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Contrast in stress–strain history during exhumation between high- and ultrahigh-pressure metamorphic units in the Western Alps: Microboudinage analysis of piemontite in metacherts

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A B S T R A C T

Our analyses of microboudinage structures of piemontite grains embedded within six samples of metachert, one collected from an ultrahigh-pressure (UHP) metamorphic unit at Lago di Cignana in Italy of the Western Alps, and the other five from surrounding high-pressure (HP) metamorphic units in Italy and France, have revealed that the structures are all symmetrical in type, and were presumably produced in coaxial strain fields. Stress–strain analyses of the microboudinaged grains revealed significant contrasts in the stress and strain histories of the UHP and HP metamorphic units, with the differential stress recorded by the UHP sample being unequivocally lower than that recorded by the five HP samples. In addition, our analyses showed that the UHP sample underwent stress-relaxation during microboudinage, whereas the five HP samples did not. On the basis of these observations and analyses we discuss the mechanical decoupling of the UHP and HP units that led to different histories in differential stress between the units during exhumation of the Western Alps.

1. Introduction

Continent–continent collision is a key geodynamic process in plate tectonics, and many deep-seated rocks have been exhumed from various depths to produce fold-and-thrust mountain belts between colliding continental blocks. The Alps is a typical example of such a belt. The aim of this study was to estimate the magnitude of differential stress imposed on the rocks in the deepest parts of the collision zone in the Alps during collision and subsequent exhumation. Given that ultrahigh-pressure (UHP) and high-pressure (HP) metamorphic rocks make up the axial zone of the Western Alps, this region provides an ideal setting for our work.

Microboudinage structures of columnar minerals such as amphibole, epidote and tourmaline, embedded within a quartzose matrix, provide quantitative stress–strain data for the period immediately prior to the cessation of plastic deformation of the quartz (e.g., Masuda et al., 2003, 2004, 2007; Kimura et al., 2006, 2010). Thus, microboudin analysis is suitable for estimating the magnitude of differential stresses during the exhumation of metamorphic belts. Among the various columnar minerals, piemontite (a manganese-rich epidote) is one of the most suitable for microboudinage analysis, as it is easy to observe in thin sections because of its characteristic pink colour under the optical microscope in plane polarized light. The occurrence of piemontite-bearing metacherts has previously been reported from UHP and HP units of the Western Alps by Dal Piaz and Ernst (1978), Dal Piaz et al. (1979) and Mottana (1986), and we found examples of piemontite microboudins at all six localities we visited.

In this paper we report on our use of the microboudinage technique for analysing the palaeostresses during Alpine UHP and HP metamorphism, and we record the stress–strain data for six samples of metachert. The most remarkable result is the contrast in

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the stress–strain histories of the UHP and HP units, and this may provide new insights into how the rocks were exhumed at mid-crustal depths.

2. Geological setting

The Lago di Cignana UHP unit, Val d'Aosta, Italy (Fig. 1), is situated in the inner Penninic Zone of the Western Alps (e.g., Reinecke, 1991; Compagnoni and Rolfo, 2003; Forster et al., 2004). Coesite was discovered in this unit by Reinecke (1991), and a locality of piemontite-bearing metachert had earlier been reported by Dal Piaz and Ernst (1978) and Dal Piaz et al. (1979). The protolith of the UHP unit is ophiolitic, and there are no intercalated continental materials; the UHP unit occurs as a ~100 m thick slice of rocks surrounded by HP metamorphic rocks of the Zermatt–Saas unit (e.g., Compagnoni and Rolfo, 2003; Fig. 11). The peak pressures and temperatures recorded by the unit are estimated to be 2.6–2.8 GPa and 590–630 °C (Reinecke, 1991). The age of metamorphism has been dated at 44.5 ± 2.3 and 43.9 ± 0.9 Ma (U–Pb dating, zircon; Rubatto et al., 1998), and at 40.6 ± 2.6 Ma (Sm–Nd dating, garnet; Amato et al., 1999). Amato et al. (1999) inferred rapid exhumation of the unit (an initial exhumation rate of 10–26 mm/year followed by slow exhumation at 0.3 mm/year). Compagnoni and Rolfo (2003) compiled *P*–*T* and chronological (*t*) data for the unit, as shown in Fig. 2a.

