Observation of ultra-microtexture of fault rocks in shearing-sliding zones*

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Abstract Based on scanning electronic microscopic observation of three fault rocks in ductile-brittle shearing-sliding zones (including one palimpsest mylonite sampled from deep bore cores of Cajon Pass, California, two flowing-structured carbargillites sampled from Shaancan Well 1 located in north Shaanxi, and Well NH located in Huanghai, respectively), micron- and nanometer-scaled ultra-fine grinding grain texture of fault rocks is discovered in this study. And the geological significance of grinding grain texture is discussed in terms of its particulate organization, rheology of particulate slipping, laminar petrography and micro dynamics including dynamothermal metamorphism, fluid transferring, particulate autorotation, and so on. In addition, the remaining problems to be solved and broad prospects in this new study field are also discussed.

Keywords: ductile-brittle shearing zone, fault rock, texture of grinding grain, rheology of particulate slipping.

With the rapid development of microbeam technologies, the application of scanning electronic microscopy (SEM), transmission electron microscopy (TEM), and atomic force microscopy (AFM) has extended the studies on textures of fault rocks from micro-scale (micron level) observation to ultra-micro scale (nanometer level)[1]. Through SEM observation of three fault rocks in ductile-brittle shearing-sliding zones[2] (including one palimpsest mylonite of Mesozoic granite sampled from deep bore cores of Cajon Pass at depth of 1741.84 m (sample 1), one Carboniferous carbargillite with slight creeping (sample 2) from Shaancan Well 1 at depth of 3440.5 m, located in northern Shaanxi, and one Permian carbargillite (sample 3) collected from Well NH at depth of 2543.0 m, located in Huanghai), ultra-micro grinding grain texture and grain-slipping texture, as a typical texture of fault rocks in ductile-brittle faulted zone[3,4], was discovered and described, which laid a basis for fault structure studies[5,6]. Although current discussion about such textures is only from the well-chosen typical samples with a size of micrometers, the scale transition of studies from micron level to nanometer level will provide more detailed information and help to develop some new approaches of modern geology. This paper discusses the analysis of particulate organization, rheology of grain slipping, laminar petrography and micro dynamic for the above three samples and points out some problems to be solved.

1 Particulate organization

The average size of the spherical micrograins, which are orderly arrayed between lamellations with preferred orientation, is 2—4 nm, 0.5—0.8 μm, and 3—6 μm for sample 1, sample 2, and sample 3, respectively. Certain difference in particulate organization between the samples can be found by careful observation. The particulates in sample 1 are flattened and tightly imbedded with preferred orientation (Fig. 1), whereas those in sample 2 are arranged sparsely and exhibit ridges and grooves (Fig. 2), and those in sample 3 are uniform in size and arranged interruptedly (Fig. 3). The above phenomena may be the results of dynamic processes involving tumbling, grinding and compresso-shearing, so these spherical particulates are called grinding grains.

Traditional fabric petrology is well-developed, which uses a polarizing microscope, a universal stage and conventional methods[8]. However, studies on organization of grinding grains by SEM and TEM

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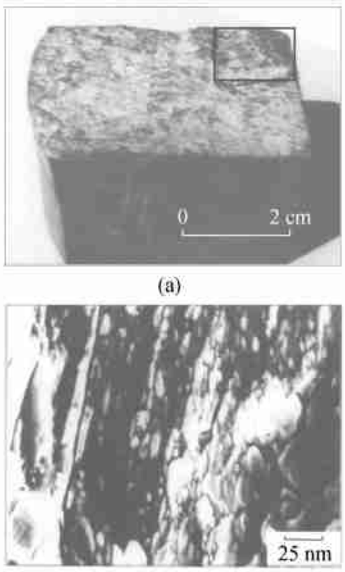

Fig. 1. Slipping band of grinding grains and its host rock. (a) Horizontal shear plane on the surface of palimpsest mylonite. The sampling location is indicated by a frame; (b) flattened and tightly imbedded grinding grains with preferred orientation (SEM image, Hitachi S-415A).

