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Deformation microstructures and textures, and regional tectonic significance of high-temperature shearing of the Diancang Shan Complex, Yunnan, China

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Abstract: The Diancang Shan Complex located at the northwestern extension along the Ailao Shan-Red River (ASRR) shear zone is a representative metamorphic complex of the ASRR tectonic belt. This complex is constituted by two units, a central high-grade metamorphic belt and an eastern low-grade superposed metamorphic belt. Structural, microstructural, sub-microstructural and texture analysis of sheared rocks in the high-grade metamorphic rocks reveal that deformation of rocks occurred at high-temperature conditions. The related structures, micro-structures and textures are attributed to left-lateral shearing along the ASRR shear zone, which also helps to constrain the timing of initiation of left-lateral shearing at early Oligocene.

Keywords: high-temperature mylonite, microstructures, hornblende textures, Ailao Shan-Red River Shear zone, Diancang Shan Complex.

As the eastern border of the Indochina block, the Ailao Shan-Red River (ASRR) shear zone in Yunnan (Southwestern China), played important roles in accommodating southeastward extrusion of the Indochina block during Indian-Eurasian plate collision and post-collisional evolution from early Oligocene to early Miocene (Tapponnier *et al.*, 1990; Searle, 2006; Leloup *et al.*, 2007) (Fig. 1a). Several blocks of high grade metamorphic rocks (Xuelong Shan, Diancang Shan and Ailao Shan in China and Day Nui Con Voi in Vietnam, figure 1b) are exposed along the ASRR shear zone. These blocks are narrow zones of high grade metamorphic rocks bounded by brittle faults against low grade metamorphic rocks to the west and unmetamorphosed or low grade metamorphic sedimentary rocks to the east. Within the blocks, the rocks are partly sheared resulting in widespread high-temperature mylonites with sub-horizontal stretching lineations. These mylonites provide constraints on large scale left-lateral strike-slip shearing displacements of at least 600 km along the shear zone. Due to the lack of detailed studies of microstructures and textures of these deformed rocks, debates exist on the timing of the initiation of left-lateral shearing, the significance of high-temperature deformation and the mechanisms of exhumation of the high grade metamorphic rocks.

The Diancang Shan block, lying to the northwestern extension of the Ailao Shan metamorphic complex, is a typical metamorphic complex in the ASRR shear zone. The metamorphic complex is mainly constitut-

