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Microscopic indicators of sliding behavior from rock deformation experiments at different temperatures

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Abstract: The present study analyzes the possible impact temperature may have on slip behavior indicators through microscopic observation on stick-slip and stable-slip experimental samples at different temperatures. The results show that deformation changes with the rise in temperature according to certain rules. As for stick-slip samples, when temperature rises, deformation develops from brittle high-speed fracture into alternation of ductile-brittle slow and high speed stick-slip and offset. As for stable-slip samples, deformation develops from slow brittle deformation to slow ductile deformation.

INTRODUCTION

Abrupt stick-slip is often regarded as indicating strong shallow focus earthquake while progressive stable-slip often represents fracture's slow creeping process (Brace and Byerlee, 1996; Byerlee, 1978; Byerlee and Brace, 1968; Wang Shengzu *et al.*, 1984; Yang Zhuen *et al.*, 1986; Zhang Liu *et al.*, 1988). The stick-slip and creep-slip of natural fracture always leave different traces in deformation materials. The authors have been probing identification of fracture slip movement indicators through oriented microscopic contrasting and analysis and preliminary theories have been raised (Lin Chuanyong *et al.*, 1990; Yao Daquan *et al.*, 1992; 1993; 1994; 1995;1996). Relative study has found that the characteristics of stick-slip and stable-slip vary according to different medium, temperature and pressure. The study starts with microscopic study of experimental deformation materials and probes microscopic indicators of slip movement under different conditions. The results are contrasted with natural deformation samples in order to identify microscopic indicators of slip movement. The present article discusses microscopic indicators of stick-slip or stable-slip in experimental deformation materials at different temperatures under certain medium and pressure.

EXPERIMENT CONDITION, SAMPLE PREPARATION, AND SAMPLE GROUPING FOR MICROSCOPIC CONTRAST AND ANALYSIS

The experiment was done with the Griggs solid medium three-axle device (Shi Liangqi *et al.*, 1988). The pressure medium is Pb at room temperature and NaCl at heated ones. The pressure has frictional correction (Wang Wei *et al.*, 1988). The experiment medium is quartzite from Qian'an, Hebei Province which has dense structure and no obvious deformation. The test sample is a cylinder with a height of 20 mm and a diameter of 10 mm. Isostrain rate is employed for loading. The experiment is to observe stick-slip or stable-slip at heated temperature under the same pressure. Several experiments at room temperature have also been done for contrast.

The samples that have experienced stick or stable-slip are consolidated with original state and made into oriented slices for observation.

The samples are classified into two groups for the convenience of contrast, i.e., stick-slip group and stable-slip group. Each group is arranged from low to high temperature (Table 1).

POSSIBLE MICROSCOPIC SLIP MOVEMENTS IN DEFORMATION MATERIALS AT DIFFERENT TEMPERATURES

Analysis of microscopic deformation characteristics in stick-slip samples at different temperatures

Samples I09 and I10 have almost similar confining pressure (350 and 400 Mpa respectively) and same room temperature. Brittle cracking deformation is seen under the microscope. The typical trace is obvious edge angle of gravel in microscopic fracture zone. The gravels are randomly arranged with transverse rupture (Fig. 1), cutting-gravel microscopic rupture and radial rupture (Fig. 2).

Sample II01 has a confining pressure of 400 Mpa and a temperature of 200°C, equivalent to conditions at 5–10 kilometers deep crust. The deformation trace is mainly zigzag rupture which is again dislocated (twice deformation). There is radial rupture (Fig. 3) and the gravels are randomly arranged. Some edge of the gravels are rounded (Fig. 4) and kink zone is seen (Fig. 5). Besides, there are conjugate cutting-gravel fracture and zigzag fracture.

With the temperature up to 400°C, the temperature and pressure conditions of II02 is equivalent to 15 km-deep crust. We can see some of the particles in the fracture zone have slight ductile deformation. We can also notice ductile-brittle transferring phenomenon such as radial deformation veins. The gravels in the side fracture zone are flattened and stretched (Fig. 6), kinked and dislocated (Fig. 7). Brittle cutting-gravel fracture develops in ductile deformation zone and then brittle tension fracture happens (Fig. 8).

Table 1. Contrasting sample slices of sliding behavior analysis.

Sample Group	Sample	Pressure	Temp.
Stick-slip sample group:	I09	350 Mpa	Rt*
	I10	400 Mpa	Rt
	II01	400 Mpa	200°C
	II02	400 Mpa	400°C
	II03	400 Mpa	600°C
Stable-slip sample group:	I02	200 Mpa	Rt
	I03	200 Mpa	Rt
	III05	200 Mpa	500°C
	II05	400 Mpa	700°C
	II04	400 Mpa	800°C

* Room temperature

With the temperature reaching 600°C, the temperature and pressure condition of II03 is equivalent to 20 km-deep crust. Ductile-brittle transferring deformation takes the main form and we can see many-time high speed brittle cutting-gravel cut ductile deformation zone (Fig. 9) and flattened and stretched zone is dislocated by brittle deformation (Fig. 10). The collided radial deformation veins are more typical than those at 400°C (Fig. 11). Besides, some parts still display deformation feature mainly of brittle cutting gravel (Fig. 12).

