The first experimental determination of the strength profile of the lithosphere: preliminary results using halite shear zones

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Received September 29, 1996.
Accepted December 7, 1995.
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Abstract

Shearing experiments on halite layers of 0.7 mm thick between three blocks of Inada granite have been performed to study mechanical properties of fault, at temperatures to 500°C and normal stresses to 40 MPa and under a slip rate of 3 μm/s, using a high temperature biaxial testing machine. Ambient temperature was increased in linear proportion to the normal stress on the simulated fault to study the effect of geothermal gradient. These results provide for the first time an experimental strength profile of the lithosphere, which can be divided into brittle, semiplastic, and fully plastic regimes, with a peak of shear strength roughly at the middle of the semiplastic regime. Stick-slip has been recognized from the brittle regime down to the middle of the semiplastic regime with maximum stress drop near the boundary between the brittle and semiplastic regimes. Microscopic observations on polished specimens under reflected light have revealed: (1) deformation becomes highly concentrated at the gouge-rock interface at the beginning of the brittle regime, (2) foliation due to grain flattening begins to form from the lower end of the brittle regime, showing dragging of foliation toward the concentrated deformation zone at gouge-rock interface with local development of R, Riedel shears, (3) foliation is pervasively developed throughout the shear zone and is distorted with R, Y and P Riedel shears below the peak in the semiplastic regime, and (4) nearly homogeneous shearing deformation changes into heterogeneous one at large strains in the fully plastic regime. The present study will be an important step towards the establishment of a realistic fault and plate boundary model.

Key words: lithosphere, strength profile, rock rheology, rock friction, friction experiment, shear zones, halite strength, semiplastic deformation

Introduction

The rheology of lithosphere is significant in many problems in earth sciences such as the generation of large crustal earthquakes, mechanical interaction of plates, and deformation of plates themselves. However, the lithosphere rheology is almost as poorly established as is the rheology of lower mantle. The large deformation of lithosphere is accommodated mostly by large shearing deformation along faults and shear zones. Hence, the establishment of the constitutive properties of shallow fault zones to deep shear zones is critical to establish the rheology of lithosphere.

Cataclastic deformation prevails at shallow portions of the earth, and the strength of rocks increases markedly with an increase in pressure due to crack closure and to increasing real contact area of asperities in fault zones (e.g., Paterson, 1978). Whereas at deeper portions, plastic flow becomes predominant, and the flow stress decreases markedly with increasing temperature (Hobbs et al., 1976). A simple strength profile was proposed by extrapolating the frictional strength from the brittle regime towards greater depths and the flow law in the fully plastic regime towards shallower depths (Bird, 1978; Brace and Kohlstedt, 1980).

This simple brittle–plastic model proved to be useful in discussing the thickness and internal structures of plates, and seismicity under various tectonic
settings (e.g., Sibson, 1982; Shimamoto, 1993). Despite the apparent success of the model, it predicts a very high strength of lithosphere, even higher than 1 GPa, which severely contradicts the estimate of the shear stress along San Andreas fault based on the heat-flow anomaly (Brune et al., 1969; Hanks and Raleigh, 1980). The current status is that the thickness and internal structures of lithosphere can be predicted reasonably well with the flow properties of rocks, but the mechanical properties of the lithosphere itself are poorly established.

The major unsolved problems in establishing the rheology of lithosphere are (1) fault constitutive properties in the semiplastic regime between brittle to fully plastic regime, (2) flow law for deformation via solution transfer processes, and (3) the effects of chemical reactions and phase changes on the mechanical properties of faults and shear zones (see; Kirby, 1980; Shimamoto, 1989). This paper addresses the first problem and reports the first series of high-temperature shearing experiments on halite, crossing over the strength of lithosphere.

**Experimental procedures**

A high-temperature biaxial testing machine (MARUI Co. Ltd.) was installed at our laboratory to systematically study the deformation in shallow to deep fault zones and associated mechanical properties (Fig. 1; Shimamoto, 1992). The machine was designed to study the frictional property at elevated temperatures, since previous experiments (e.g., Shimamoto, 1986, 1989; Shimamoto and Logan, 1986; Hiraga and Shimamoto, 1987) were done mostly at room temperature. The machine consists of a gear-train loading system equipped with a servo-motor, a ball screw that converts rotary motion to axial displacement, axial and normal force gauges, specimen assembly, a horizontal hydraulic press to apply the normal force to the sliding surface, and displacement transducers.