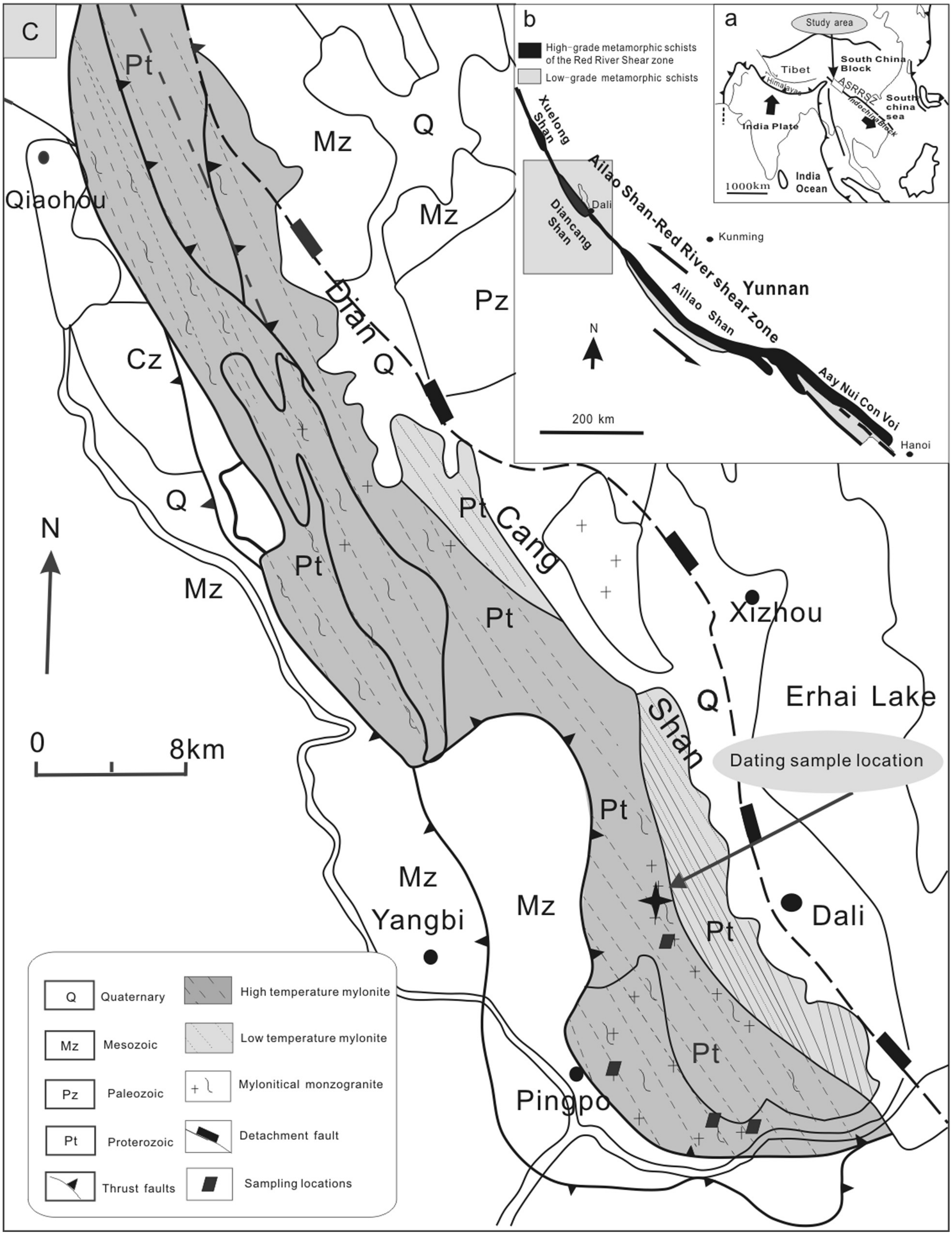

Figure 1. Tectonic setting and structural outline of the Diancang Shan area. (a) Regional tectonic framework of Southeast Asia; ASRRSZ: Ailao Shan-Red River shear zone, (b) Xuelong Shan, Diancang Shan, Ailao Shan and Day Noi Con Voi metamorphic blocks along the Ailao Shan-Red River shear zone, (c) structural framework of the Diancang Shan area.

ed by two units, a central high grade metamorphic belt to the west and a low grade superimposed metamorphic belt to the east (Fig. 1c).

The central high grade metamorphic belt is constituted by a sequence of metamorphic rocks of amphibolites facies, including amphibolites, marbles, schists, gneisses and mylonites with typical high-temperature mineral assemblages: sillimanite + garnet + staurolite + kyanite, hornblende + plagioclase, and tremolite + diopside + olivine + calcite + dolomite. The metamorphic rocks together with multi-phase granitic dikes and intrusions are often mylonitized by intensive left-lateral strike-slip, resulting in the formation of typical L-tectonites (Figs. 2a, 2b and 2d).

A low-grade shear zone related to exhumation of the Diancang Shan metamorphic complex (or metamorphic core complex, Liu *et al.*, 2007) in a later event occurs as a low-grade superimposed metamorphic belt along the eastern flank of the Diancang Shan range. The high-temperature metamorphic rocks are overprinted by the low grade shear deformation at greenschist facies conditions. Low temperature mineral assemblages and fabrics are well preserved. The resultant mylonites displaying L-S type fabrics are characterized by retrogressive chloritic mylonites. Macro- and micro-shear sense indicators suggest a top to the east shearing.