The experiment shows that deformation characteristic of stick-slip vary at different temperatures. With the temperature rising, the brittle deformation such as cutting-gravel radial fracture transfers to ductile-brittle deformation. The latter shows radial deformation veins and ductile-brittle cutting gravels, etc.

Analysis of microscopic deformation characteristics in stable-slip samples at different temperatures

I02 and I03 are stable-slip experimental samples under 200 Mpa at room temperature. We can see fracture in parallel crystal (Fig. 13) and arcuate fracture. The gravels are slightly oriented with the edge rounded (Fig. 14).

III05 is a sample under 200 Mpa at 500°C. We can see dispersing and penetrating deformation (Fig. 15) and some parts have ductile twisted deformation (Fig. 16). We can also see an orientatedly arranged zone of rounded gravels (Fig. 17).

The deformation condition for II05 is 400 Mpa and 700°C. We can see obvious ductile deformation, curved extinction deformation zone (Fig. 18), and crumpled and rounded gravels are orientatedly arranged (Fig. 19). Different extinctions form flame-like deformation structure, *en echelon* ductile deformation gravel and parallel deformation veins (Fig. 20).

The deformation condition for II04 is 400 Mpa and 800°C. It mainly displays ductile deformation, penetrating oriented structure and core mantle (ribbon) structure. We can see subgrain and dynamic barite particles, tense ductile deformation quartz which is twisted like a 'fish' (Fig. 21), crumpled floating structure (Fig. 22) and the flattening and stretching of quartz particles parallel to the border of deformation zone (Fig. 23).

We can see that stable-slip deformation traces have obvious differences at different temperatures. At room temperature, stable-slip deformation mainly displays brittle deformation such as parallel fracture in crystal, arcuate fracture, and cataclastic gravel is rounded and slightly orientated. With the

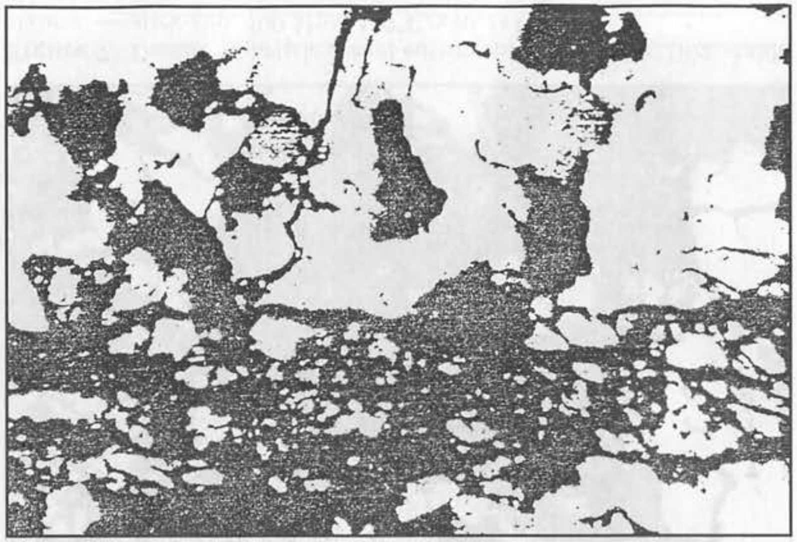

Figure 1. Random arrangement of gravel and tensile cracking. I10, stick-slip, 400 Mpa, Rt, x40, (+).

Figure 2. Radial cracking. I09, stick-slip, 400 Mpa, Rt, x400, (+).

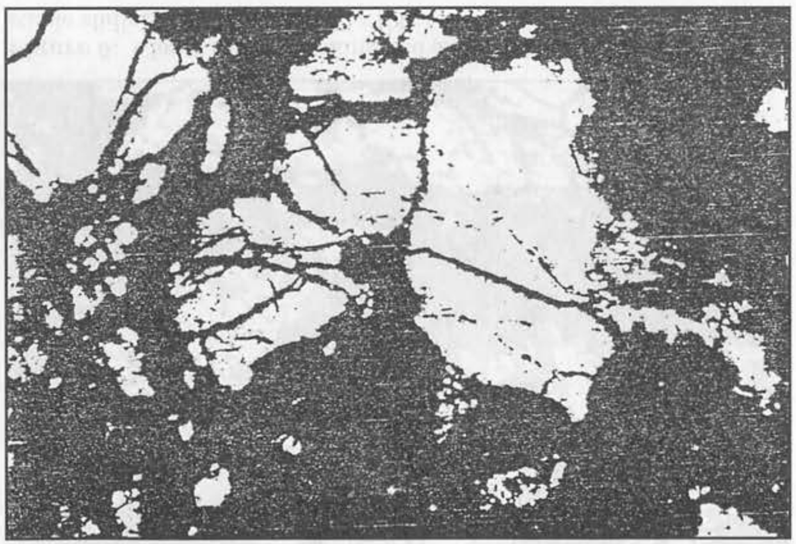

Figure 3. Closed radial cracking. II01, stick-slip — stable sliding, 400 Mpa, 200°C, x100, (+).

