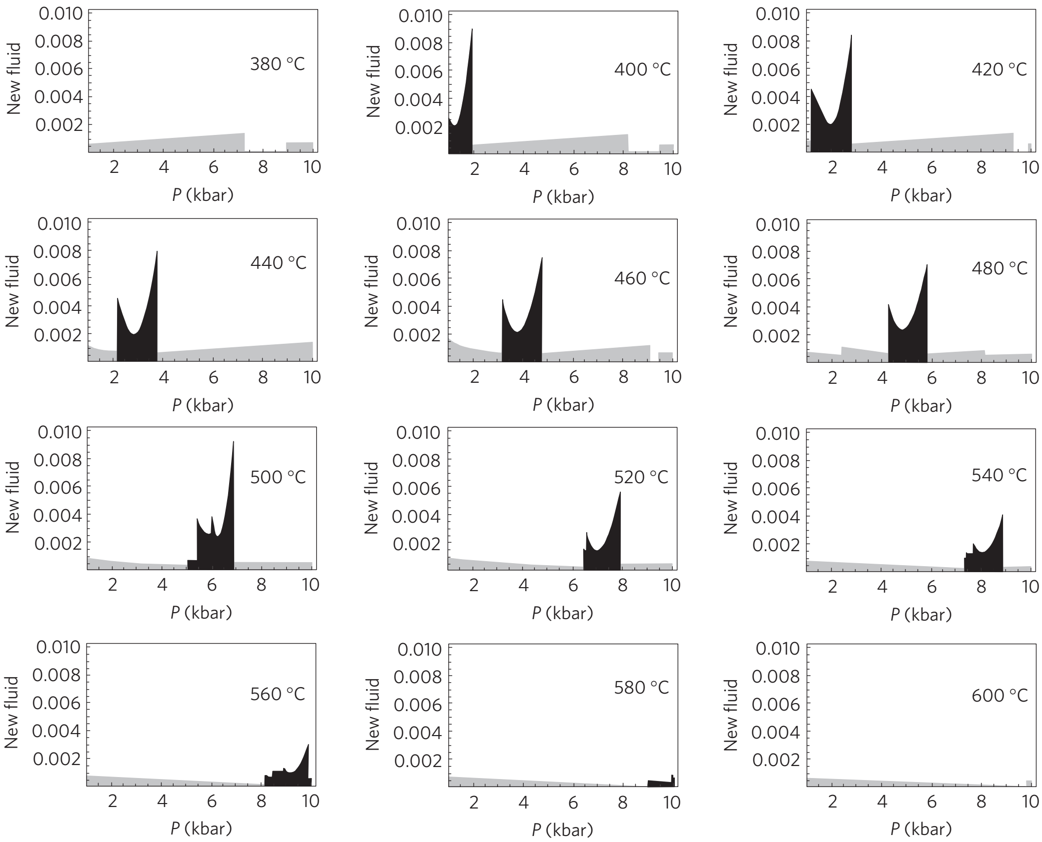

Figure 3 | Enhanced fluid generation occurs during decompression across the reaction zone identified in Fig. 2. Enhanced fluid generation (black shading) occurs during decompression across the reaction zone identified in Fig. 2. The shaded areas in this series of panels shows the amount of new metamorphic fluid (moles new fluid/mole rock) that is progressively generated from a typical sample of Alpine schist during decompression at specific temperatures. For comparison, decompression across the reaction zone at 480 °C generates ~0.46 vol% of fluid.

the paired geophysical anomalies might reflect migration and concentration of previously generated fluid, our modelling suggests that new fluid is generated where the anomalies are. The existence and location of the anomalies is thus consistent with them being an expression of the generation of new metamorphic fluid in the orogen during exhumation. This neither requires nor excludes a contribution from pre-existing fluids.

Grain-edge tubules that were presumably once filled by fluid are visible in scanning electron microscope images of broken rock surfaces. Measured tubules are all smaller than 0.5 μm in diameter along grain edges, and rarely widen to ~2 μm at grain triple junctions. By using a simple three-dimensional cubic lattice to model the system together with an average grain edge length of about 35 μm, the critical fluid volume at the percolation threshold is 0.02–0.2% for tubule diameters of 0.5–2 μm (ref. 19). This shows that the estimates of new fluid generated, as shown in Fig. 4, are consistent with the system being near the percolation threshold, and with the observed magnetotelluric anomaly resulting from fluid connectivity.