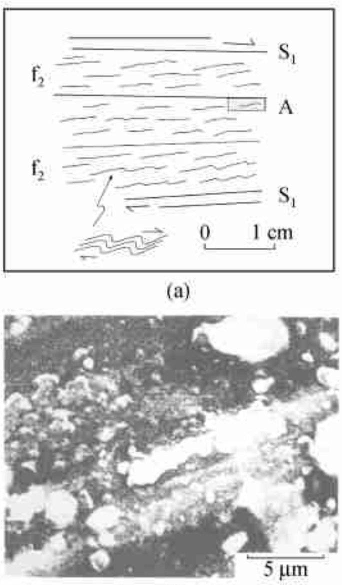

Fig. 2. Magnifying sketch of bore core of sample 2 and grinding grain band. (a) S_1 denotes the horizontal shear plane, f_2 presents slipping lamellae, A is the sampling site; (b) aggregated grains form raised ridges (the bands in the central photo), and sparse grains form depressions (top left and bottom right). The large bright area is the aggregation of grinding grains (SEM image, Hitachi S-3200N).

have no "reference system". During his study on graphite, Berezkin[9] discovered the film structure and spherical nanoparticles with radius of 3—5 nm, which were arranged in bunchy rows with uniform interparticle pores and displayed a platy texture (Fig. 3). Although graphite particulates are similar to grinding grains in shape and size, there is obvious difference fundamentally between them. The former is protogenetic hollow particles, whereas the latter is secondary solid ones as the products of grinding and sliding. It should be noted that the study of Berezkin covered organization of particulates, chemical composition, formation mechanism, and practical application. In fact, he proposed a potential study pattern on particulate organization combining thermal and pressure conditions[10].

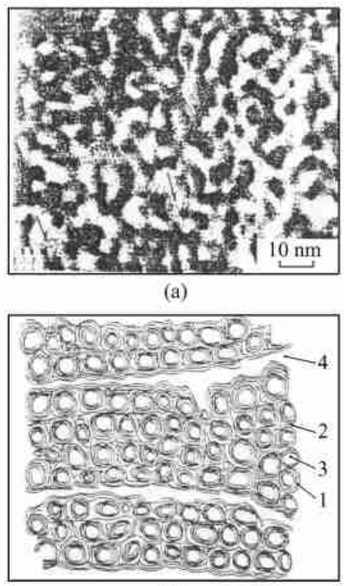

Fig. 3. Platy texture and ultra-fine particulate texture in graphite. (a) TEM image of thin platy layer graphite with ultra-fine particulates. The arrows point to the ultra-fine particulates; (b) organization pattern of spherical graphite particulates. 1—4 indicate ultra-fine particulates, interparticle carbon material, intraparticle pores, and interlayered pore, respectively (Berezkin, 2001)[9].

BET surface area of samples 2 and 3 (measured on the ASAP2010M + C volumetric adsorption analyzer, Micromeritics) ranges within 6.31—11.02 m^2/g, and 3.23—4.25 m^2/g, respectively, which is lower than that of their primary rocks, i.e. 22.30—47.50 m^2/g[3]. The breakthrough pressure of sample 2 was measured, which is over 15.0 MPa[4]. The above results indicate that the structural density of ductile-brittle fault rocks is raised evidently by the formation of ultra-fine grinding grains, suggesting that even a thin layer could act as caprock in petroleum systems due to smear efficiency of grinding grains[11]. In fact, this viewpoint has been confirmed preliminarily by the experimental studies in Changqing Oilfield, north Shaanxi[4]. In southern China the oil and gas prospecting of Mesozoic/Paleozoic strata has been repetitively explored since the 1970s, and although oil stream had been found at Jurong Well 0 (487.00—497.02 m), there is no significant approach yet. This area recently attracts attention again due to new discovery in reef researches, but the conservation condition is still a key problem[12]. So, the existence and effects of shearing-sliding zone with the texture of ultra-fine grinding grain, which widely exists in this area, is necessary to be investigated comprehensively.