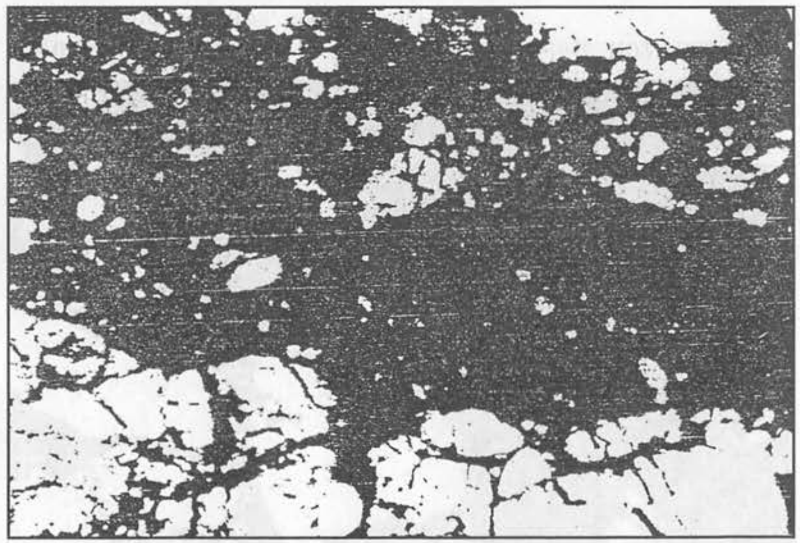

Figure 4. Random arrangement of gravel and roundness gravel. II01, stick-slip — stable sliding, 400 Mpa, 200°C, x40, (+).

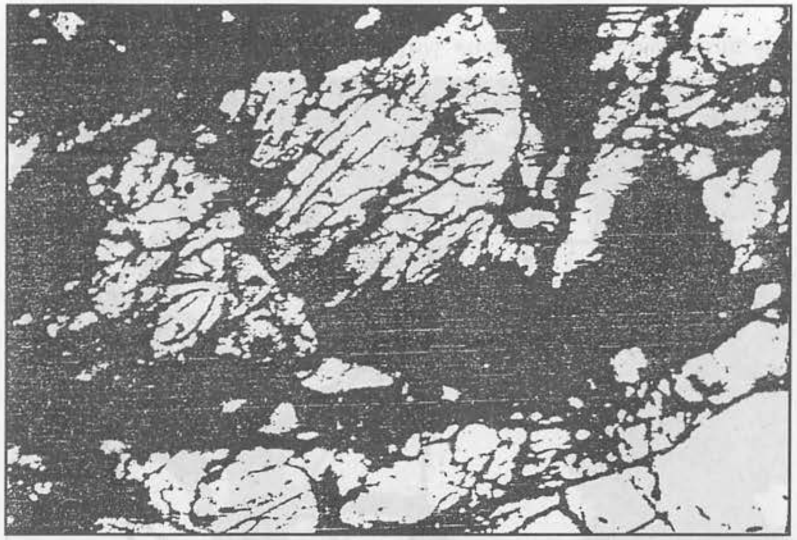

Figure 5. Closed radial cracking and distorted belt. II01, stick-slip — stable sliding, 400 Mpa, 200°C, x100, (+).

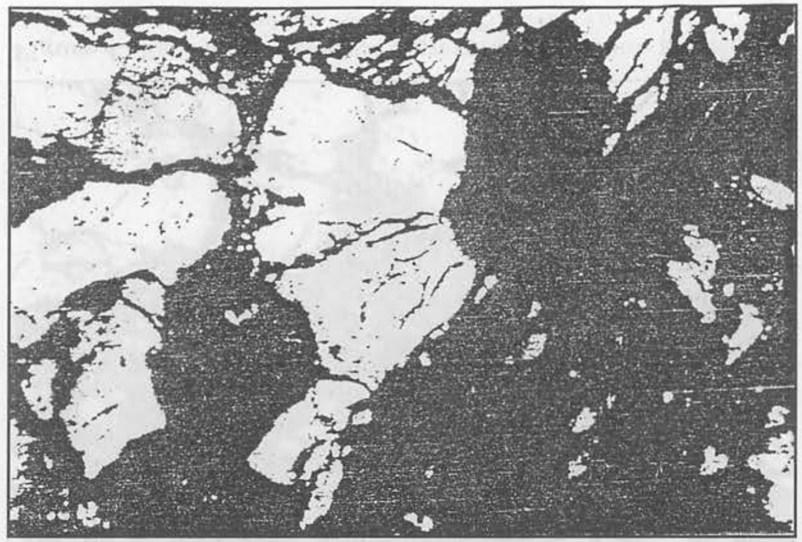

Figure 6. Closed radial cracking and oriented fabric. II02, stick-slip — stable sliding, 400 Mpa, 400°C, x40, (+).