Techniques

Standard thin sections are cut parallel to the lineation and perpendicular to the foliation of mylonite samples. Microstructures are analyzed by optical microscopy (OM) and sub-microstructures are observed by high

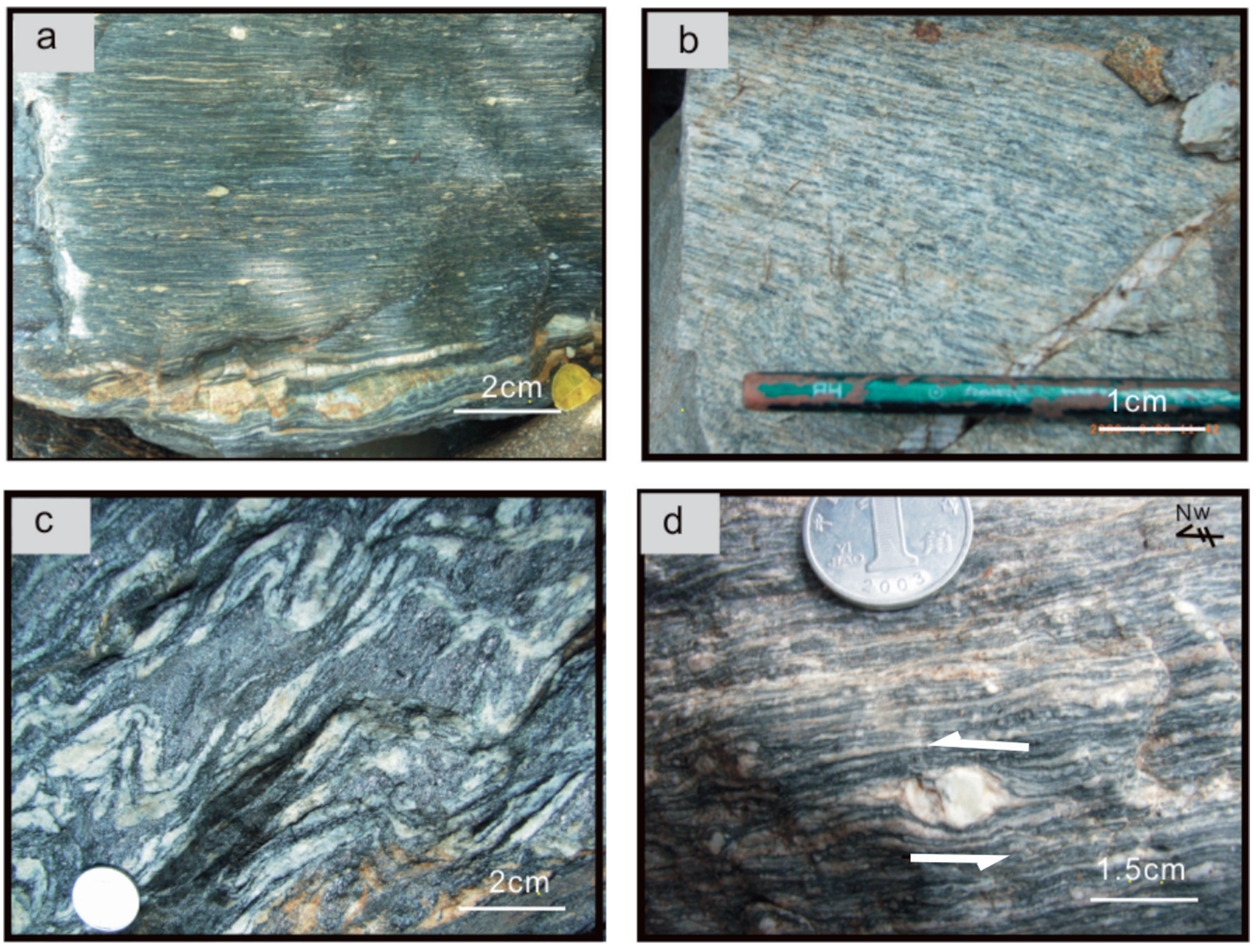

Figure 2. Outcrop scale structural evidences of high-temperature ductile deformation, observed in high grade metamorphic rocks in Diancang Shan: (a) amphibolitic ultramylonite with strong stretching lineation (L-tectonite), (b) stretching lineation (L-tectonite) shown by diorite xenoliths in granite, (c) tight folds in biotite gneiss, (d) feldspar porphyroclasts indicating left-lateral shear by asymmetric recrystallized tails (L-tectonite).