2 Grain slipping rheology

Previous studies on rock rheology, rheological layer and rheological stratification adopted physics conception of "structural rheology" all the while[13, 14]. But nanosized grinding grain texture is the product of grain slipping. From the viewpoint of theoretical mechanics, the former rheology is definitely a type of sliding friction along the common tangent plane, whereas the latter is rolling friction[15]. According to the rule that the moment of friction is proportional to the reverse of the normal force, the rolling friction is only 1/15—1/20 of the sliding friction under the same condition1). Moreover, rolling and flowing of point particles is closely related to shearing rate, and it was confirmed by experimental result that such rolling and flowing can raise shearing rate to 6—55 s^{-1} at the maximum[16].

In fact, the grain slipping rheology shown in Figs. 1 and 2 is creeping of grinding grains between slipping lamellae or between micro-cleavage in fault rocks, which appears as slipping layer by layer on scale of several centimeters or thinner (in the cases of mudstone the thickness can reach several meters, e.g. samples 2 and 3 in this study), and occurs generally in slipping mylonite or clastmylonite in ductile-brittle fault zone[17]. All these deformation zones definitely belong to frictional-viscous (FV) zone[18], a type of lamella zone with high strain[19], which should be interpreted theoretically using the well-known Kelvin (K) or Maxwell (M) four parameter model in geology[13, 20].

In recent years, it was discovered during investigation of pseudotachylite in fault zone, active fault and seismotectonics that there exists creeping rheological band of only several centimeters in thickness in major fault zone. And such rheological band is closely related to seismic structures[21, 22].

3 Laminar petrography

The formation of ultra-fine grinding grains is generally related to slipping lamellae, and laminar textures. Studies on the dynamometamorphism, petrography and mineragraphy, elements migration of the grinding grains can be named crack petrography[23], an independent subject[24]. Ideal samples can be obtained generally from the fault rocks with the well-developed laminar texture in ductile-brittle faults. In order to avoid scale limitation and uncertainty of microstructure petrography, digitalization of geoinformation in geology should be encouraged[25]. Especially, for the research combining tectonic and mineralization, the parameters concerning rock mechanics, petrophysics, rock rheology and petrochemistry of ductile-brittle fault rocks containing grinding grains should be analyzed systematicially, because these rocks commonly control the distribution of geofluids, transportation of materials and thermal alteration, and influence the activation and precipitation of metallogenic elements, and provide spaces for mineral deposit[27, 28].

Because the fault rocks containing grinding grains is influenced to a certain extent by tectonic separating[29] and lamellae micro-texture[30], the bulk modulus parallel to the layer plane (3.14×10^{10} Pa) of sample 2 fault rock is only half of that vertical to the layer (6.00×10^{10} Pa)[4]. So parameters characterizing textural anisotropy, such as lateral heterogeneity (η) and viscosity (Cw) deserve close attention besides regular analytical items in rock mechanics measurement[31]. Among the petrophysics parameters concerning petroleum evaluation, breakthrough pressure of fault rocks is sometimes too high to be measured on normal instruments[4]. So the variation in P wave velocity and V_p/V_s ratio, which are generally higher than primary rocks, should be investigated emphatically[32]. In addition, rheological parameters (e.g. dislocation density, stationary flow stress) of fault rocks are all higher than wall rocks, which may be attributed to the silicification due to the shearing of slipping lamellae[33].