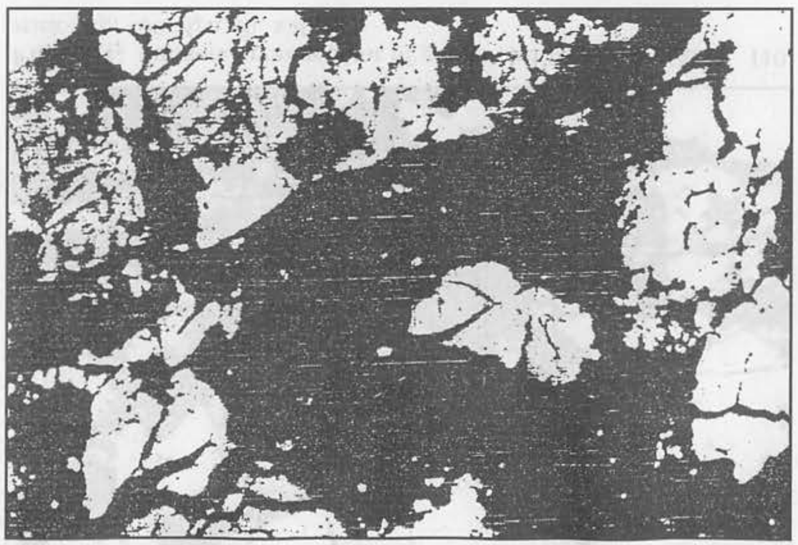

Figure 7. Ductile — brittle gravel-cutting microfractures. II02, stable sliding — stick-slip, 400 Mpa, 400°C, x40, (+)

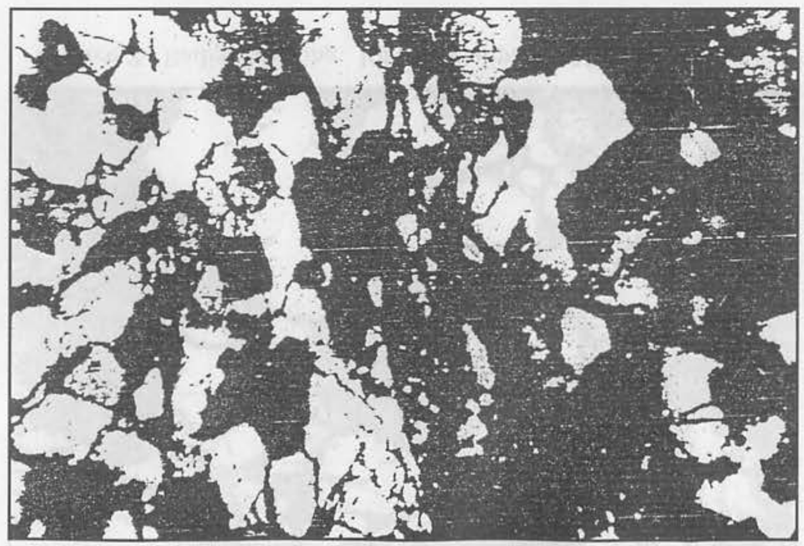

Figure 8. Ductile — brittle gravel-cutting microfracture. II02, stable sliding — stick-slip, 400 Mpa, 400°C, x40, (+).

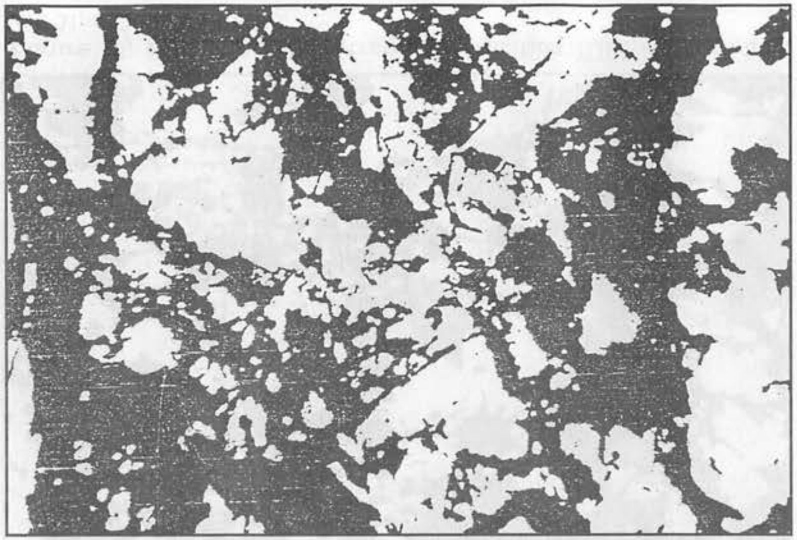

Figure 9. Ductile deformation belt dislocated many time by gravel-cutting microfracture. II03, stable sliding — stick-slip, 400 Mpa, 600°C, x40, (+).

