Tectonics

Supporting Information for

Middle-late Miocene age for the end of amphibolite-facies mylonitization of the Alpine Schist, New Zealand: Implications for onset of transpression across the Alpine Fault

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1. Introduction

This supporting information provides detailed descriptions of the five samples used for P-T work and geochronology, a summary of the methods used, a figure with X-ray maps and five tables showing our data and data compilations.

2. Sample descriptions

SCMY1 is a dark-grey, pelitic mylonite, rich in Fe-phases (garnet, biotite, ilmenite). The rock is fine-to medium grained, with a very tightly spaced (~0.5 mm) planar foliation. The mineral assemblage is quartz, feldspar, biotite, garnet, muscovitic white mica, ilmenite, apatite (with a possibly bimodal grain-size distribution), tourmaline, pyrite and graphite. Garnet is up to 3 mm in diameter, and considerably exceeds the grain size of the other phases. There is a nearly

equigranular grain-size distribution for the micas. Feldspar, quartz and apatite are mostly fine-grained (50-300 µm). Slightly bigger, ovoidal feldspar porphyroclasts ('augen') and unusually big (300 to 400 µm) apatite crystals are present but rare. Whitish layers dominated by quartz, feldspar and white mica are recrystallized and provide textural evidence for pervasive ductile deformation.

SCMY2 is a psammitic, quartz-feldspar-dominated, fine- to medium-grained, equigranular mylonite with a tightly spaced (~1 mm) planar foliation. The foliation is macroscopically defined by the alternation of quartz-feldspar-rich ribbons and biotite-muscovite-garnet-rich layers. The foliation comprises intergrown flakes of muscovite and biotite. Garnet is up to 800 µm in diameter and wrapped by mica-rich layers with a strong crystal-shape orientation. There are no pre-mylonitic feldspar porphyroclasts evident in hand specimen. Thin sections show rare, faint relics of mainly carbonate after potential porphyroclasts/porphyroblasts of an unknown phase. Quartz-feldspar-mica layers are again thoroughly recrystallized indicating pervasive ductile deformation.

GC5 is a dark, fine- to medium-grained, biotite-rich, pelitic mylonite, with a tightly spaced (~0.5 mm) planar foliation. The foliation is mainly defined by a mica grain-shape orientation. Parallel to this mylonitic foliation are strongly stretched quartz layers (mobilisates), which are up to 2 mm thick. The mineral assemblage comprises feldspar, quartz, white mica, biotite (in part intimately intergrown with white mica, feldspar and quartz), rare garnet up to 1 mm in size, apatite, zircon, pyrite and graphite. Rare feldspar augen (up to 2 mm in diameter) show dynamic recrystallization. Biotite shows a bimodal grain-size distribution with some crystals up to 500 µm and abundant smaller (50 µm) grains. White mica is up to 400 µm in size with most grains being distinctly smaller (median estimated at ~100 µm). Microtextures suggest that, with exception of garnet and rare feldspar augen, the entire assemblage experienced pervasive ductile deformation and synkinematic recrystallization.

GC6 is a quartz-feldspar-dominated, fine-to medium-grained, psammitic mylonite, with a tightly spaced (0.5 to 1 mm) planar foliation. The foliation is macroscopically defined by alternation of quartz-feldspar-rich and mica-garnet-rich layers. Some quartz layers are thicker and tend to form flat, synfolial, up to several millimeter thick spindle-shaped bodies (segregations) in which garnet grew (Fig. 2d in main manuscript). The mineral assemblage is quartz, feldspar, biotite, muscovitic white mica, garnet, apatite, minor tourmaline, pyrite, ilmenite, graphite, carbonate and some minor (secondary?) chlorite. Both mica phases are up to 300 µm in size, feldspar (mostly plagioclase) is up to 400 µm. Garnet reaches a size of up to 1 mm and the continuity of its internal (Si) and external (Se) foliations indicates syntectonic growth (Fig. 2e-f). The quartz-feldspar-mica assemblage again is entirely deformed ductily.

