# The role of exhumation in metamorphic dehydration and fluid production

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**During progressive metamorphism accompanying orogeny, fluid is released by the breakdown of volatile-bearing minerals. This amounts to a significant fractionation of the crust, with the fluids passing towards the Earth's surface having the capacity to cause mineralisation, enhance deformation, affect geophysical characteristics, and change major element and isotope compositions. Metamorphic devolatilisation has long been considered to occur dominantly during temperature increase associated with burial of rocks and their metamorphism. In contrast, a significant proportion of the exhumation history of regional metamorphic belts has not been expected to generate large amounts of fluid[1-4]. Here we use mineral equilibria modelling to show that during rapid erosional exhumation, greywacke, a common rock type in orogenic belts, can generate a continuing supply of new fluid, especially at temperatures below ~500 °C. The paired seismic and electrical conductivity anomaly zones in the Southern Alps, New Zealand, are suggested to be related to such fluid release. Fluid generated during exhumation could source post-metamorphic peak orogenic gold mineralisation, post-metamorphic peak quartz veins and retrograde alteration.**

The common simplifying assumption that metamorphic devolatilisation results solely from heating[1-4] has not been properly assessed, and although it is usual to assume that fluids present during exhumation have an external source[5,6], this may not be the case. Metamorphic devolatilisation depends strongly on both rock chemistry and on the shape of the metamorphic pressure-temperature *(P-T)* path[7]. Devolatilisation 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 devolatilisation ceases. The key to this paper 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 many active orogenic belts, rapid exhumation, by processes such as normal faulting in extensional settings or erosion in collisional belts[8], causes nearly-isothermal decompression. Here, we examine metamorphic dehydration during this decompression. The Southern Alps of New Zealand (Fig. 1a, b) is ideal for considering this. The Southern Alps is 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[9-14] (Fig. 1b, c). The Southern Alps has been forming since ~6 Ma by the oblique continent-continent collision of the Pacific Plate against the Australian Plate, at the Alpine Fault. Movement of the Pacific Plate WSW at c. 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 SE-dipping Alpine Fault, and erosionally exhumed. Uplift rates (~10 mm $yr^{-1}$) are some of the highest in the world[9, 10, 14], resulting in *P*-*T* paths for a significant part of the exhumation history that are characterised by isothermal decompression[15, 16]. 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[17]. Fluid calculations, done for one representative greywacke composition, have 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 results of our petrological calculations, by showing where effects attributable to the existence of significant amounts of conductive aqueous fluid are recognisable.

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 from the Southern Alps. 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[17]. The results show that significant devolatilisation occurs as the rocks are exhumed. This devolatilisation occurs mainly as the *P*-*T* paths of the rocks cross through the shaded reaction zone in Fig. 2. The effect of this zone 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 unrecognised way for significant amounts of new fluid to be generated as rocks undergo uplift towards the surface at near peak metamorphic temperatures.

The results of this study have several important implications. Metamorphic fluids are powerful agents of geological change. Our results provide 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), as well as a previously unrecognised source of fluid for post-metamorphic peak orogenic gold mineralisation, post-metamorphic peak quartz veins and retrograde alteration. Prior to this study, all of these features were attributed to the results of devolatilisation accompanying increases in *P* and particularly *T*, with deeper rocks attaining maximum temperatures later than rocks at shallower levels[6,18]. 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 seawater[11-13]. They are most simply explained as resulting directly from generation of new metamorphic fluid during exhumation. The simplest model, and one in complete accord with the mineral equilibria modelling, is that fluids which produce the geophysical anomalies are being generated at that location.

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 3D 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% to 0.2% for tubule diameters of 0.5 to 2μm[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 (on 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 enought salt to lower electrical resistivities. In particular, primary fluid inclusions trapped in garnet[21] and other fluid inclusion data[22,23] record salinities approaching that of seawater (~ 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 (~$10^5$ years) to geologically long (~$10^8$ years) for rock with initial porosities of ~ 1%[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[14]. 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[4,26,27]. 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 devolatilisation 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 could occur in other orogenic belts where rocks have undergone or are undergoing rapid exhumation.