By combining the speed change of the servo-motor with four different sets of gear arrangements, the machine is capable of producing nine-orders of magnitude speed-change, the slip rate along simulated faults ranging from 1.5 mm/s down to less than 0.1 mm/yr. The displacement rate can be varied almost instantly by any amount within these 9 orders of magnitude either by changing the motor speed or by turning electromagnetic clutches on or off to select a gear assembly. Thus, the machine is suitable for the velocity stepping experiments to study frictional properties of faults. The furnace can be used at temperatures to 1000°C since canthal wire is used as the heating element (Fig. 2). This machine will be used to establish the constitutive laws for soft minerals, such as calcite and halite, in the brittle, semiplastic, and fully plastic regimes. Use of no pressure vessel and sample jackets makes precise force measurement possible. A disadvantage of the machine as it is now is that wet experiments cannot be performed.

I used iodized cooking salt from Maruni Co. Ltd. for 0.7 mm-thick halite shear zones between three blocks of Inada granite in the biaxial machine (Fig. 3). First, the three-block specimens were pressed for 30 minutes at room temperature and normal stress of 40 MPa to compact the halite layers, before the specimens were set in the biaxial machine. The test temperature was increased in proportion to the normal stress, trying to simulate the geothermal gradient in the earth. The maximum normal stress, which can be sustained by the specimens, is limited by the uniaxial strength of the block samples. As the uniaxial strength substantially decreases with temperature due to thermal cracks (Bauer and Johnson, 1979), the temperature versus pressure gradient used in my experiments is much greater than the actual geotherm.

Experiments have been performed on the specimens at temperatures to 500°C, at the normal stresses to 40 MPa, and under the slip rate of 3μm/s. Prior to experiments, temperature and normal stress were raised to 300°C and 26 MPa, respectively, in 3 hours and were kept at this condition for 1 hour to eliminate moisture in the specimen. Subsequently the temperature and normal stress were changed to a test condition, and a
run at the condition was continued until a steady-state or nearly steady-state in the shear stress is reached. The test condition was then changed for the next test at different conditions. A few tests were performed until the total displacement reached the limit of 20 mm.

**Experimental results**

Figure 4 shows the shear stress and normal stress during steady-state or nearly steady-state shear resistances from several runs on the halite shear zones. Temperatures and pressures are given, respectively, on the right and left vertical axes. At lower temperatures and normal stresses, the shear stress increases in proportion to the normal stress with the frictional coefficient of 0.6, which is slightly smaller than that for many rocks (c.f., Byerlee, 1978). At higher temperatures and normal stresses, the data deviate from this linear relationship and reach the strength peak. At further higher temperatures and normal stresses, the shear strength decreases with increasing temperature irrespective of increasing normal stress.

For the sake of convenience, the boundary between brittle and semiplastic regimes was taken at the point where the friction law breaks down (P in Fig. 4). The strength versus normal stress curve is concave towards the upper-left side below the strength peak, and it changes to be concave towards the lower-right side at higher normal stresses. The boundary between fully plastic and semiplastic regimes is taken at the inflection point of the high-temperature strength curve between the two segments (FP in Fig. 4). Based on these definitions, the semiplastic regime is found to be as broad as the brittle regime. Stick-slip was clearly recognized in the brittle regime and at least down to the peak strength in the semiplastic regime (closed symbols in Fig. 4). However, the unstable slip changed to the stable slip towards the fully plastic regime. The stick-slip amplitude increases with increasing normal stress in the brittle regime and reaches its maximum near the boundary between the brittle and the semiplastic regimes, and subsequently decreases towards the base of the semiplastic regime.

Figure 5 shows the shear stress versus normal stress on the simulated halite shear zones at steady-state or nearly steady-state shearing deformation at elevated temperatures. At 200°C and 250°C, the shear stress increases in proportion to the normal stress until about 15 MPa and 10 MPa, respectively, and then deviates from the linear relationship. At 350°C and 500°C, the shear stress becomes nearly insensitive to the normal stress above about 20 MPa and 5 MPa, respectively. Fully plastic flow is characterized by the shear stress nearly independent of the normal stress (i.e., Bridgman effect). The halite shear zone seems to be in fully plastic regime at a normal stress of about 300 MPa (Shimamoto, 1986, 1989) at room temperature. On the contrary, the fully plastic flow takes place at much lower normal stress at high temperatures. The arrows in Fig. 5 point the normal stress values for the experiments in Fig. 4. It is obvious that the halite shear zones were in fully plastic regime at 350°C and 500°C, whereas the shear zones are
Microscopic observation

Observations were carried out with a polarized microscope under reflected light. Specimens were first polished dry with sandpaper and emery paper, and the final polish was made with carborundum (#6000) using benzine as a lubricant. Grain boundaries were etched using a small amount of saliva and were enhanced by vacuum-coating with carbon.