WAI is fine- to coarse-grained mylonite with a gneissic appearance. The sample contains large, ovoidal feldspar porphyroclasts ('augen') and mica fish in a fine- to medium-grained matrix. The mineral assemblage is plagioclase, white mica, quartz, biotite, garnet, apatite, minor chlorite and traces of carbonate. Feldspar and white mica depict a bimodal grain-size distribution. Euhedral white-mica porphyroclasts reach up 1 cm, and plagioclase is up to several millimeter in size. Synfolial, at least partially recrystallized white mica and biotite is up to ~500 µm. The texture is characteristic for strong, greenschist- to amphibolite-facies shearing of rocks with a former magmatic-pegmatitic texture.

3. Methods

SEM, electron probe micro-analyses and pseudosection modeling

Microtextural characterization using the back scattered electron mode has been performed using a Scanning Electron Microscope (SEM) Ultra 55 Plus (Zeiss) at GFZ Potsdam with 20 kV acceleration voltage and equipped with an ultra-dry Energy Dispersive Spectroscopy (EDS) detector. A sample surface composition estimate for SCMY2 has been obtained by averaging five surface composition estimates (each 3 x 1.5 mm, 30 s counting time).

Electron probe microanalyses have been performed at the GFZ Potsdam using a JEOL-JXA 8230 probe under common analytical conditions (15 kV, 20 nA, wavelength-dispersive spectroscopy mode) and using a 10 µm beam. Standards used for the calibration were the following: orthoclase (Al, Si, K), fluorite (F), rutile (Ti), Cr_2O_3 (Cr), wollastonite (Ca), tugtupite (Cl), albite (Na), MgO (Mg), Fe_2O_3 (Fe) and rhodonite (Mn). Table 1 presents some selected analyses of major phases. Mineral abbreviations used in this work are after Whitney and Evans (2010). Representative mineral analyses are given in Appendix A2.

For pseudosection modeling we used the software package Perplex (v.6.7.4; Connolly, 2005). The thermodynamic modeling has been performed in the NCTiKFMASH system (manganese, not detected by the SEM EDS detectors, and ferric iron have been neglected for simplicity). The bulk composition used for the modeling, derived from SEM surface estimates, is (in wt.%): SiO_2 (67.80), TiO_2 (0.56), Al_2O_3 (15.5), FeO (3.73), MgO (1.54), CaO (2.17), Na_2O (4.54), K_2O (1.4). Pure water has been considered in excess for this calculation. Activity models used here are the following: biotite (Holland and Powell, 1998) amphibole (Dale et al., 2005), ilmenite (White et al., 2000), chlorite (Holland et al., 1998), phengite, garnet, chloritoid and staurolite (Holland and Powell, 1998) and feldspar (Fuhrman and Lindsley, 1988). MnO and Fe_2O_3 have been neglected in sake of simplicity and as they are both very minor components in the system.

The garnet cores of our samples are not necessarily in equilibrium with the deformed matrix where peak temperature is recorded. The conventional way of addressing this problem is by removing garnet cores from the effective bulk composition used for the modeling. This is commonly done for eclogite-facies assemblages where garnet represents more than 30 vol.% of the total volume (e.g. Konrad-Schmolke et al., 2008). In our samples, the garnet volumetric fraction to be subtracted from the effective bulk composition would correspond to less than 1 vol.%, with no or only extremely minor effect on final topology. The garnet-core effect is already partially taken into consideration in our calculations by excluding Mn from the system. Mn is known to strongly fractionate into garnet cores. The apparent mismatch regarding the absence of clinozoisite in the matrix derives from this simplification. Including Mn in the calculation would shift the garnet-in boundary towards lower temperatures (Mahar et al., 1997), and hence favor co-stability of zoisite and garnet, as seen in the rock record (Fig. 4a in main manuscript). This has not been done in our calculations for the reason that Mn would certainly be fractionated in the garnet cores and be consequently absent in the effective reaction volume in the matrix. In other words, we do not need Mn in the system to model near-peak-temperature phase relationships. We therefore believe that our approach represents the most sensible compromise in order to reproduce as accurately as possible phase relationships near-peak-temperature mylonitization.