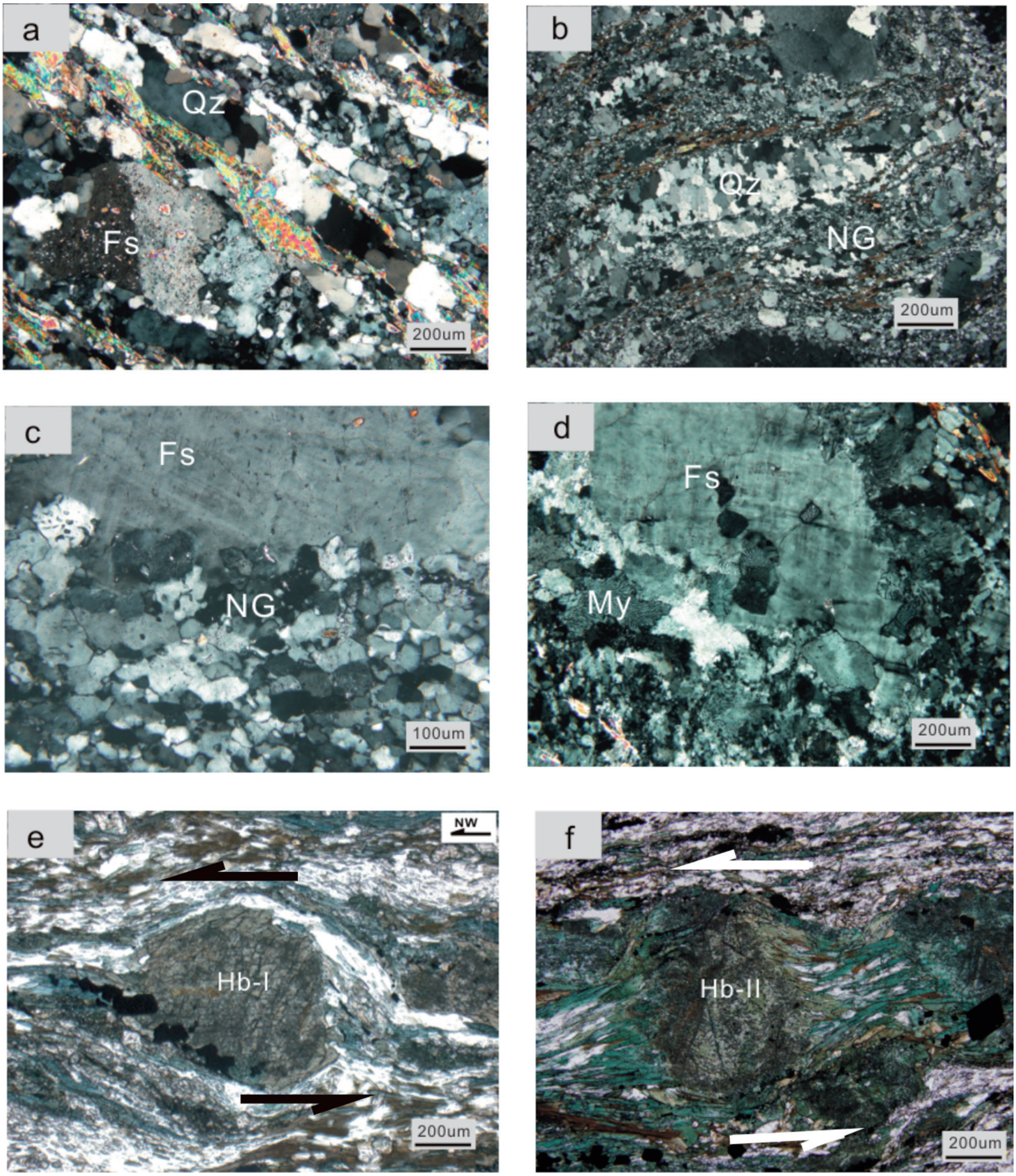

Figure 3. Microscopic high-temperature deformation characteristics of high grade metamorphic rocks in Diancang Shan: (a) polycrystalline quartz (Qz) ribbons and fine-grained feldspar porphyroclasts (Fs), (b) sigmoidal quartz aggregate and new fine-grained feldspar (NG), (c) K-feldspar porphyroclasts (Fs) and transition to recrystallized grains in the matrix, (d) myrmekites (My) around a K-feldspar porphyroclast (Fs), (e) hornblende type I porphyroclasts (Hb-I) with [001] normal to shear direction, (f) hornblende typical type II porphyroclasts (Hb-II) with [001] parallel to the shearing direction.

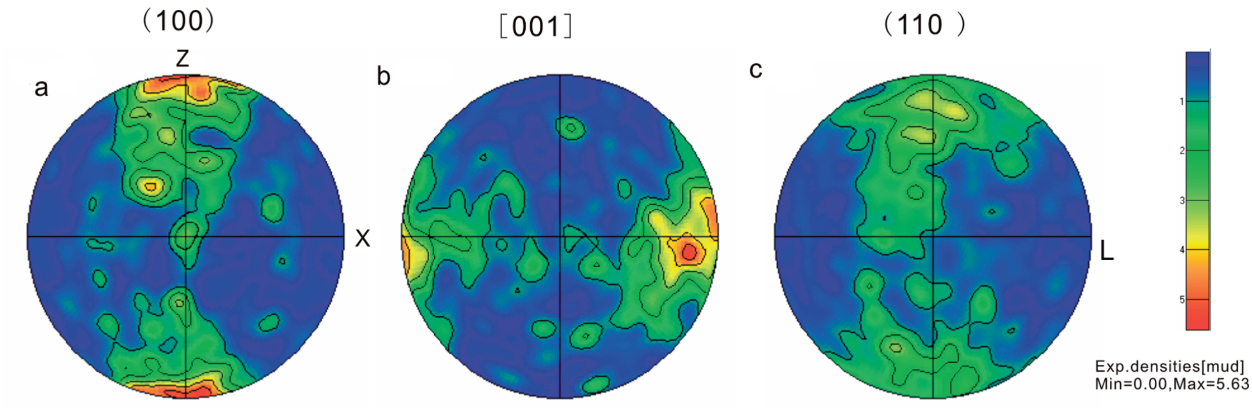

Figure 4. Hornblende textures of recrystallized matrix grains of amphibolitic mylonite obtained by EBSD analysis: (a) (100)-planes, (b) [001]-axes, (c) (110)-planes; foliation- XY–solid line, lineation-X direction; equal area projection and lower hemisphere.

resolution transmission electron microscope (TEM). Energy dispersion spectroscopy (EDS) is applied to identify the composition of minerals. Shimadzu EPMA-1600 electron microprobe analysis is used to carry out quantitative analysis of mineral chemistry. Textures of hornblende are measured on a Hitachi 3400N scanning electron microscope (SEM) equipped with a HKL Channel 5 electron back-scattered diffraction (EBSD) detector. All the analyses were finished at the State Key Laboratory of Geological Processes and Mineral Resources (Beijing).

Results

Macro-and micro-structures of mylonites from high grade metamorphic complex

High-temperature mylonites derived from either granitic rocks or amphibolitic rocks constitute the main part of the shear zones in the high grade metamorphic complex. At the outcrop scale, asymmetric folds (e.g. hook-like folds) and tight folds (Fig. 2c) are well-developed in sheared gneisses (such as sillimanite or amphibolitic gneisses) and are characteristic for high-temperature ductile flow. Hinges of the folds are mostly parallel to subhorizontal NNW-SSE stretching lineations. Elongated quartz, feldspar and fine-grained biotite mineral aggregates form the extremely strongly developed stretching lineation fabrics, which is the most remarkable feature of high-temperature mylonites in the shear zone (Figs. 2a, 2b and 2d). Such fabrics occur in both sheared metamorphic rocks and sheared granitic dykes or monzogranitic intrusions. The widespread and penetrative occurrence of these structures suggests that the gneisses experienced very intense progressive left-lateral strike-slip deformation (Fig. 2b).

