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Oscillating brittle and viscous behavior through the earthquake cycle in the Red River Shear Zone: Monitoring flips between reaction and textural softening and hardening

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ABSTRACT

Microstructures associated with cataclasites and mylonites in the Red River shear zone in the Diancang Shan block, Yunnan Province, China show evidence for both reaction hardening and softening at lower greenschist facies metamorphic conditions. The earliest fault-rocks derived from Triassic porphyritic orthogneiss protoliths are cataclasites. Brittle fractures and crushed grains are cemented by newly precipitated quartz. These cataclasites are subsequently overprinted by mylonitic fabrics. Truncations and embayments of relic feldspars and biotites show that these protolith minerals have been dissolved and incompletely replaced by muscovite, chlorite, and quartz. Both K-feldspar and plagioclase porphyroclasts are truncated by muscovite alone, suggesting locally metasomatic reactions of the form: 3K-feldspar + 2H$^+$ = muscovite + 6SiO$_{2(aq)}$ + 2K$^+$. Such reactions produce muscovite folia and fish, and quartz bands and ribbons. Muscovite and quartz are much weaker than the reactant feldspars and these reactions result in reaction softening. Moreover, the muscovite tends to align in contiguous bands that constitute textural softening. These mineral and textural modifications occurred at constant temperature and drove the transition from brittle to viscous deformation and the shift in deformation mechanism from cataclasis to dissolution–precipitation and reaction creep. These mylonitic rocks so produced are cut by K-feldspar veins that interrupt the mylonitic fabric. The veins add K-feldspar to the assemblage and these structures constitute both reaction and textural hardening. Finally these veins are boudinaged by continued viscous deformation in the mylonitic matrix, thus defining a late ductile strain event. Together these overprinting textures and microstructures demonstrate several oscillations between brittle and viscous deformation, all at lower greenschist facies conditions where only frictional behavior is predicted by experiments. The overlap of the depths of greenschist facies conditions with the base of the crustal seismic zone suggests that the implied oscillations in strain rate may have been related to the earthquake cycle.

1. Introduction

The strength of the crust is limited by several competing processes. Frictional and cataclastic processes dominate deformation in the upper crust, while thermally activated dislocation creep is thought to dominate at the higher temperatures of the middle and lower crust (e.g. Brace and Kohlstedt, 1980) before partial melting and anatexis cause further weakening (Handy et al., 2001). The strength of frictional upper crustal fault zones increases with confining pressure (depth) until the temperature is high enough to activate dislocation creep processes. At higher temperatures crystal plastic deformation mechanisms dominate, and increasing temperature progressively weakens a feldspathic crust at greater depths. The intersection of these two strength envelopes identifies the depth and temperature of the maximum strength and critical stress of the crust (Regenauer-Lieb and Yuen, 2008; Sibson, 1983), where the two deformation mechanisms compete equally. This shift in deformation mechanism – from cataclasis to dislocation creep – is variably known as the *elastic–crystal plastic* or *brittle–viscous* transition (Fig. 1). This transition is significant because it is thought to define the base of the crustal seismic zone.

The actual depth and temperature of this transition depends on several variables, including the geothermal gradient, strain rate, mineralogy, texture, fault orientation, and fluid pressure (e.g. Chernak et al., 2009; Gueydan et al., 2004; Holyoke and Tullis, 2006a; Ikari et al., 2011; Kohlstedt et al., 1995; Montési and Zuber, 2002; Sibson, 1983; Tullis and Yund, 1992). Thus the maximum depth of significant seismicity varies with temperature from <10 km to >20 km, even in a limited area such as California (Bonner et al., 2003). At geologic strain rates, dislocation creep in feldspar and quartz is expected to become important at temperatures of ~450 °C and ~300 °C respectively (Dunlap, 1997; Rybacki and Dresen, 2000; Tullis, 2002, points A and B, Fig. 1), but mica content and grain contiguity will lower this