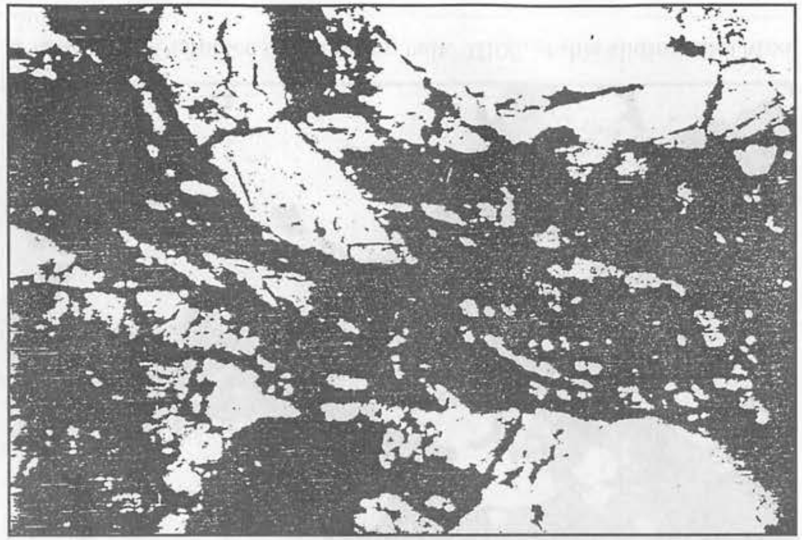

Figure 10. Flattened and stretched belt disclosed by gravel-cutting microfracture. II03, stable sliding — stick-slip, 400 Mpa, 600°C, x40, (+).

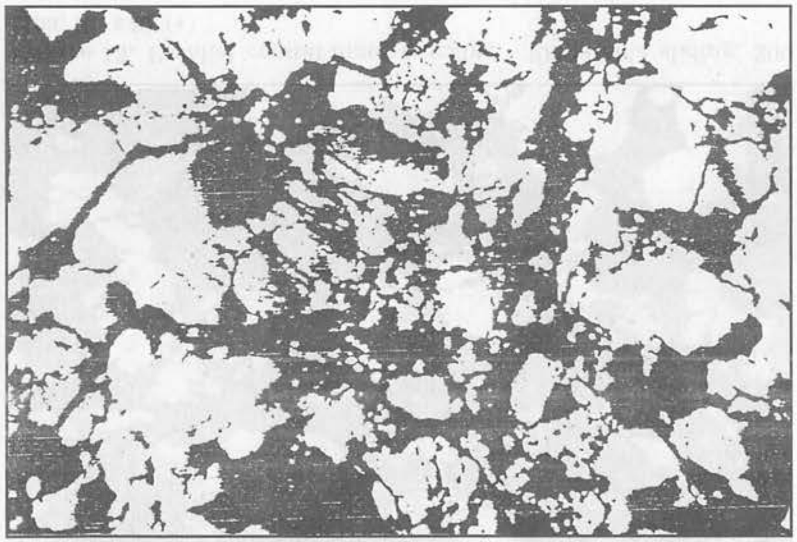

Figure 11. Collision radial deformation lamination. II03, stable sliding — stick-slip, 400 Mpa, 600°C, x40, (+).

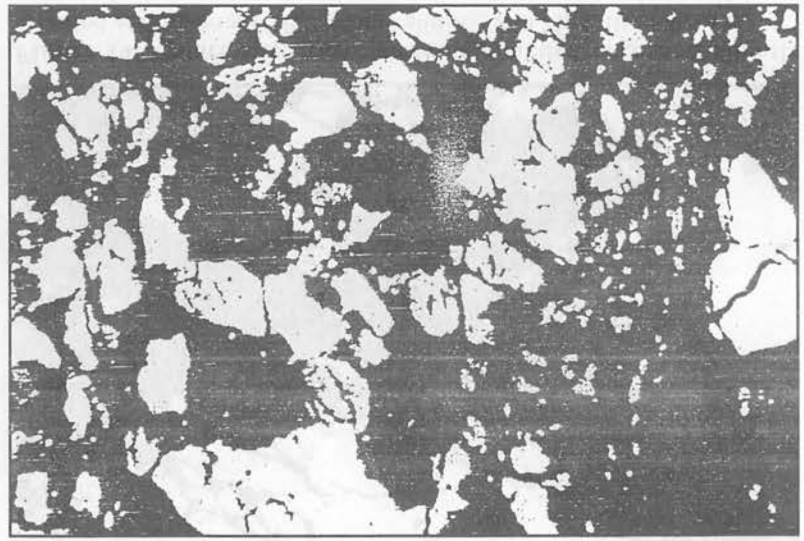

Figure 12. Two-time gravel-cutting microfracture. II03, stick-slip, 400 Mpa, 600°C, x40, (+).