The calculated amounts of fluid generated in a rock from passage across the fluid-generating zone (of the order of 0.5 vol%) are of an appropriate magnitude to account for the observed low resistivities if the fluid is sufficiently saline and if the residence time of fluid in the rocks is long enough. The limited existing observations are consistent with previous evidence that accretionary prism sequences yield fluids with salinities close to seawater values, almost irrespective of metamorphic grade[20], supporting the possibility that the newly generated metamorphic fluid could contain enough salt to lower electrical resistivities. In particular, primary fluid inclusions trapped in garnet[21] and

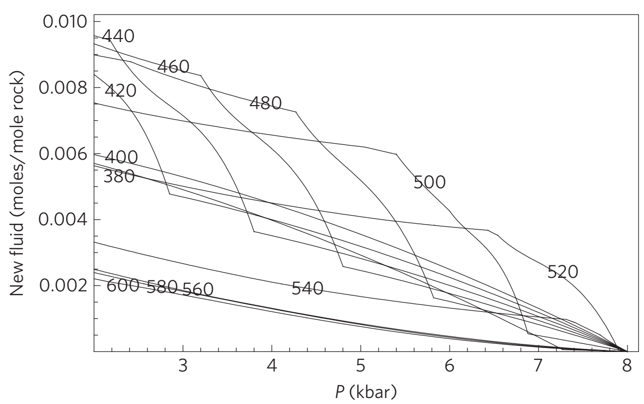

Figure 4 | Cumulative moles of H_2O generated from one mole of Alpine schist during decompression at different temperatures. The steep sections show the main contribution of fluid.

other fluid inclusion data[22,23] record salinities approaching that of sea water (~3.5 wt% NaCl). The measured intensities of the geophysical anomalies will depend on the porosity, permeability and the rate of fluid loss, and the capacity of the rocks to retain original salinity.

The generation of a steady and continuing supply of new fluid, at depths deeper than the brittle–ductile transition, will produce a situation that is inherently mechanically unstable. In a metamorphic system, increasing porosity is considered to lead to hydrofracturing and fracture propagation in an overall upward direction, and results at least intermittently in the development of an extensive permeability structure that extends upwards to near the brittle–ductile transition. This permeability will lead to fluid loss to the surface, but the overall rate of fluid escape is likely to change profoundly at the brittle–ductile transition[24], where calculated characteristic fluid emptying times change from geologically short ($\sim 10^5$ yr) to geologically long ($\sim 10^8$ yr) for rock with initial porosities of ~1% (ref. 25). The change in fluid emptying time at the brittle–ductile transition, together with a continuing input of significant amounts of new fluid from the reaction zone (Figs 2 and 3) has probably produced the geophysical anomaly zone by restricting fluid escape from a vertically extensive permeability structure.

The low resistivity zone under the Southern Alps does not project all the way up to the surface trace of the Alpine fault, but instead deflects surfaceward some 5–10 km inboard of the trace at a depth of ~10 km. This presumably results from fluids reaching the brittle–ductile transition[13]. Worldwide surveys of deep electrical resistivity commonly show that high conductivity anomalies have an upper depth bound near the brittle–ductile transition, where a permeability contrast is likely to exist[4,24,25]. As rock crosses this transition it becomes embrittled, and fluid pressures change from lithostatic to hydrostatic, with deep-sourced fluids being released upwards to the surface and mixing with meteoric water. Cooling will cause dehydration reactions to cease in the Alpine schist.

Above the position where a fluid pulse zone begins, the rock properties will be affected by the amount of fluid that is being fed into the system. The presence of significant amounts of newly generated aqueous fluid, and the volume expansion of that fluid as it migrates upwards should weaken the rocks, enhance creep rates and generate rheological instabilities[3,26,27]. Fluids in concentrations <0.5 vol% (less than those that can be produced as rocks pass through a fluid pulse zone) can weaken feldspathic rocks and enhance and concentrate shear deformation[27], and high pore pressure has been suggested to be a direct cause of silent earthquake slip events[28].