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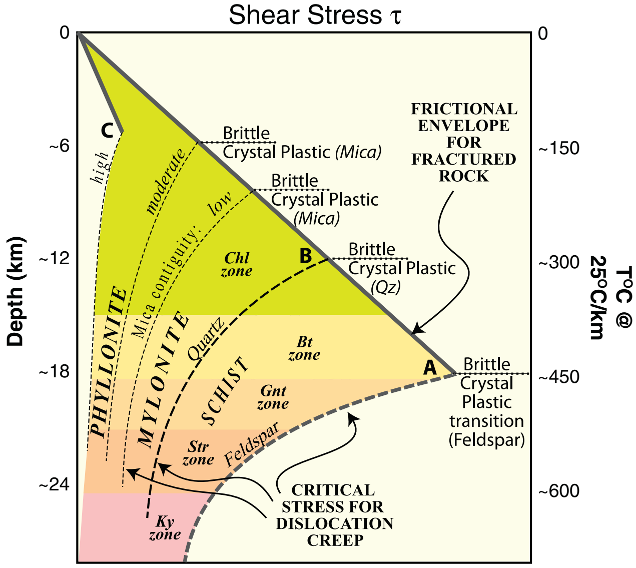

Fig. 1. A qualitative depth–strength diagram showing the maximum shear strength supported by (fractured) crustal rocks deforming by frictional processes (upper straight line A–B) and by dislocation creep (dashed curves) in several minerals (after Kohlstedt et al., 1995; Wintsch et al., 1995). In the frictional domain the strength of the crust is a linear function of depth, whereas in the region of dislocation creep, strength is a function of temperature, mineralogy, and mica contiguity (Shea and Kronenberg, 1993, see text). The intersection of these two lines defines the brittle-crystal plastic transition; this transition climbs to lower temperatures and shallower depths and lower temperatures as the mineralogy and texture becomes weaker, from feldspar (A), to quartz (B), to mica (C). Dissolution–precipitation creep may be activated at strengths lower than this envelope under aqueous diagenetic and metamorphic conditions (colored regions: chlorite, Chl; biotite, Bt; garnet, Gnt; staurolite, Str; and kyanite, Ky zones indicated). The temperature scale (right) corresponds to depth at a linear 25 °C/km.

temperature further to the limit of point C, Fig. 1 (Shea and Kronenberg, 1993). Dislocation creep is not sensitive to confining pressure so the depth of this transition is highly dependent on geothermal gradient. Frictional processes are a linear function of depth (pressure) and are essentially independent of temperature.

The shear strength of rocks in the crystal plastic regime is complicated by variables involving mineralogy, texture, and microstructure (e.g. Fagereng and Toy, 2011). In particular, the strength of polymineralic rocks is defined by the strongest minerals in a network of load-bearing grains. The strength of granite could approach that of a syenite if a load-bearing framework of feldspars existed, in spite of a modest content of weaker quartz and phyllosilicates in its mineral aggregate (Dell'Angelo and Tullis, 1996). In fact, the mechanical work of deforming a fault zone can be transformed into chemical work, and it alone can change the mineralogy, texture, and thus the strength of metamorphic rocks (e.g. Hobbs et al., 2011; Wintsch, 1985).

The general observation – that mineral mode correlates with rock strength – breaks down where mineral preferred orientation and especially mineral distribution are non-random. In rocks where the load-bearing network of strong minerals is interrupted by a network of anastomosing bands of weaker minerals, the lower strength of this network will prevail. The overall strength of the aggregate will be no stronger than the weakest mineral defining this network, in spite of the larger mode of the stronger minerals (Shea and Kronenberg, 1993). Anastomosing bands of weaker minerals are common in metamorphic rocks. Bands of weaker phyllosilicates are generally referred to as folia or P-domains, whereas bands of quartz are commonly called Q-domains and may form ribbons. The development of these folia by the redistribution of minerals occurs by a solution-precipitation mechanism that can lead to textural softening; weakening has been confirmed experimentally (e.g. Shea and Kronenberg, 1993) and is commonly recognized in natural rocks (e.g. Rahimi-Chakdel et al., 2006). The development of these bands in rocks initially lacking weak minerals (metamorphic differentiation) is an important weakening mechanism (e.g. Knipe and Wintsch, 1985; Oliot et al., 2010).