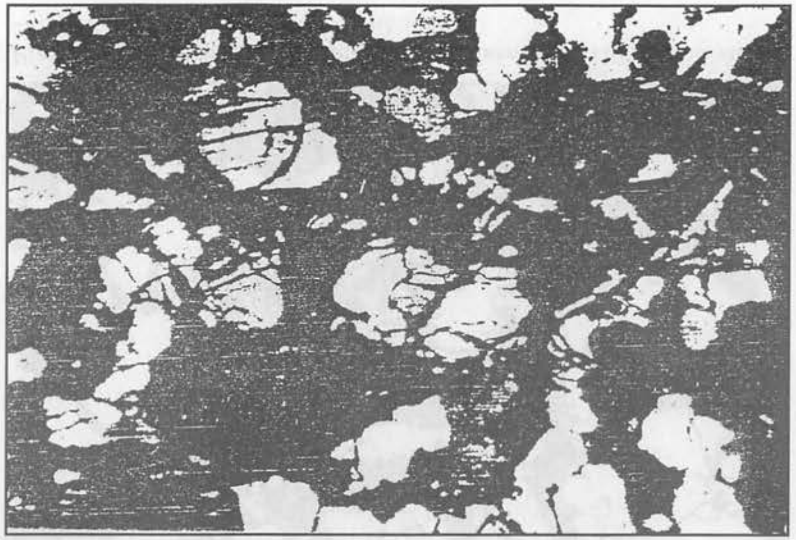

Figure 13. Parallel crystal-inner cracking. I03, stable sliding, 200 Mpa, Rt, x40, (+).

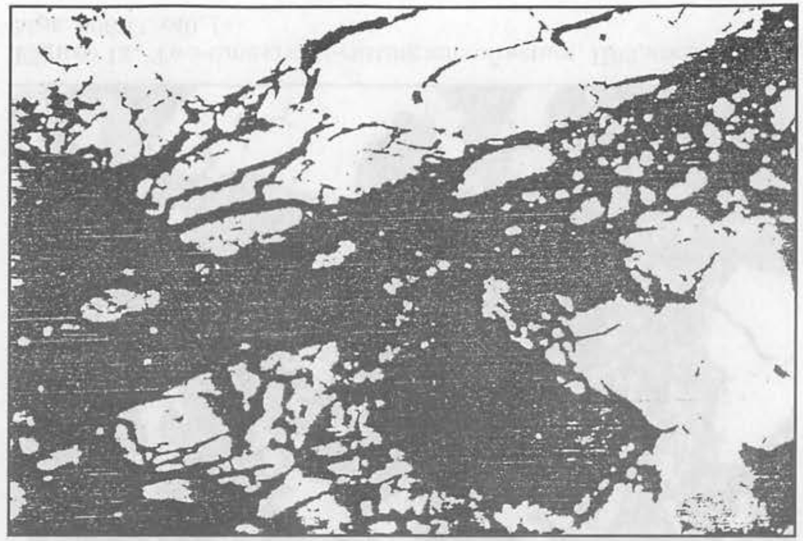

Figure 14. Cataclastic gravel showing rounded edge and slightly oriented arrangement. I02, stable sliding, 200 Mpa, Rt, x40, (+).

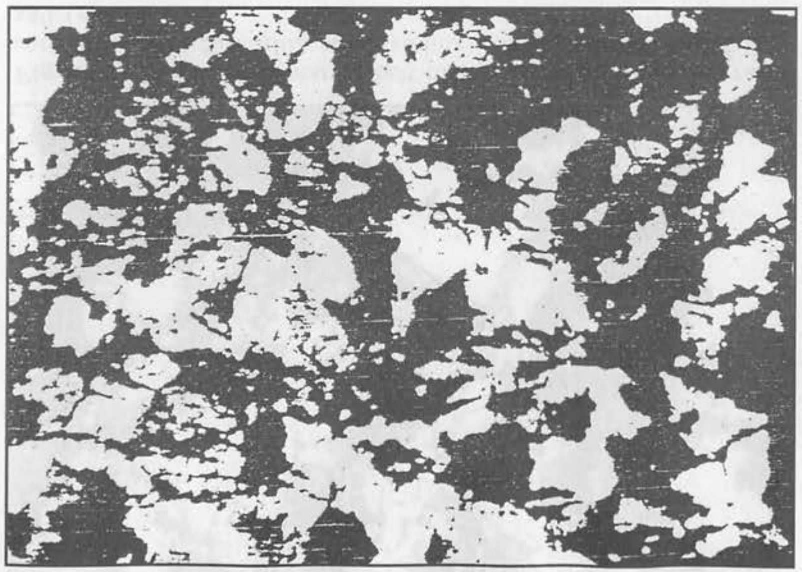

Figure 15. Diffusing and penetrating deformation. III05, stable sliding, 200 Mpa, 500°C, x40, (+).

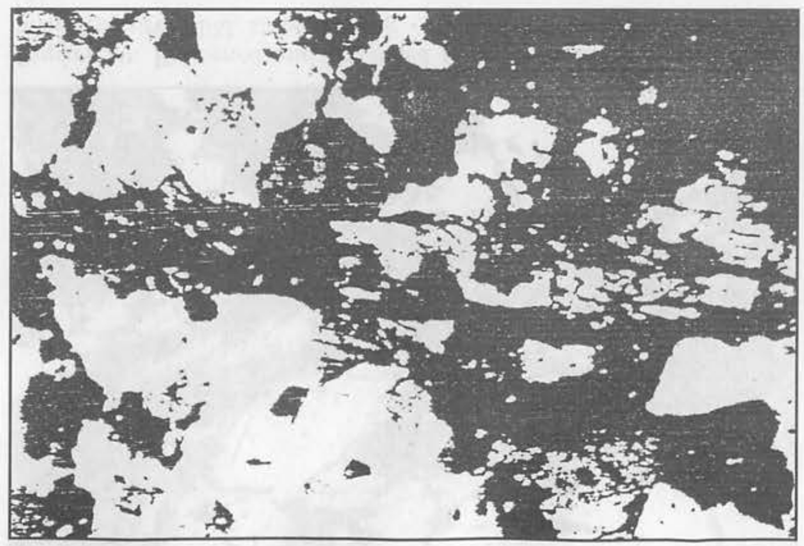

Figure 16. Distorted deformation belt. III05, stable sliding, 200 Mpa, 500°C, x40, (+).