We have shown that rapid exhumation of rock from an orogen has the potential to produce dehydration that can produce amounts of fluid that are sufficient to affect a wide range of rock properties, as a consequence of a continuing supply of new metamorphic fluid generated as rock passes up through the orogen. This process provides an explanation for the location and origin of the paired geophysical anomaly zones under the Southern Alps. Dehydration accompanying exhumation may possibly also occur in other orogenic belts where rocks have undergone or are undergoing rapid exhumation.

Methods

Calculation of the P–T pseudosection diagram showing the mineral assemblages and reaction relationships for this sample was done using THERMOCALC version 3.25 (ref. 29) and the internally consistent thermodynamic data set 5.5 (ref. 30) following the methods previously outlined[7,17]. The calculation of the molar amount of new fluid that is generated by dehydration reactions during isothermal decompression is produced by processing THERMOCALC output in Mathematica, using the following equations. The moles of fluid, m, generated in a P interval at T is

$$m = \int_{P_1}^{P_2} \mathrm{d}p_{H_2O}$$

but the differential, the change in the number of moles of fluid as a function of P, can be represented in terms of P through

$$\mathrm{d}p_{H_2O} = \left(\frac{\mathrm{d}p_{H_2O}}{\mathrm{d}P}\right)\mathrm{d}P$$

Thus, in decompression from P_1 to P_2 the number of moles of fluid generated is

$$m = \int_{P_1}^{P_2} \left(\frac{\mathrm{d}p_{H_2O}}{\mathrm{d}P}\right)\mathrm{d}P$$