Augen structures in mylonitized monzogranite and amphibolites are also typical features of the high-temperature mylonites. They are composed of K-feldspar, plagioclase and hornblende porphyroclasts and fine matrix of feldspar, quartz, hornblende and other mineral phases. Microstructural features like σ, δ and S-C fabrics consistently document a left-lateral shear (Fig. 2d).

Different mineral phases show distinctive deformation structures. Quartz grain boundaries of equigranular grains often form triple junctions. Serrated grain boundaries are observed in some cases, suggesting local high-temperature grain boundary migration. Rectangular and sigmoidal quartz aggregates are parallel to the major foliation and lineation of the rocks. Rare occurrence of dislocation substructures in quartz grains points to the importance of high-temperature recovery and recrystallization during or after high-temperature shearing (Fig. 3). Feldspar grains show typical characteristics of high-temperature plastic deformation (Fig. 3c): they are elongated or partly twinned, and some are partly or completely dynamically recrystallized into fine-grained matrix. The porphyroclastic cores show undulatory and inhomogeneous extinction, and have core-mantle structures and subgrains. Mechanical twinning and a few free dislocations near twin boundaries are also the effects of plastic deformation. TEM analyses show that some dislocations are organized into dislocation walls and form subgrains. Thus K-feldspar recrystallization seems to be dominated by the subgrain rotation process. Deformation of K-