Figure 17. Rounded gravel showing oriented arrangement. III05, stable sliding, 200 Mpa, 500°C, x40, (+).

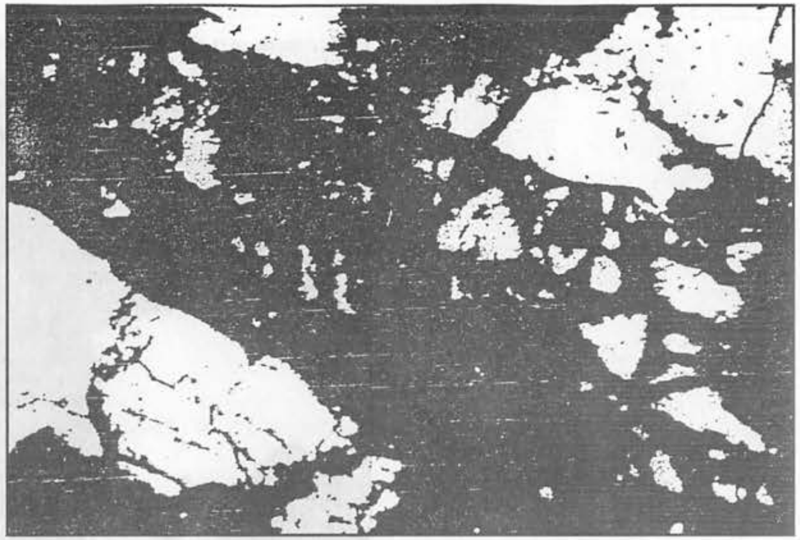

Figure 18. Bending extinction belt. III05, stable sliding, 400 Mpa, 700°C, x40, (+).

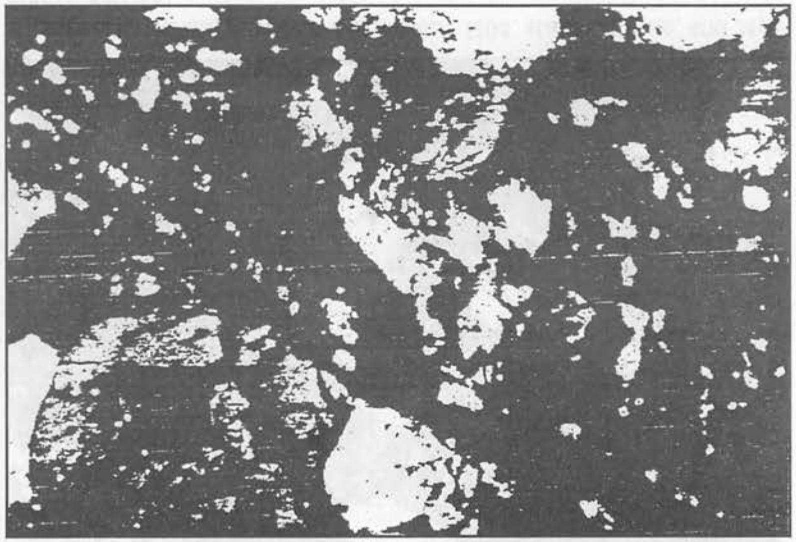

Figure 19. Crumpled and rounded gravel showing oriented arrangement. III05, stable sliding, 400 Mpa, 700°C, x40, (+).

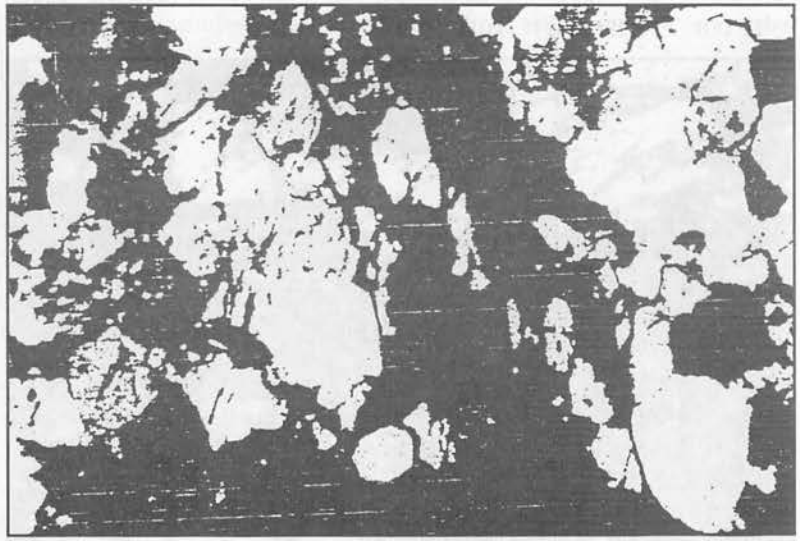

Figure 20. *En echelon* ductile deformation gravel and parallel deformation lamination. II05, stable sliding, 400 Mpa, 700°C, x40, (+).