## METHODS SUMMARY

Calculation of the *P*-*T* pseudosection diagram showing the mineral assemblages and reaction relationships for this sample was done using THERMOCALC v. 3.25[29] and the internally consistent thermodynamic dataset 5.5[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 a *BBEdit*™ Text Factory then in *Mathematica*™, using the following equations. The moles of fluid, $m$, generated in a $P$ interval at $T$ is

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

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

$$dp_{\mathrm{H_2O}} = \left(\frac{dp_{\mathrm{H_2O}}}{dP}\right) dP$$

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

$$m = \int_{P_1}^{P_2} \left(\frac{dp_{\mathrm{H_2O}}}{dP}\right) dP$$

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**Competing Financial Interests statement**

There are no competing financial interests.

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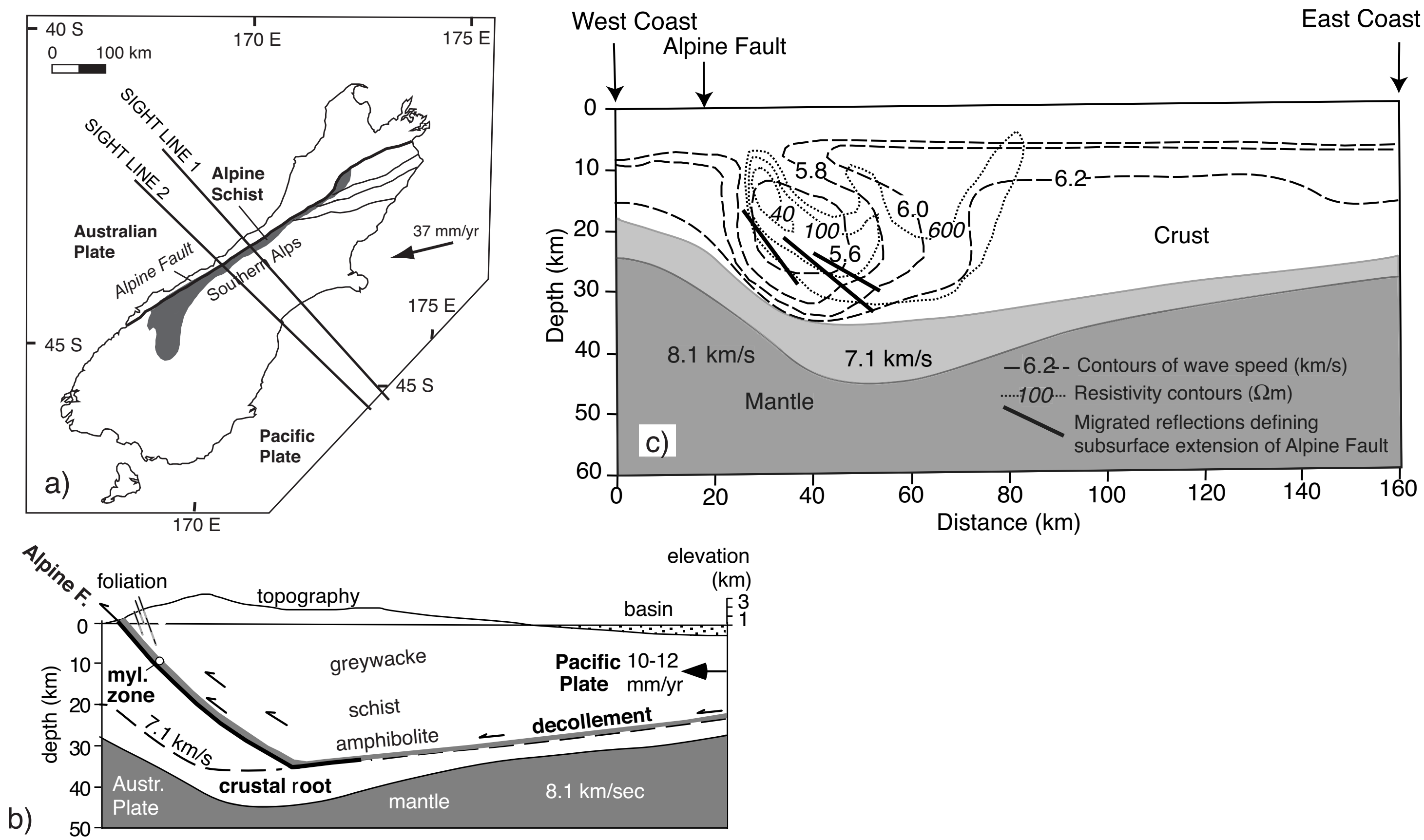
## Figure Legends