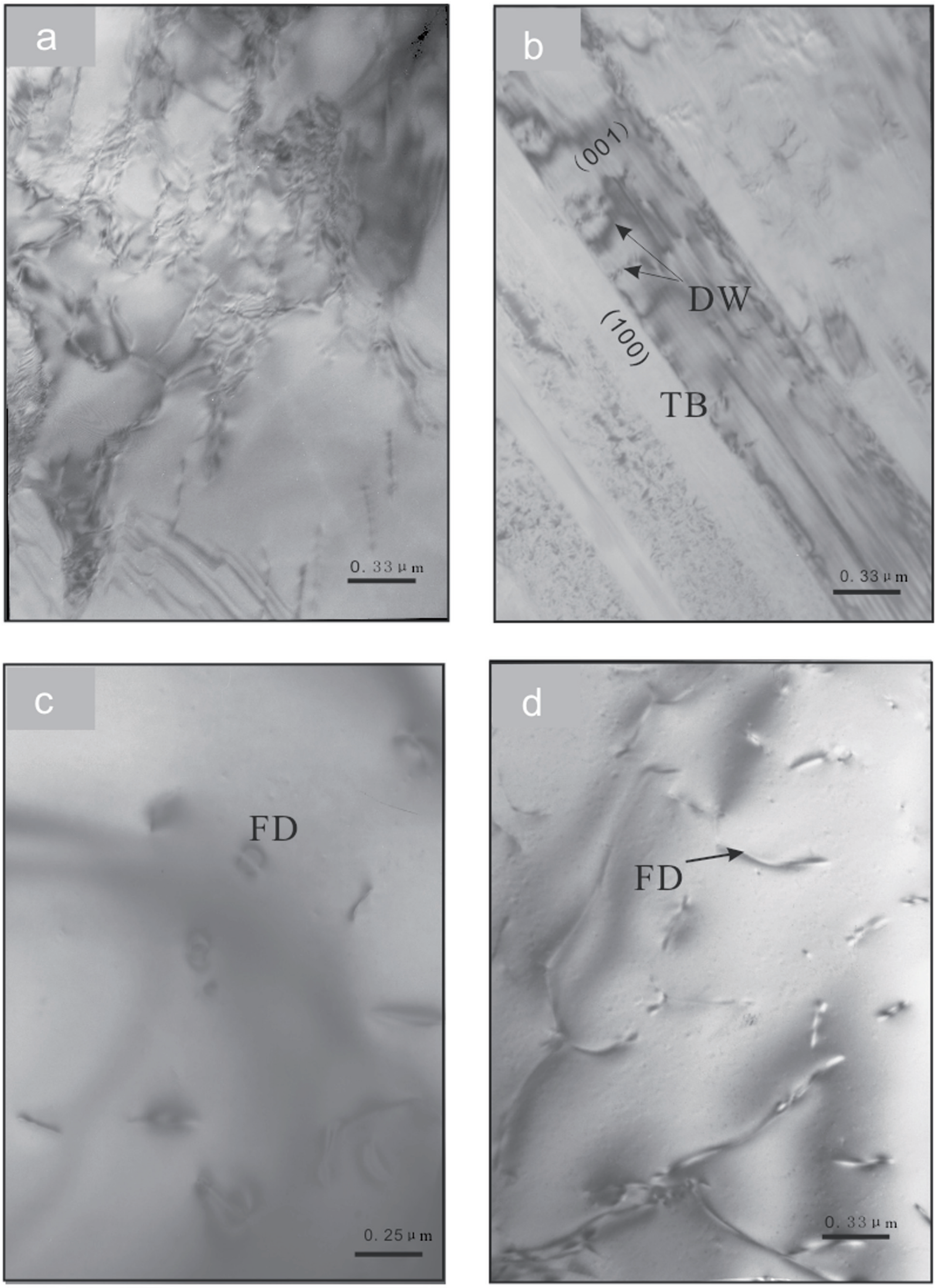

Figure 5. TEM submicrostructural characteristics in hornblende and quartz from high grade metamorphic rocks: (a) tangled dislocations from the core of a type I hornblende porphyroclast, (b) regular twin boundaries (TB), dislocations in twins and twinned hosts, and dislocation walls (DW) perpendicular to twin boundaries from margins of type II hornblende porphyroclasts, (c) matrix hornblende grains containing only a few free dislocations (FD), (d) some free dislocations (FD) in quartz grains.

feldspar was associated with metasomatism by relatively calcium-rich plagioclase to form myrmekite structure (Fig. 3d), suggesting plastic deformation at feldspar recrystallization temperature above 550 °C (Vernon, 1991; Menegon *et al.*, 2006).

Amphibolitic mylonites have typical mylonitic microstructures, shown by coarse hornblende porphyroclasts and fine-grained matrix. Two distinct types of hornblende porphyroclasts are distinguished:

Type I porphyroclasts are oriented with their [001]-axis perpendicular to the stretching lineation, i.e. the shearing direction. They generally have regular shapes, and most retain euhedral shapes with rhombic or polygonal outlines in (100) section. Grain boundaries are typically straight and regular or slightly curved (Fig. 3e); the grains have rare evidences of weak crystal plastic deformation. Instead, they are characterized by frequent occurrence of microfractures (particularly along cleavage planes), and by sharp changes between porphyroclasts and new fine grains in the matrix.

Type II hornblende porphyroclasts are oriented with their [001]-axis parallel or subparallel to the stretching lineation or shearing direction (Fig. 3f). They are either lens-shaped or fish-shaped and show ϕ, σ or δ fabrics. Undulatory, partly discontinuous extinction, deformation twins, subgrains, core-mantle structures etc. are widespread in type II porphyroclasts. They generally show a gradual transition into fine recrystallized grains in the matrix. New fine grains are heterogeneously distributed, constituting alternating domains of hornblende-rich and quartzofeldspathic zones. TEM observation reveals that they generally have acicular shapes with long axes parallel to the stretching lineation. Various dislocation substructures are observed in hornblende grains, especially within deformed porphyroclasts. Free dislocations, dislocation dipoles, dislocation arrays, dislocation walls, subgrains formed by dislocation walls, and twin boundaries are the most commonly observed dislocation microstructures. Tangled dislocations are the dominant dislocation patterns in type I porphyroclasts (Fig. 4a). Variations of dislocation patterns are common in type II porphyroclasts. In the core of type II porphyroclasts, dislocations are irregularly organized into tangled dislocation walls and regularly organized towards marginal zones of the porphyroclasts. Twins of micron scale are generally straight and regular, and some twin boundaries are constituted by well-organized dislocations (Fig. 4b). New fine grains in the matrix show few free dislocations (Fig. 4c).