The starting material, precompacted under a normal stress of 26 MPa and at a temperature of 300°C for an hour, is a structureless aggregate of halite clasts. Some recrystallized subgrains with clear surfaces are recognized along the original grain boundaries (Fig. 6a).

1. Textures in the brittle regime

Figure 6b shows a halite shear zone deformed at 50°C with normal stress of 4 MPa. At a glance, the shear zone consists of a structureless aggregate of halite grains because the deformation is highly concentrated at a rock–halite interface. Since halite grains were nearly perfectly compacted prior to the shearing experiments, the major part of gouge remained nearly undeformed before deformation was concentrated at gouge–rock interface. A few tension cracks are recognized within the shear zone.

Figure 7 show a halite shear zone deformed at 100°C with normal stress of 9 MPa. Although the mechanical behavior is still of brittle type, the halite shear zone exhibits foliation defined by elongated grains, suggesting partial operation of plastic deformation. Foliation is markedly dragged towards the zone of concentrated deformation at a rock–halite interface (Fig. 7a). Foliation is often cut by shear surfaces, the most predominant being R, Riedel shears (Fig. 9a, b). Figure 7b displays an example of such R, Riedel shear. Tension cracks, probably due to unloading, are also remarkable.

2. Textures in the semiplastic regime

Before the peak strength, the texture of halite shear zone resemble Fig. 7a, in which the original grain boundaries are visible. However, after the peak strength at 250°C with normal stress of 22 MPa, the original grain boundaries disappear and two layers composed of fine and very fine recrystallized grains are formed (Fig. 8a). Foliation, which is defined by straight and continuous grain boundaries, develops almost uniformly in the fine–grained region. On the
other hand, foliation in the very-fine-grained region is distorted throughout the shear zone along some discontinuities which have the orientation of R₁, Y and P Riedel shears (Fig. 9 a, c). Figure 8 b displays examples of such R₁ and Y Riedel shears.

3. **Texture in the fully plastic regime**

Figure 10 show a halite shear zone deformed at 350°C with normal stress of 31 MPa. The shear zone consists of coarser grains than those in the semiplastic regime. Foliation is almost uniformly developed (Fig. 10 a) but partially folded by some discontinuities when shear strain, γ, is large enough (Fig. 10 b). Foliation is uniformly and pervasively developed when γ is small, and the observed angle, θ_{obs}, between the
foliation and the shear zone boundary agrees closely with the calculated angle, $\theta_{\text{cal}}$, between the shear zone boundary and the orientation of the maximum elongation (Fig. 11). $\theta_{\text{cal}}$ was calculated with the following equation:
\[
\tan 2\theta_{\text{cal}} = 2/\gamma
\]
where the shear strain, $\gamma$, is given by the measured displacement divided by the thickness of a halite shear zone (e.g., Nicolas and Poirier, 1976). Datum points fall on the one-to-one line for $\theta_{\text{obs}}$ and $\theta_{\text{cal}}$, indicating that the uniformly developed foliation coincides with the direction of maximum elongation.

**Discussions**

Figure 12a exhibits a fault model based on the shearing experiments at room temperature (Shimamoto, 1989), whereas Fig. 12b shows a revised fault model based on the high-temperature experimental data of this study. As in the previous model, the revised model consists of brittle, semiplastic and fully plastic regimes of about the same extent. It must be emphasized that mylonitic textures form not only in fully plastic regime, but also from the lower end of the brittle regime, being consistent with previous work (Shimamoto, 1985, 1989; Shimamoto and Logan, 1986; Hiraga and Shimamoto, 1987). The revised model in Fig. 12b is on the whole very similar to the previous model, except that the flat region near the peak strength does not exist, and the seismic behavior of the fault extends nearly to the peak strength in the updated model.