**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)[9,10]. **b**, Schematic interpretation of crustal structure across the South Island in the vicinity of the two SIGHT (South Island GeopHysical Transect) lines. **c**, Location of paired seismic and magnetotelluric anomalies under the Southern Alps. Seismic wave speeds are mainly from SIGHT line 2[11,12], and the low resistivity zone[13,14] was documented using data from SIGHT line 1.

**Figure 2** ***P-T*** **location of reaction zone (shaded) where significant dehydration can take place during decompression.** *P-T* pseudosection for a typical sample of Alpine Schist[17]. Larger amounts of dehydration in reaction zone 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. Other mineral abbreviations: ab, albite; bt, biotite; chl, chlorite; grt, garnet; ilm, ilmenite; ms, muscovite, pg, paragonite; pl, plagioclase; qtz, quartz. Italicised labels in parentheses at the ends of lines indicate which phase is gained or lost with increasing temperature.

**Figure 3 Enhanced fluid generation (darker shading) occurs during decompression across reaction zone identified in Fig. 3.** 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.

**Figure 4 Cumulative moles of $H_2O$ generated from one mole of Alpine Schist during decompression at different temperatures.** Steep sections show main contribution of fluid.

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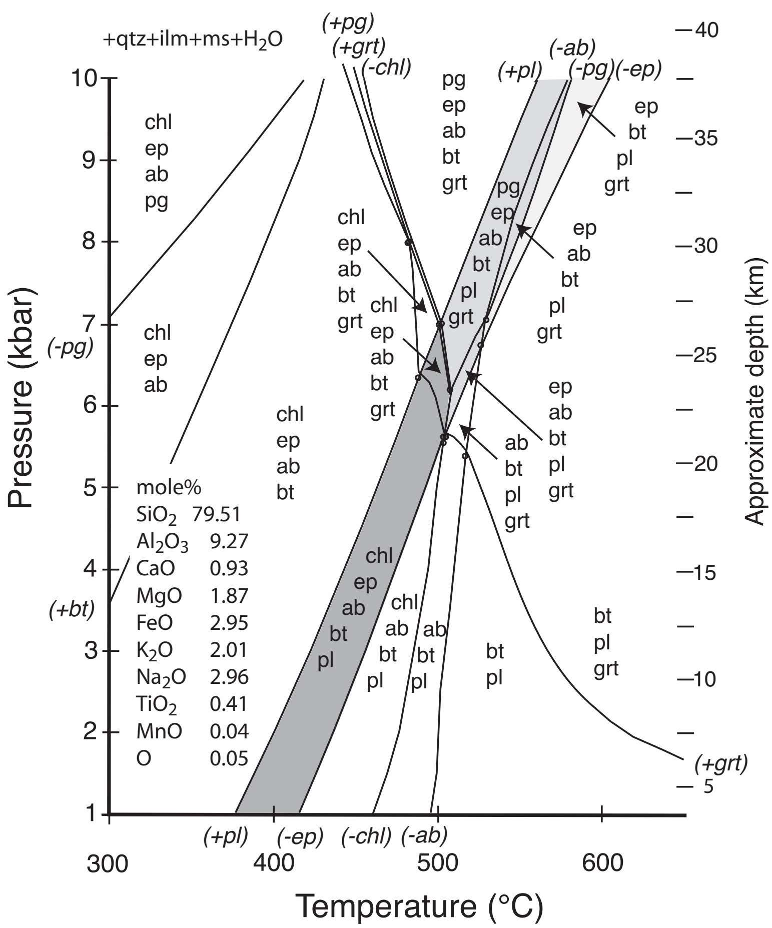