Figure 21. Strong ductile deformation. II04, stable sliding, 400 Mpa, 800°C, x40, (+).

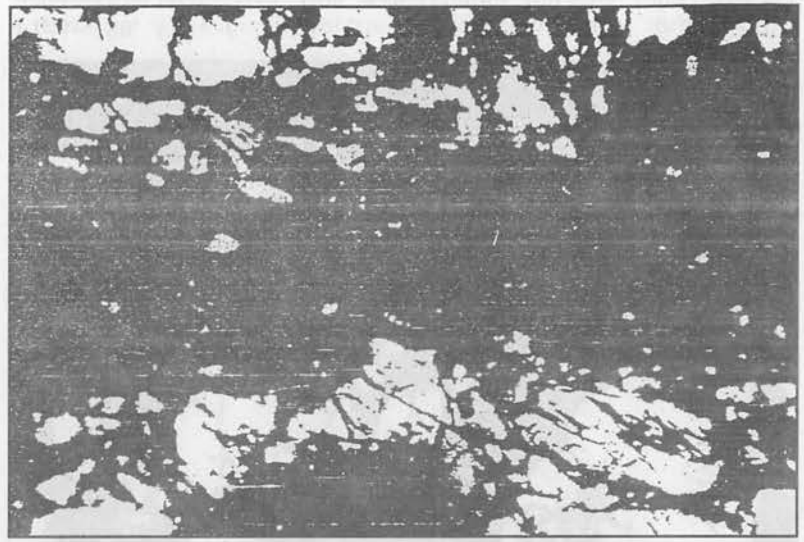

Figure 22. Crumpled flow structure. II04, stable sliding, 400 Mpa, 800°C, x40, (+).

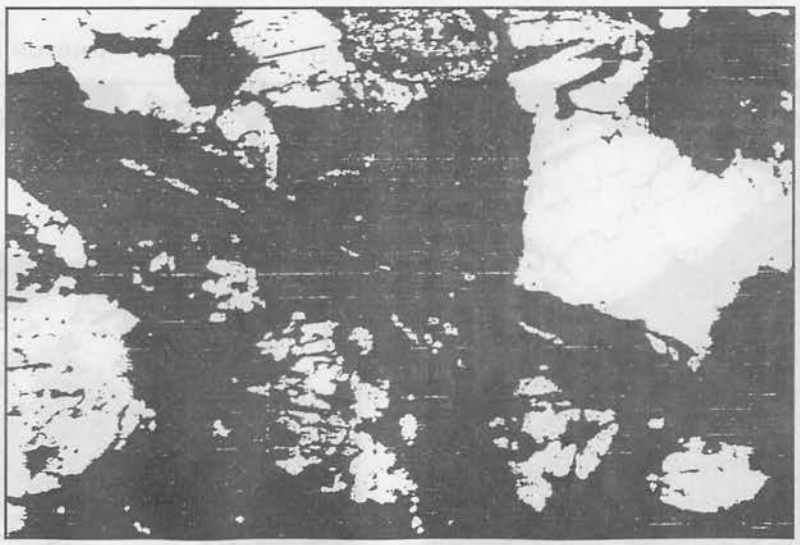

Figure 23. Ductile oriented deformation parallel with the microfault plane. II04, stable sliding, 400 Mpa, 800°C, x40, (+).

rise in temperature, degree of ductile deformation increases and develops towards dispersing and penetrating deformation.

RELATIVE DISCUSSION

From the above-mentioned contrast and analysis of two groups of samples we can see that, no matter what it is stick-slip or stable-slip, deformation changes with the rise in temperature according to certain rules. As for stick-slip samples, when temperature rises, deformation develops from brittle high-speed fracture into alternation of ductile-brittle slow and high speed stick-slip and offset. As for stable-slip samples, deformation develops from slow brittle deformation to slow ductile deformation. Therefore, deformation development of stick-slip and stable-slip is different with the rise in temperature.

Actually, under certain confining pressure, from low to high temperature, the stick-slip deformation develops from stick-slip between crystal to the alternation of slip within crystal and stick-slip. There is no stress drop for stable-slip and stable deformation develops from slow slip between crystal to slow slip within crystal.

The experiment reveals another fact, i.e., the deformation alternation of slip within crystal and stick-slip at high temperature has limitation. When the temperature reaches a certain level(> 600°C), this deformation will have qualitative change and the alternation from ductile to brittle deformation stops, i.e., the deformation will develop from stick-slip to stable-slip. Strong earthquakes in the mainland mostly developing in the eventful layer 5–30 kilometer under the surface is evident proof.

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