Scholz (1988) proposed a fault model consisting of

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**Fig. 9.** (a) A complete set of Riedel shears and their notations. (b) and (c): Rose diagrams showing the orientation of relatively straight discontinuities of foliation within halite shear zones deformed (b) at 100°C with normal stress of 9 MPa, and (c) at 250°C with normal stress of 22 MPa. The orientation of the discontinuities is shown by the frequency in percent. 114 and 116 measurements were made in (b) and (c), respectively.
Fig. 10. Photomicrographs of halite shear zone deformed at 350°C with normal stress of 31 MPa: (a) nearly uniformly developed foliation, and (b) locally heterogeneous deformation. Foliation in the upper central part exhibits anticlockwise rotation relative to the general trend of foliation in the shear zone.

Fig. 11. The measured orientation of nearly uniformly developed foliation plotted against the predicted orientation of the maximum elongation assuming homogeneous simple shear with the standard deviation shown by vertical bars. The dashed line has a slope of 1.0, i.e., observed angle = calculated angle, and the data fall on this line.

\[
\dot{\gamma} = f(\tau) \exp \left( -\frac{Q}{RT} \right)
\]  

(1)

where \( \dot{\gamma} \) is the shear strain rate, \( \tau \) is the shear stress, \( Q \) is the activation energy, \( R \) is the gas constant, and \( T \) is the absolute temperature (e.g., Poirier, 1985). Many experimental data have suggested that the power law and exponential law for \( f(\tau) \) are applicable to high-temperature and low-temperature plastic deformations, respectively. My data so far suggest that the present experiments correspond to the transitional from the exponential to power law.

This paper has dealt only with steady-state or nearly steady-state behaviors. However, the establishment of transient behavior is critical in solving problems such as the earthquake generation. Servo-controlled high-temperature biaxial machine, recently installed in our laboratory, will be used for determining constitutive properties including transient properties from brittle to fully plastic regimes. The effects of pressure solution transfer processes, chemical reactions, and ultra-fine rocks constituting the concentrated deformation zone in fault zones are still largely unexplored and must be studied systematically in the future, in order to establish the rheology of the lithosphere.

Conclusions

The major results from this study are listed as follows.

(1) As predicted from the experimental results at room temperature, the deformation regimes of lithosphere can be divided into brittle, semiplastic, and
Fig. 12. A fault model based (a) on room temperature (Shimamoto, 1989) and (b) on the present experimental data at high temperature.

plastic ones. The semiplastic regime is as broad as the brittle regime, and the peak of shear strength is located roughly at the middle of this regime.

2. Stick–slip is recognized from the brittle regime down to the middle of the semiplastic regime near the peak strength.

3. The stick–slip amplitude has its maximum near the boundary between the brittle and semiplastic regimes.

4. Deformation is highly concentrated at the gouge–rock interface at the beginning of the brittle regime.

5. The plastic deformation occurs even in the mechanically brittle regime with elongate grains to form foliation dragged towards the concentrated deformation zone.

6. The distortion of the foliation with R, Y and P Riedel shears is characteristic of semiplastic deformation below the peak.

7. Fully plastic deformation is characterized by uniformly and pervasively developed foliation, but the deformation becomes heterogeneous at large strains.

Acknowledgments

I thank Professor Toshihiko Shimamoto for his constructive review of this paper and Dr. Akito Tsutsumi and Professor John M. Logan for many helpful suggestions and discussions. I also thank T. Nakazono and A. Yamamura of Marui Co. Ltd. for building the biaxial testing machine and Takata Co. Ltd. for making many granite blocks I used in this study.

References


Shimamoto, T., 1986, Transition between frictional slip and

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<td>地下深所から深所に至る断層の挙動を明らかにしリソスフェアの強度断面を決定するために、岩塩剪断帯を用いて高温二軸摩擦試験機による剪断実験を行った。変位速度は3μm/sで、地温勾配の影響を調べるため、実験温度(500℃まで)は垂直応力(40 MPaまで)に比例するように増加させた。実験の結果、強度断面は脆性・準塑性・完全塑性領域に三分され、強度のピークは準塑性領域のほぼ真上に位置する。地震性の動きを示す不安定すべりは、脆性および準塑性領域の前半で観察され、応力降下は両領域の境界付近で最大になる。本論文では、それぞれの領域で特徴的に見られる岩塩の高温剪断変形組織についても述べる。本研究は断層およびアレート境界モデルを確立する上で重要なステップになるだろう。</td>
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