Texture analysis of hornblende in amphibolitic mylonites

Textures of hornblende grains from the matrix of ultramylonites, cores of type I and type II porphyroclasts and matrix grains around the porphyroclasts are analyzed by EBSD. It is shown that [001] crystallographic axes and (100) crystallographic planes of dynamically recrystallized hornblende grains lie within these mylonitic foliation and parallel to the stretching lineation (Figs. 5a and 5b). Such a parallelism implies that the texture of dynamically recrystallized hornblende grains resulted from a dominant activation of (100) [001] slip system (twinning) (Fig. 5c), which is related to high-temperature deformation (Dollinger and Blacic, 1975; Cao *et al.*, 2007).

Estimation and calculation of pressure and temperature during deformation

The estimation and calculation of pressure and temperature of deformation and metamorphism of type I porphyroclasts, type II porphyroclasts and matrix grains in the hornblende mylonites are made by applying the geobarometer of Schmidt (1992) and hornblende-plagioclase geothermometer of Holland and Blundy (1994). The estimated pressures are between 0.599-0.710 GPa, with an average of 0.653 GPa and the calculated temperatures vary between 604-674 °C, with an average of 636 °C. These estimates indicate amphibolites facies conditions.

Discussion and conclusions

Indication of high-temperature deformation

All the above described observations indicate high-temperature deformation in Diancang Shan during left-lateral shearing along the ASRR. Macroscopic fold patterns and microstructural features are typical of high-temperature flow of rocks. OM and TEM analysis reveals the dominance of high-temperature recovery and recrystallization of quartz, feldspar and hornblende. Hornblende texture analyses give clues to the importance of (100) [001] slip systems during dynamic recrystallization. P/T calculations give pressures and temperatures of lower amphibolite facies.

Significance of high-temperature shearing

Whether left-lateral shearing occurred prior or postdated high-temperature metamorphism remains the key to understanding the timing of initiation and duration of left lateral shearing along the ASRR. Leloup *et al.* (1995, 2001) and Schärer *et al.* (1990, 1994) stressed on the simultaneity of shearing, the generation of granitic magma by shear heating, and the intrusion of the magma into veins. In combination of structural analysis of mylonitic rocks and U-Pb dating of zircon, monazite and xenotime in the intrusions, they suggested that large scale shearing along the ASRR initiated at about 35 Ma and lasted until 17 Ma. High-temperature left-lateral shear in the Ailao Shan and Diancang Shan is also documented by left-laterally sheared garnet-sillimanite bearing mylonitic paragneiss (Leloup *et al.*, 2007). Tran *et al.* (1998), however, revealed that the peak metamorphism took place under amphibolite-facies conditions and the subsequent mylonitization occurred under greenschist-facies conditions. Searle (2006) also interpreted the ASRR shear zone as an upper crustal, left-lateral strike-slip fault that cuts through previous high grade metamorphic rocks and early formed granites. Metamorphism of the Day Nui Con Voi metamorphic rocks in Vietnam predated and is unrelated to shearing along the ASRR shear zone. Searle (2006) then argued that shear fabrics associated with left-lateral slip postdate peak metamorphism, constraining the timing of initiation of shearing to 21 Ma at relatively low temperature conditions.

Our observations on the Diancang Shan mylonites suggest that the deformation microstructures and textures resulted from high-temperature deformation and dynamic recrystallization are attributed to left-lateral shearing along the ASRR shear zone. The emplacement of magmatic dikes and mozogranitic intrusion are synkinematic. Our recent SHRIMP dating from a synkinematic mozogranitic intrusion displaying the above-mentioned high-temperature microstructures and textures give an age of 30.88 Ma, which constrains the timing of initiation of left-lateral shearing at early Oligocene.

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