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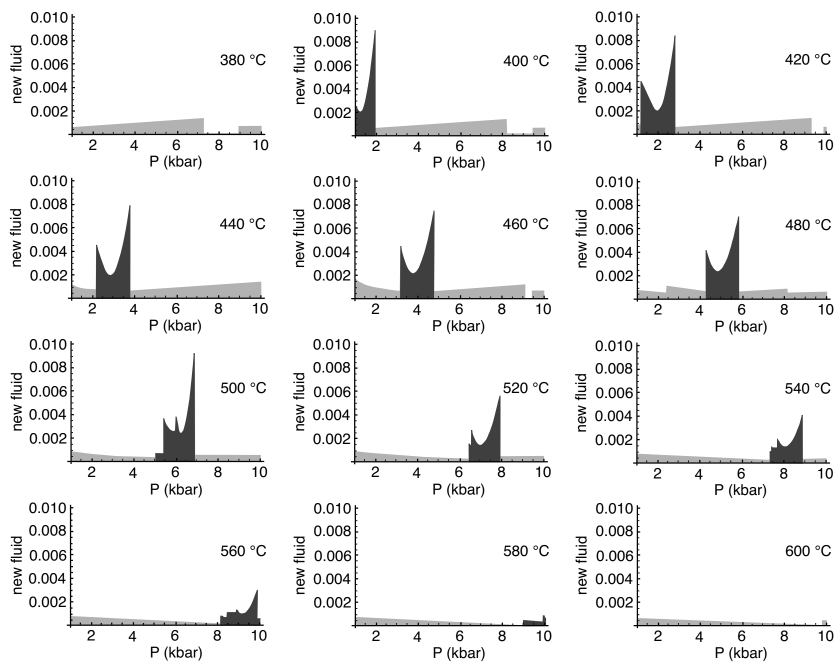


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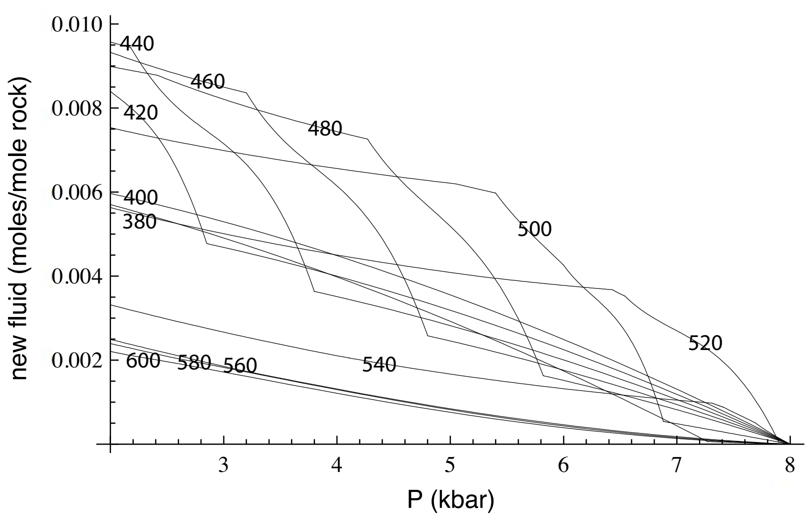


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