The ferric iron content of clinozoisite, X_{Fe} (X_{Fe}=Fe/Fe+Al), in our samples ranges between 0.14 and 0.18, which is very low. Including ferric iron in pseudosection calculations

would make the model more complicated (involving relatively poorly constrained Fe^{3+}-bearing solid-solution models). Therefore, we did not consider ferric iron in our calculations.

The textures of our samples are complicated. We presented them in the manuscript in a way to focus the reader's attention on the arguments used to reconstruct a P-T path (e.g. mineral zoning, overgrowths, mica fish). In the studied samples (which may vary as a function of bulk composition thus explaining differences among samples), indications of local disequilibrium are scarce. As often in Barrovian metamorphic rocks, the climax of deformation and metamorphic imprints occur near-peak-temperature conditions, as we are concluding in our thermo-barometric study. There is some local re-equilibration during exhumation or incomplete peak-burial erasing of the prograde memory (e.g. the garnet core) but this is volumetrically insignificant (< 5 vol.%, optically estimated). The surface compositional estimates (used as input for pseudosection modeling) have been derived from pervasively deformed parts of the thin sections, where micro-structural inheritance/disequilibrium is scarce.

Rb–Sr isotope analyses

For Rb-Sr work, minerals were separated from small samples (less than 100 g) to avoid large-scale disequilibria. Isotopic data were generated at GFZ Potsdam using a Thermo Scientific TRITON thermal ionization mass spectrometer. Sr isotopic composition was measured in dynamic multicollection mode. Rb isotope dilution analysis was done in static multicollection mode. The value obtained for $^{87}Sr/^{86}Sr$ in the NIST SRM 987 isotopic standard during the period of analytical work was 0.710242 ± 0.000020 (2σ, n=16). For age calculation, standard uncertainties of ± 0.005% for $^{87}Sr/^{86}Sr$ and of ± 1.5% for $^{87}Rb/^{86}Sr$ ratios were assigned to the results. Individual analytical uncertainties were generally smaller than these values. Handling of mineral separates and analytical procedures are described in more detail in Glodny et al. (2008). Uncertainties of Rb-Sr isotope and age data are quoted at 2σ. The program ISOPLOT/EX 3.71 (Ludwig, 2009) was used to calculate regression lines. The ^{87}Rb decay constant is used as recommended by Villa et al. (2015).

$^{40}Ar/^{39}Ar$ dating

$^{40}Ar/^{39}Ar$ analyses of various grain size fractions of muscovite and biotite were performed at the Argon Geochronology Laboratory of University of Michigan using a continuous laser for step heating and a VG 1200S noble gas mass spectrometer equipped with a Daly detector operated in analogue mode. The mass spectrometer was operated using the methods outlined in Streepey et al. (2000) and Keane et al. (2006). The sample was packed within a pure Al foil pack and irradiated with fast neutrons in a medium flux location inside the McMaster Nuclear Reactor (Hamilton, Ontario) for 90 MWh. Quoted ages are calculated relative to an age of 520.4 Ma for hornblende standard MMHb-1. After irradiation, mineral grains were processed for extraction and purification of argon by the step-heating method.

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Data Repository captions:

DR1. (top) X-ray map for garnet from GC6 sample (counts). Note presence of ilmenite (Ilm) and epidote (Ep) inclusions inside garnet (Gt); biotite (Bt) and plagioclase (Pl) occur in foliation wrapping around garnet; late chlorite (Chl) forms around garnet. (bottom) X-ray map

of garnet from SCMY2. Most garnet inclusions are quartz and epidote; biotite and plagioclase occur in matrix; chlorite grew in late cracks.

DR2. Representative electron-probe chemical analyses for samples GC6 and SCMY2.

DR3. Comparison of thin-section petrographic and micro-chemical results together with pseudosection modeling results for sample SCMY2.

DR4. Rb-Sr analytical data.

DR5. 40Ar/39Ar analytical data.

DR6. Summary of Late Cretaceous to Paleogene isotopic and fission-track ages.