The petrochemical studies on the lamellar pet-

1) Measured by Professor Gou Fuyi at Hohai University, China, in 2004.

rography and fault petrography should integrate geochemistry, genetic petrology and lithologic stratigraphy closely[34,35]. Just as Apraiz pointed out, the rocks with shearing deformation must be impressed by tectono-metamorphic imprints[29]. The shallow-level ductile-brittle fault rock is generally composed of low-rank greenschist facies rocks, phyllosillicate minerals and even some amorphous materials[36]. There are many petrochemical variations in ultra-fine grinding grains, from outband to the band, from band margin to the center, from intergranular materials to grinding grain, and from the crust to the core of grinding grains. For example, in sample 1, the SiO_2 content ranges from 4.11%—16.11% in band margin to 33.81%—56.27% in the center[3,4], the Nb content increases from 22.61%—38.34% in band margin to 70.77%—92.85% (the maximum content is 95.89%) in the center although it is at a trace-level in primary rock[3], and the regularity of variation in major elements and trace elements was summarized[37]. For sample 2, the content of potassium, with large ionic radius, is as high as 15.38% in the central shear zone. Depletion of Eu, variation in ΣREE and HREE/LREE are complicated, so employment of much more spectrum analysis and comparative studies is helpful to find the regularity comprehensively[38]. By this token, the Nb, Ta deposits in south China classified as weathering mineral deposit (such as 414 mine in Wugongshan, Jiangxi Province), and the nonmetalliferous ores distributed in the south of the lower reaches of the Yangtze River are attributed to the layer-sliding and dynamometamorphism (such as Yangshan kaolinite deposit in Jiangsu Province) and are supposed to be related in genesis to the ultra-fine texture in shearing-sliding fault rocks.

4 Micro-scaled dynamics

4.1 Dynamothermal metamorphism

Because the formation and evolution of ultra-fine grinding grains involve the changes in spatial distribution of temperature and pressure, elements migration and chemical differentiation in ductile-brittle shear faulted zone, micro-scale dynamic study of tectonic geochemistry should be carried out[35]. Compared to traditional geochemical dynamics, micro-scale dynamics emphasizes the influence of pressure condition and thermal gradient on dynamothermal metamorphism. Based on the studies of stress minerals and fluid inclusions in fault rocks, ductile-brittle shearing zone containing grinding grains generally coexists with low-rank metamorphism of greenschist facies[3]. For example, in sample 1, there are multi-staged inclusions as well as sericites, pennines and other stress minerals in fault rocks. While ascertaining the dynamometamorphism temperature through measurement of homogenization temperature of inclusions, secondary and primary inclusions should be identified carefully. Secondary inclusions are easily formed in stratiform tectonite in most cases with certain structural orientations[39].

4.2 Fluid transferring

In micro-scale dynamics study, more attention should be paid to fluid transferring as well as the solid laminar flow[40]. So carbon, oxygen isotopes and other geochemical indicators are employed[41,42]. Conti first carried out isotope geochemical studies on various mechanical properties of the fault system in Monferrato, Italy[47]. It was found that $\delta^{13}C$, $\delta^{18}O$, and $^{87}Sr/^{86}Sr$ of brittle tension faults, an open system, ranged from −11.2 to −0.1, −7.8 to −0.4, and 0.708017 to 0.71018, respectively. For ductile compression faults, which is a confined system, values ranged from −7.3 to <3.6, from −6.0 to 0.2 and from 0.70736 to 0.709615[41]. It is evident that isotope geochemical data depends on mechanical properties of fault system. At present, the isotope geochemistry of ductile-brittle fault system is untouched yet, which is crucial for the studies of fluid circulation, formation of grinding grains, and elements migration.

4.3 Particulate autorotation

It is reasonable and witnessed that the ulta-fine grinding grains in laminar shear zone are ground and rotated by the structural stress. According to magnetism research on $Fe\cdot In_2O_3$ nanoparticles, autorotation state of particles is achieved as the Fe content in outer sphere reaches 35%[43]. In sample 2 of this study, Ti content in the crust of some big grinding grains (radius $>1\mu m$) is as high as 63.01%, and Fe content nearly twice of that in the core, which is consistent with the bright margin found in SEM image of grinding grains[3]. Many unsolved problems triggered by the discovery lie in the probability of existence of autorotation state and the relationship between this state and activation, and migration of some elements in faulted zone, and so on.

References

1 Bloo M. C., Haitjema H. and Pril W. O. Deformation and wear of pyramidal, silicon-nitride AFM tip scanning micrometer-size features in contact mode. Measurement, 1999, 25: 203—211.