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References

1. Fyfe, W. S., Price, N. J. & Thompson, A. B. *Fluids in the Earth's Crust* (Elsevier, 1978).
2. Walther, J. V. & Orville, P. M. Volatile production and transport in regional metamorphism. *Contrib. Mineral. Petrol.* **79,** 252–257 (1982).
3. Connolly, J. A. D. Devolatilization-generated fluid pressure and deformation-propagated fluid flow during prograde regional metamorphism. *J. Geophys. Res.* **102,** 18149–18173 (1997).
4. Yardley, B., Gleeson, S. B. & Banks, D. Origin of retrograde fluids in metamorphic rocks. *J. Geochem. Explor.* **69–70,** 281–285 (2000).
5. Stüwe, K. Tectonic constraints on the timing relationships of metamorphism, fluid production and gold-bearing quartz vein emplacement. *Ore Geol. Rev.* **13,** 219–228 (1998).
6. Guiraud, M., Powell, R. & Rebay, G. H_2O in metamorphism and unexpected behaviour in the preservation of metamorphic mineral assemblages. *J. Metamorphic Geol.* **19,** 445–454 (2001).
7. Ring, U., Brandon, M. T., Willett, S. D. & Lister, G. S. in *Exhumation Processes: Normal Faulting, Ductile Flow and Erosion* (eds Ring, U., Brandon, M. T., Lister, G. S. & Willet, S. D.) 1–27 (Geol. Soc., London, Spec. Publ., Vol. 154, 1999).
8. Norris, R. J., Koons, P. O. & Cooper, A. F. The obliquely-convergent plate boundary in the South Island of New Zealand: implications for ancient collision zones. *J. Struct. Geol.* **12,** 715–725 (1990).
9. Walcott, R. I. Modes of oblique compression: Late Cenozoic tectonics of the South Island of New Zealand. *Rev. Geophys.* **36,** 1–26 (1998).
10. Stern, T. *et al.* in *A Continental Plate Boundary: Tectonics at South Island, New Zealand* (eds Okaya, D., Stern, T. & Davey, F.) 207–233 (Geophys. Monograph Ser., Vol. 175, American Geophysical Union, 2007).
11. Stern, T., Kleffmann, S., Okaya, D., Scherwath, M. & Bannister, S. Low seismic wave-speeds and enhanced fluid pressure beneath the Southern Alps, New Zealand. *Geology* **29,** 679–682 (2001).
12. Wannamaker, P. E. *et al.* Fluid generation and pathways beneath an active compressional orogen, the New Zealand Southern Alps, inferred from magnetotelluric data. *J. Geophys. Res.* **107,** 2117 (2002).
13. Jiracek, G. R., Gonzalez, V. M., Caldwell, T. G., Wannamaker, P. E. & Kilb, D. in *A Continental Plate Boundary: Tectonics at South Island, New Zealand* (eds Okaya, D., Stern, T. & Davey, F.) 347–369 (Geophys. Monograph Ser., Vol. 175, American Geophysical Union, 2007).
14. Batt, G. E. & Braun, J. On the thermomechanical evolution of compressional orogens. *Geophys. J. Int.* **128,** 364–382 (1997).
15. Batt, G. E. & Braun, J. The tectonic evolution of the Southern Alps, New Zealand: Insights from fully thermally coupled dynamical modelling. *Geophys. J. Int.* **136,** 403–420 (1999).
16. Vry, J. K., Powell, R. & Williams, J. Establishing the *P–T* path for Alpine Schist, Southern Alps near Hokitika, New Zealand. *J. Metamorph. Geol.* **26,** 81–97 (2007).
17. Little, T. A., Cox, S., Vry, J. K. & Batt, G. Variations in exhumation level and uplift rate along the oblique-slip Alpine Fault, central Southern Alps, New Zealand. *Geol. Soc. Am. Bull.* **117,** 707–723 (2005).
18. Powell, R., Will, T. M. & Phillips, G. N. Metamorphism in Archaean greenstone belts: calculated fluid compositions and implications for gold mineralisation. *J. Metamorph. Geol.* **9,** 141–150 (1991).
19. Stauffer, D. & Aharony, A. *Introduction to Percolation Theory* 2nd edn (Taylor Francis, 1992).
20. Yardley, B. W. D. & Graham, J. T. The origins of salinity in metamorphic fluids. *Geofluids* **1,** 1–8 (2002).
21. Vry, J. & McHaffie, K. Garnet growth during uplift and mylonitisation along the Alpine Fault bends, New Zealand: Fluid inclusion results. *Geol. Soc. NZ Misc. Publ.* **95A,** 162 (1997).
22. Smith, M. P. & Yardley, B. W. D. Fluid evolution during metamorphism of the Otago Schist, New Zealand: (I) Evidence from fluid inclusions. *J. Metamorph. Geol.* **17,** 173–186 (1999).
23. Craw, D. Fluid evolution, fluid immiscibility and gold deposition during Cretaceous-Recent tectonics and uplift of the Otago and Alpine Schist, New Zealand. *Chem. Geol.* **98,** 221–236 (1992).
24. Sibson, R. H. & Scott, J. Stress/fault controls on the containment and release of overpressured fluids: Examples from gold-quartz vein systems in Juneau, Alaska; Victoria, Australia and Otago, New Zealand. *Ore Geol. Rev.* **13,** 293–306 (1998).
25. Bailey, R. C. Trapping of aqueous fluids in the deep crust. *Geophys. Res. Lett.* **17,** 1129–1132 (1990).
26. Etheridge, M. A., Wall, V. J., Cox, S. F. & Vernon, R. H. High fluid pressure during regional metamorphism and deformation: Implications for mass transport and deformation mechanisms. *J. Geophys. Res.* **89,** 4344–4358 (1984).
27. Tullis, J., Yund, R. & Farver, J. Deformation-enhanced fluid distribution in feldspar aggregates and implications for ductile shear zones. *Geology* **24,** 63–66 (1996).

28. Kodaira, S. *et al*. High pore fluid pressure may cause silent slip in the Nankai Trough. *Science* **304,** 1295–1298 (2004).
29. Powell, R. & Holland, T. J. B. An internally consistent dataset with uncertainties and correlations: 3, applications to geobarometry, worked examples and a computer program. *J. Metamorph. Geol.* **6,** 173–204 (1988).
30. Holland, T. J. B. & Powell, R. An internally consistent thermodynamic data set for phases of petrological interest. *J. Metamorphic Geol.* **16,** 309–343 (1998).

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Author contributions

J.V. identified the problem as being of interest. The final calculation and design of Figs 3, 4 and Supplementary Fig. S2 was done by R.P. with input and data provided by J.V., and J.V. and R.P. contributed equally to the writing of the letter. K.M.G. and K.P. undertook early calculations that were instrumental in bringing the Letter to its present focus, and contributed insights and feedback during the writing process.

Additional information

The authors declare no competing financial interests. Supplementary information accompanies this paper on www.nature.com/naturegeoscience. Reprints and permissions information is available online at http://npg.nature.com/reprintsandpermissions. Correspondence and requests for materials should be addressed to J.V.