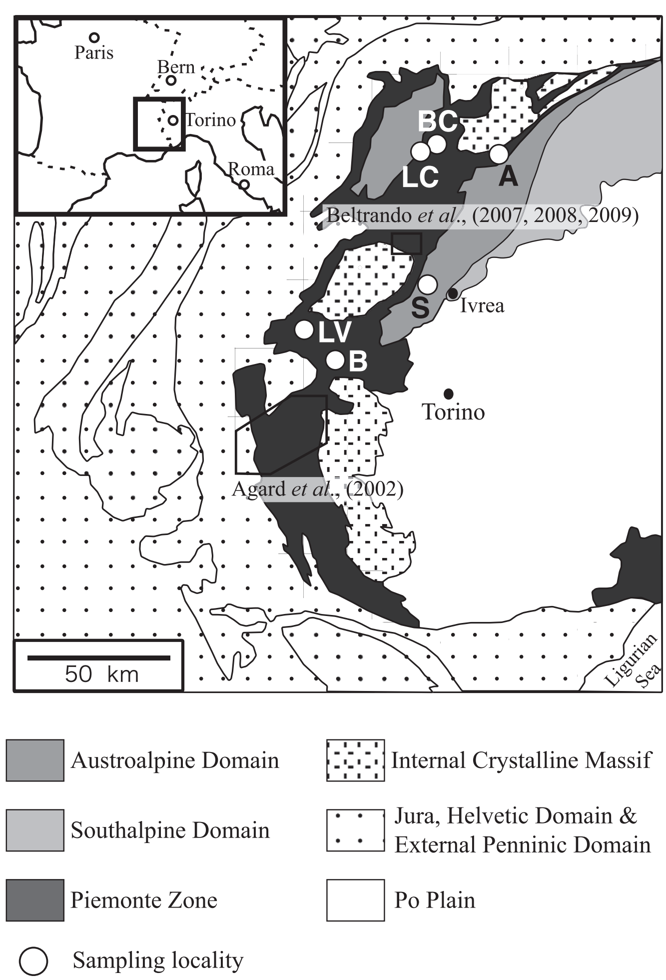

Fig. 1. Geological sketch map of the Western Alps (after Compagnoni, 2003). LC, Lago di Cignana; BC, Breuil Cervinia; A, Alagna; LV, Le Villaron; B, Biolai; S, Sparone. The small rectangle and the hexagon in the main map indicate the areas studied by Beltrando et al. (2007, 2008, 2009) and Agard et al. (2002), respectively.

Four of our samples of piemontite-bearing metachert were collected from the Piemonte Zone (Breuil Cervinia, Alagna, Le Villaron and Biolai), and one sample from the Sesia Zone (Sparone) of the Austroalpine Domain (Fig. 1). All samples are Alpine HP metamorphic rocks. The Piemonte Zone is divided into two units (e.g., Bearth, 1967; Compagnoni, 2003): a quartz-eclogite facies unit (Zermatt–Saas unit) and an epidote-blueschist facies unit (Combin unit). The samples from Breuil Cervinia and Alagna belong to the quartz-eclogite facies unit, while those from Le Villaron and Biolai belong to the epidote-blueschist facies unit (see the Appendix for details on sampling locations). The peak pressure and temperature for the Alagna sample are estimated to be 0.5–1.45 GPa and 450–590 °C, respectively (e.g., Frey et al., 1976; Peters et al., 1978; Liati and Froitzheim, 2006). Although the peak pressures and temperatures for the other three samples from the Piemonte Zone have yet to be directly estimated, similar rocks in adjacent areas have been analysed (Agard et al., 2001, 2002; Beltrando et al., 2007). Agard et al. (2001) studied the tectonometamorphic evolution of the blueschist-facies rocks in the Cottian Alps, about 30 km south of Biolai, and reconstructed pressure–temperature–time (*P*–*T*–*t*) paths for these rocks (see Fig. 2b). The Cottian Alps record a temperature gradient, with higher temperatures in the east. These data are helpful in evaluating the *P*–*T*–*t* path of the Breuil Cervinia and Alagna samples.

Beltrando et al. (2007) proposed two burial–exhumation cycles for the eclogite-facies rocks of the Urtier Valley area (Fig. 2c), but it is uncertain whether the rocks analysed in the present study experienced these two cycles. In summary, the peak temperatures recorded by the HP samples collected from the Piemonte Zone range from 350 to 500 °C, and the peak pressures range from 0.5 to 2.0 GPa. The peak pressures and temperatures at Sparone, within the Austroalpine Domain, are estimated to be > 0.8–1.0 GPa and 300–400 °C, respectively (e.g., Pognante et al., 1988). The age of the HP metamorphism is estimated to be Eocene for the Piemonte Zone and Late Cretaceous for the Sesia Zone (e.g., Rubatto et al., 1998, 1999; Liati and Froitzheim, 2006).

Previous structural analyses have demonstrated that the metamorphic rocks in the Western Alps exhibit intense, polyphase and complex fabrics produced by plastic deformation (e.g., Agard et al., 2001; Reddy et al., 2003; Beltrando et al., 2008), but there are few quantitative analyses of the stresses and strains in this region (e.g., van der Klauw et al., 1997; Küster and Stöckhert, 1999; Stöckhert, 2002).

3. Foliation and lineation within the analysed samples

All six samples of metachert show a clear foliation defined by aligned muscovite and compositional domains (~1 mm thick). An obscure lineation occurs on the foliation surface that can be difficult to detect by eye. Samples were carefully selected to avoid foliation that had been folded. For a description of the mineral grains in the samples, see the Appendix. Fig. 3 shows photomicrographs of the samples.

In each sample, the orientation of the lineation (denoted as the X axis) on the foliation surface (XY section) was determined under the microscope using the statistical method proposed by Masuda et al. (1999). As all samples had been collected from loose blocks (float), the orientation was used only to place the sample in a mechanical framework for microboudinage analysis. The orientations of the long axes of all piemontite grains in a certain area were measured on the foliation surface, and the von Mises distribution function was applied to the data (Fig. 4). The intensity of the lineation is represented by the *k*-value (see Fig. 4), which in this case ranges from 0.49 to 1.3. The *k*-value varies from 0 when the orientations of the long axes are random, to ∞ when all the