In this study, we examine the effects of brittle and ductile deformation on the microstructural evolution of some orthogneisses deformed along a major strike-slip fault zone: the Ailao Shan–Red River shear zone. The fault system is significant because it is thought to have accommodated the extrusion of the Indochina block during the Cenozoic indentation of southern Asia by India (Tapponnier et al., 1986; Wang et al., 1998; Fig. 2 inset), perhaps along a reactivated Paleozoic fault (Cai and Zhang, 2009). As a monitor of this collision, some studies have focused on the timing and amount of displacement on the fault (Molnar and Tapponnier, 1975; Schoenbohm et al., 2006), while other studies discuss the possible depth of penetration of the fault: limited to crustal depths (e.g. Burchfiel et al., 1989; Jolivet et al., 2001; Searle, 2006) or fully lithospheric (e.g. Leloup et al., 1995, 2001; Tapponnier et al., 1990). Most of the crystalline rocks in the area of this fault zone are covered by Paleozoic, Mesozoic, and Cenozoic sediments (e.g. Cai and Zhang, 2009; Fig. 2), but crystalline rocks are exposed in four fault slivers: from north to south these are the Xuelong Shan, Diancang Shan, and Ailao Shan blocks in China, and the Day Nui-Con Vui block in Viet Nam (Fig. 2). These slivers are thought to record lower- to mid-crustal deformation during this extrusion (e.g. Anczkiewicz et al., 2007; Harrison et al., 1992) and have received greater interest since the interpretation of significant shear heating associated with the displacement (e.g. Gilley et al., 2003; Leloup and Kienast, 1993; Leloup et al., 1993, 1999). Our study focuses on the evolution of the fabrics of the fault rocks at the southern end of the Diancang Shan belt, west and southwest of Dali, Yunnan province, China. We conclude that dissolution/reaction creep known to dominate in some higher-grade rocks (Marsh et al., 2009; McWilliams et al., 2007; Menegon et al., 2008; Oliot et al., 2010; Stokes et al., 2012; Wawrzenitz et al., 2012; Wintsch and Yi, 2002; Wintsch et al., 1999) may control the brittle–viscous transition.

2. Geologic Setting

A number of divergent studies in the crystalline rocks of the Diancang Shan belt have revealed a complicated history. Rocks in this belt include pelitic schists, marbles, and amphibolites in addition to the orthogneisses studied here; all are now moderately to strongly foliated (e.g. Cao et al., 2011b, 2012). The oldest zircon ages identified in this block are Neoproterozoic, reflecting a time that produced migmatites associated with high grade metamorphic paragneisses (Liu et al., 2008). These rocks are intruded by locally porphyritic Carboniferous (~350 Ma) and Triassic (~245–235 Ma) plutonic rocks of generally granitic to granodioritic composition (e.g. Li et al., 2008; Lin et al., 2012; Searle et al., 2010). The early Mesozoic time of their crystallization suggests that they were emplaced and perhaps deformed at near magmatic conditions during the Indosinian accretion of the Sibumasu block to Indochina (e.g. Cai and Zhang, 2009; Carter and Clift, 2008; Carter et al., 2001; see Fig. 2 inset). Proterozoic inheritance in the cores of some of these zircons suggests these magmas were derived from a Proterozoic and older lower crust that is present regionally (e.g. Greentree and Li, 2008; Guo et al., 2009; Lin et al., 2012; Liu et al., 2006, 2012). All of these rocks have been subsequently intruded by thin Oligocene granitic and pegmatitic dikes (Cao et al., 2011b; Liang et al., 2007), coinciding with the extrusion of the Indochina block along the Red River shear zone.

The thermal/metamorphic history of the rocks of the Diancang Shan block is complicated by its history of intrusion. High-grade metamorphism occurred in the Neoproterozoic (Liu et al., 2006) and is overprinted by metamorphism associated with Mesozoic intrusions. This metamorphism is, in turn, overprinted by a high-grade Oligocene event (Cao et al., 2011b; Liang et al., 2007; Lin et al., 2012; see Fig. 3). The available data shows a rather wide