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Peak metamorphic temperature and thermal history of the Southern Alps (New Zealand)

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ABSTRACT

The Southern Alps orogen of New Zealand results from late Cenozoic convergence between the Indo-Australian and Pacific plates and is one of the most active mountain belts in the world. Metamorphic rocks carrying a polymetamorphic legacy, ranging from low-greenschist to high-grade amphibolites, are exhumed in the hanging wall of the Alpine Fault. On a regional scale, the metamorphic grade has previously been described in terms of metamorphic zones and mineral isograds; application of quantitative petrology being severely limited owing to unfavorable quartzofeldspathic lithologies. This study quantifies peak metamorphic temperatures (T) in a 300 × 20 km area, based on samples forming 13 transects along-strike from Haast in the south to Hokitika in the north, using thermometry based on Raman spectroscopy of carbonaceous material (RSCM). Peak metamorphic T decreases across each transect from ≥640 °C locally in the direct vicinity of the Alpine Fault to less than 330 °C at the drainage divide 15–20 km southeast of the fault. Thermal field gradients exhibit a degree of similarity from the southernmost to the northernmost transects, are greater in low-grade semischist than high-grade schist, are affected by folding or discontinuous juxtaposition of metamorphic zones, and contain limited information on crustal-scale geothermal gradients. Temperatures derived by RSCM thermometry are slightly (≤50 °C) higher than those derived by traditional quantitative petrology using garnet–biotite thermometry and THERMOCALC modeling. The age of RSCM T appears to be mostly pre-Cenozoic over most of the area except in central Southern Alps (Franz Josef–Fox area), where the amphibolite facies schists have T of likely Cenozoic age. The RSCM T data place some constraints on the mode of exhumation along the Alpine Fault and have implications for models of Southern Alps tectonics.

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1. Introduction

The kinematics and thermal structure of orogenic wedges result from the coupling between crustal and surface processes at convergent plate boundaries. Being one of the most active mountain belts in terms of both tectonic and surface processes, the Southern Alps of New Zealand offers a unique tectonophysical laboratory to investigate these interactions. The rocks of this mountain belt were formed by Paleozoic and Mesozoic subduction–accretion processes at the paleo-Pacific margin of Gondwana, split from Gondwana and were thinned during the Late Cretaceous, then rent by dextral strike-slip displacement as the Alpine Fault plate-boundary developed during the Neogene.

The Southern Alps, which comprise much of the South Island (Fig. 1), began forming during the late Cenozoic as the Indo-Australian–Pacific plate motion became increasingly convergent in the Pliocene–Pleistocene. These mountains form against the Alpine Fault—a transpressive section of the Pacific and Indo-Australian plate boundary (see Cox and Sutherland, 2007 for review). The Pacific Plate presently appears to delaminate (e.g. Molnar et al., 1999) or subduct (e.g. Beaumont et al., 1996) within the orogen, actively exhuming a belt of mid-upper crustal material obliquely on the Alpine Fault, and accreting lower crustal material into a thickened crustal root (e.g. Gerbault et al., 2002; Lamb et al., 2016). The plate boundary is widely cited as a type-example of deep geological processes and continent–continent collision (e.g. Okaya et al., 2007).

Over the past 20 years, there has been considerable scientific effort trying to understand the architecture of the Indo-Australian–Pacific plate convergence in the South Island (e.g. Okaya et al., 2007). Evidence has been gathered on the depth of the crustal root, nature of lithosphere, and geometry of faults (see Okaya et al., 2007). This effort has been complemented by thermochronologic work to decipher the timing and thermal structure associated with mountain building and exhumation (e.g.; Tippett and Kamp, 1993a,b; Batt et al., 2000; Herman et al., 2009). Other studies have noted perturbations of the geotherm, producing high thermal gradients and hot spring activity (e.g. Allis et al., 1979;

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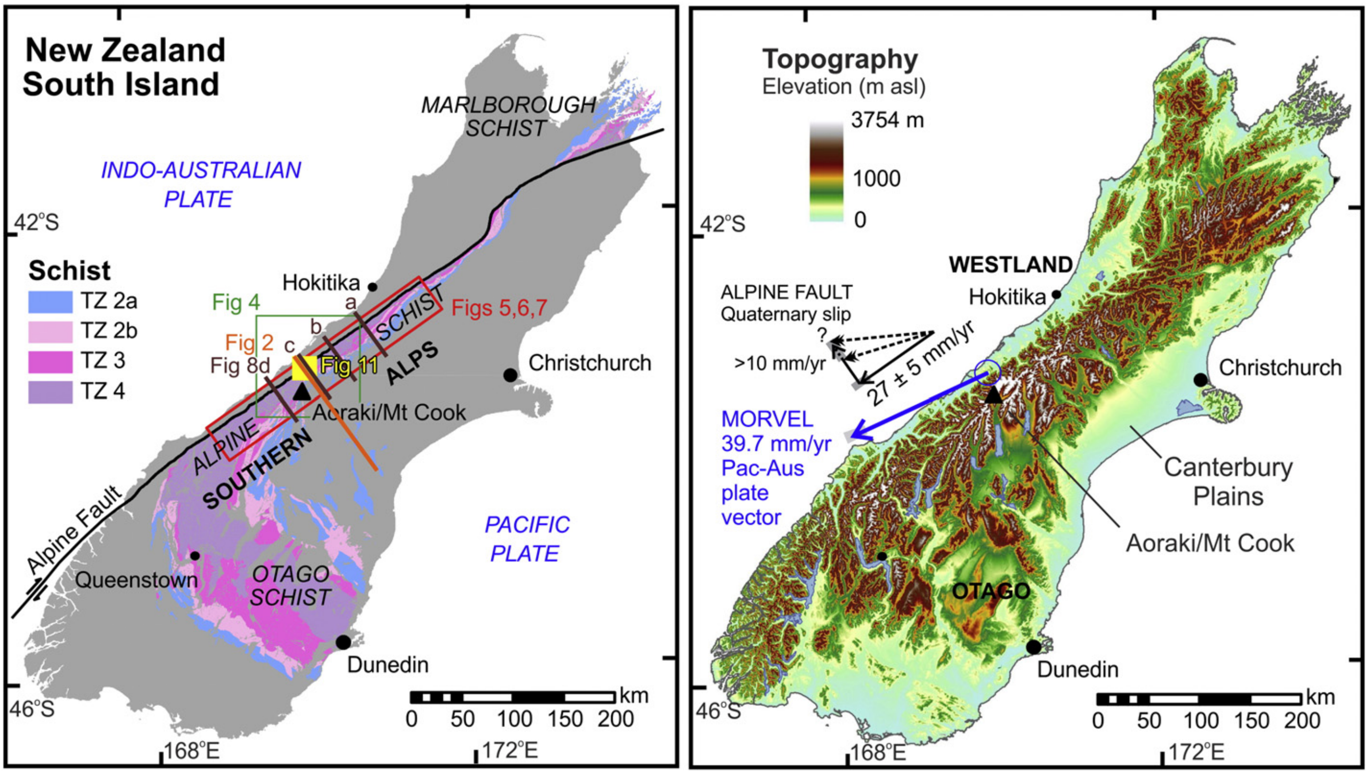