2 Walter T. R. and Schmincke H. U. Rifting, recurrent landsliding and miocene structural reorganization on NW-Tenerife (Canary Islands). Int. J. Earth Sci., 2002, 91: 615—628.

3 Ge H. P., Sun Y., Lu X. C. et al. Discovery and analysis of ultra-micro grinding grain texture in slipping lamellae of ductile-brittle zone. Science in China (D), 2004, 47(3): 265—271.

4 Guo J., Sun Y., Zhu W. B. et al. A new explanation for the genetic mechanism on the smear efficiency within oil-gas sealing covers. Journal of Nanjing University (Natural Sciences), 2002, 38 (6): 766—770.

5 Lu X. C., Sun Y., Liu Q. et al. Micropore and surface properties of mudstone caprock in ductile-brittle shearing zone. In: Collection of 4th Symposium of World Chinese Geologists. Nanjing, China, 2002, 114—115.

6 Holoviak J. C. Scientific e-journals. Geotimes, 2001, (1): 14—15.

7 Ding Z. Z. The Importance of Basic Research in the Development of Technology, World Famous Scientists Forum. Nanjing: Nanjing University Press, 2002, 1—3.

8 Liu R. X. Review of microstructure geology in China. In: Collection of 6th Conference of Microstructure and Fabric Geology. Beijing: Beijing University Press, 2001, 1—7.

9 Berezkin V. L. Genesis of Karelian shungite with reference to its distinctive structural features. Geochem. International, 2001, 30: 220—227.

10 Li H. L. and Matsumoto R. Preliminary experimental result of the stable P-T conditions of mechanic hydrate in nanofossil rich claystone column. Geochem. J., 2002, 36: 21—30.

11 Yielding G., Freeman B. and Needham D. T. Quantitative fault seal prediction. AAPG Bulltin, 1997, 81: 897—917.

12 Yang X. N., Shen A. J., Chen Z. Z. et al. Genetic types for petroliferous system of organic reefs in the Permian system of south China. Acta Petrolei Sinica, 2002, 23(3): 6—10.

13 Liu X. Introduction to Rheology of Rocks. Beijing: Geological Publishing House, 1994, 19—111.

14 Ruger D. and Hansma P. Atomic force microscopy. Physics Today, 1990, 10: 23—41.

15 Fei X. B. and Xu Z. L. Theoretical Mechanics. Beijing: Higher Education Press, 2000, 238—265.

16 Parsons J. D., Whipple K. X. and Simoni A. Experimental study of the grain-flow, fluid-mud transition in debris flow. J. Geol., 2001, 109: 427—447.

17 Handy M. R., Wissing S. B. and Streit L. E. Friction-viscous flow in mylonite with varied bimineralic composition and its effect on lithospheric strength. Tectonophysics, 1999, 303: 175—191.

18 Snoke A. W. and Tulis J. A. An overview of fault rocks. In: Fault-related Rocks—A Photographic Atalas. Princeton: Princeton University Press, 1998, 1—18.

19 Sun Y., Zhu W. B., Guo J. C. et al. A review of the mylonite. Geological Journal of China Universities, 2001, 7: 369—378.

20 Lin W. H. and Chopra A. K. Earthquake response of elastic single degree of freedom systems with nonlinear vicoelastic dampers. J. Engineering Mechanics, 2003, 129: 597—606.

21 Fabbri O., Lin A. M. and Tokushige H. Pseudotachlytes found in the middle Miocene granodiorite, Osumi Peninsula, Southwest Japan. J. Struc. Geol., 2000, 22: 1015—1025.

22 Maruyama T. and Lin A. M. Tectonic history of the Rokko active fault zone (southwest Japan) as inferred from the accumulative offsets of stream channels and basement. Tectonophysics, 2000, 323: 197—216.

23 Dey T. N. Some mechanism of microcrack growth and interaction in compressive rock failure. Int. J. Rock Mech. Min. Sci. & Geomech., 1981, 18: 199—209.