Fig. 1. Simplified geological (left) and topographic map of the South Island of New Zealand. The left map depicts the main textural zones in schists and location for the other figures. The right map shows the topography of the South Island and the main kinematic vectors for the Pacific Plate relative to the Indo-Australian Plate (De Mets et al., 2010), and late Quaternary slip on the Alpine Fault (Norris and Cooper, 2001).

Koons 1987; Allis and Shi 1995; Sutherland et al., 2012; Cox et al., 2015). However, while the general metamorphic structure of the Southern Alps is qualitatively well established, there are very few quantitative constraints on the thermal state and thermal history of the crust. An understanding of the thermal history of the orogen is needed to constrain the information low-temperature thermochronometers provide about erosion rates and the stability of landforms, as well as the rheology of rocks, behavior of faults at seismogenic depth (Toy et al., 2010), and ultimately seismic hazard (Sutherland et al., 2007). The lack of thermal state information is largely attributable to the bulk rock compositions (mainly metamorphosed quartzofeldspathic greywacke) that are chemically unfavorable for precise metamorphic petrology, and complicated further by the polymetamorphic and polydeformational history of the rocks and potential overprinting effects of fluid flow (Koons et al., 1998; Vry et al., 2004; Menzies et al., 2014).

In this study, we introduce thermometry based on Raman spectroscopy of carbonaceous material (RSCM) (Beyssac et al. 2002) that allows the quantitative estimate of peak metamorphic temperature (T) independently from the extent of retrogression and presence of diagnostic mineral assemblages. Owing to widespread presence of carbonaceous material in the local Alpine Schist and greywacke, this technique has enabled the generation of a large dataset covering most of the Alpine Fault hanging wall, both along-strike and perpendicular to the fault. We present a dataset of 142 new temperature estimates covering a 300 × 20 km area (Table 1). We have also revisited traditional garnet–biotite thermometry results for some of the same samples used for RSCM thermometry, or collected from nearby locations. We provide those results for comparison, along with a few insights gained through comparison of the observed mineral assemblages with their stability fields in P–T pseudosections calculated using THERMOCALC. We then discuss the age of these temperatures by reviewing existing geochronologic constraints to separate the Mesozoic legacy from the late Cenozoic thermal overprint and the extent to which this varies along the plate boundary. Finally, we highlight some constraints these RSCM temperature distributions place on the style and nature of Southern Alps tectonics.

2. Geological setting

2.1. General tectonics of the Southern Alps

Fig. 1 depicts simplified geological and topographic maps of the South Island. Pacific Plate motion relative to the Indo-Australian Plate is 39.7 ± 0.7 mm/a at 245 ± 1° in the central South Island (MORVEL model of De Mets et al., 2010). The vector is 12° anticlockwise of the Alpine Fault, which strikes 053° and is inferred to dip ~40–60° SE (Norris and Cooper, 2007; Stern et al., 2007), extending downward to depths of 25–30 km based on the presence of amphibolite facies schist exhumed in its hanging wall (Grapes, 1995). The generally accepted crustal model depicts the Alpine Fault shallowing eastward into a lower crustal décollement that delaminates the Pacific Plate (Fig. 2, e.g., Wellman, 1979; Norris et al., 1990; Okaya et al., 2007), although there is no conclusive evidence for such a detachment. Thermochronological modeling indicates that uplift/cooling must be a two-stage process first initiating on a gently rising trajectory beneath the dry pro-side of the mountains then occurring more-rapidly up the Alpine Fault ramp (Herman et al., 2009). While the maximum metamorphic grade of exhumed rocks has been used to infer the approximate depth of the Alpine Fault and Pacific Plate delamination, it is predicated on an assumed geothermal gradient and the assumption that previously stable metamorphic assemblages were exhumed in the late Cenozoic. Although low-temperature thermochronologic ages are clearly the result of Neogene–Quaternary cooling and exhumation, many of the rocks reached peak metamorphic temperatures during the Mesozoic, so much care is needed when using metamorphic assemblages to constrain the present crustal structure.

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