24 Kowallis B. J. and Wang H. F. Microcrack study of granitic cores from Illinois deep borehole. J. Geophs. Res., 1983, 88: 7373—7380.

25 Tahirkheli S. N. Becoming digital. Geotimes, 2001, 46: 5.

26 Li J. H., Niu X. L., Chen Z. et al. The discovery of podiform chromite in west Liaoning and its implication for plate tectonics. Acta Petrologica Sinica, 2002, 18(2): 187—192.

27 Cameron E. M. Derivation of gold by oxidative metamorphism of a deep ductile zone II: Evidence from the Bamble Belt, south Norway. J. Geochem. Exploration, 1989, 31: 149—169.

28 Liu Z. M. Relationship of alteration, gold mineralization between fluid in shear zones. Earth Science Frontiers, 2001, 8: 271—275.

29 Apraiz A. and Eguiluz L. Hercynian tectono-thermal evolution associated with crustal extension and exhumation of the Loradel metamorphic core complex (Ossa-Morena zone Iberian Massif, SW Spain). Int. J. Earth Sciences, 2002, 91: 76—92.

30 Aydin A. and Egeli I. Stability of slopes in metasedimetary saprolites in Hong Kong. Bull. Eng. Geol. Env., 2001, 60: 315—319.

31 Tien Y. M. and Kuo M. C. A failure criterion for transversely isotropic rocks. Int. J. Rock Mech. & Mining Sci., 2001, 38: 399—412.

32 Durast H., Rasolofosaon R. N. J. and Siegesmund S. P-wave velocity and distribution of sandstones from a fractured gas reservoir. Geophysics, 2002, 67: 241—253.

33 Min M. Z., Luo X. Z., Mao S. L. et al. The Saqisan mine—A paleokarst uranium deposit, south China. Ore Geol. Reviews, 2002, 19: 79—93.

34 Yurtmen S. and Rowbotham G. Geochemistry, mineralogy and petrogenesis of the northeast Nigde volcanics, central Anatolia Turkey. Geol. J., 2002, 37: 189—215.

35 Zhu W. B., Sun Y., Guo J. C. et al. Prospect for study of tectono-geochemistry. Progress in Natural Science, 2003, 13: 161—165.

36 Ueshlma M. and Tazaki K. Possible role of microbial polysaccharides in nontronite formation. Clays & Clay Minerals, 2001, 49: 292—299.

37 Sun Y., Shu L. S., Guo J. C. et al. Tectono-geochemistry analyses of fault rocks in shear zone of metamorphic core complex in north Jiangxi, China. Progress in Natural Science, 2003, 13: 1274—1279.

38 O'Hara M. J., Fry N. and Prichard H. M. Minor phases as carriers of trace elements in non-model crystal-liquid separation processes II: Illustrations and bearing on behaviour of REE, U, Th and PGE in igneous processes. J. Petrology, 2001, 42: 1887—1910.

39 Torok K., De Vivo B., Nilson A. A. et al. Fluid inclusion in Niquelandia and Borro Alto complex, Goias State, Brazil. Mineralogy & Petrology, 2002, 96: 75—98.

40 Davison I., McCarthy M., Powell D. et al. Laminar flow in shear zones: the Pernambuco shear zone, NE Brazil. J. Struct. Geol., 1995, 17: 149—161.

41 Conti A., Turpin L., Polino R. et al. The relationship between evolution of fluid chemistry and the style of brittle deformation: Examples from the northern Apennines (Italy). Tectonophysics, 2001, 330: 103—117.

42 Rumble D. and Yui T. F. Qinglongshan oxygen and hydrogen isotope anomaly near Donghai in Jiangsu Province, China. Geochim. Cosmochim. Acta, 1999, 62: 3307—3321.

43 Zhang L., Liu Y. H. and Huang B. X. Magnetic properties and giant magnetoresistance effect of nanometer Fe-In_2O_3 granular films. Chinese Science Bulletin, 2002, 47(24): 2025—2028.