京都大学防災研究所年報 第43号 B-1 平成12年4月
Annuals of Disas. Prev. Res. Inst., Kyoto Univ., No. 43 B-1, 2000

Temperature Dependence of Strength of Rocks under High Confining Pressure
—— Micromechanism and Implications ——

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Synopsis

Triaxial testing on a dry granite was conducted at a confining pressure of 1500 MPa and temperatures to 600°C in small temperature intervals with an averaged strain rate of approximately 2×10^{-6} s^{-1}. All the experiments fall in the high-pressure type fracture regime, which occurs when the compressive strength equals the frictional strength. The strength of the granite decreases with increase of temperature but it is unusually low at around 250°C. Micromechanical studies suggest that such behavior is caused by switching the dominating factors from the activation of crack groups to the inhibition of them and the dominance of crystal plasticity with increase of temperature. These results suggest to provide an alternative explanation for the brittle-ductile hypothesis of the seismogenic zone in the crust: earthquakes could occur or nucleate more easily where the strength is low.

Keywords: high confining pressure; high temperature; granite; strength; lithostatic strength; brittle-ductile hypothesis

1. Introduction

The strength of rocks in the lithosphere depends on temperature in the brittle regime as well as in the ductile regime. In estimates of lithospheric strength, Byerlee's (1978) frictional law is ordinarily assumed for the brittle regime (e.g., Goetze and Evans, 1979; Brace and Kohlstedt, 1980), since the frictional strength of rocks is lower than the fracture strength and is independent of temperature up to ~600°C (Stesky et al., 1974; Byerlee, 1978). Shimada (1993a, b), Cho (1993) and Kohlstedt et al. (1995) have suggested the possibility that the frictional strength equals the fracture strength at crustal conditions. Therefore, it is significant to determine the fracture strength as well as the frictional strength in crustal conditions.

In a series of triaxial tests at confining pressures up to 3000 MPa (Shimada et al., 1983; Shimada and Cho, 1990; Shimada. 1992), we have concluded that the fracture mechanism changes at the confining pressure where the compressive strength equals the frictional strength, from the ordinary brittle fracture (designated as the low-pressure type) to the high-pressure type. The high-pressure type fracture is different from the ordinary brittle fracture in the following three manners: (1) the strength increases linearly with increase of confining pressure; (2) the activity of acoustic emission (AE) does not increase rapidly before a final fracture; and (3) there is no concentration of microcracks close to a main fault that is sharp and oriented at ~45° to the compressive stress direction. The high-pressure type fracture is considered to be identical to those observed previously by others in the transitional regime between the brittle faulting and the ductile creep regimes (Tullis and Yund, 1977, 1992; Shelton et al., 1981; Caristan 1982; Hirth and Tullis, 1994). We have also suggested the possibility that the high-pressure type of fracture occurs in the crust, considering the size effect on rock strength: for example, between 2.5 and 12.5 km depth in the granitic crust in the case of dry thrust faulting (Shimada, 1993a, b).

Subsequent experiments showed an unusual behavior of strength of granite in the high-pressure type regime at 250°C (Shimada, 1997). There, the strength appears to decrease with increase of confining pressure or to have a minimum value (Fig. 1). The 250°C data were contrasted with 100° and 300°C data, although the scatter in these data is large probably due to the large grain size compared to the specimen size. The object of this article is to ascertain the unusual behavior of strength from measurements of temperature dependence of strength in small temperature intervals at a confining pressure of 1500 MPa in the high-pressure type regime, which has been preliminarily described in Shimada (1999). Micromechanical studies provide an explanation for the unusual behavior. Implications of results in the lithospheric strength are discussed, and an alternative explanation for the brittle-ductile hypothesis of the seismogenic zone in the crust is also proposed.

2. Experimental method

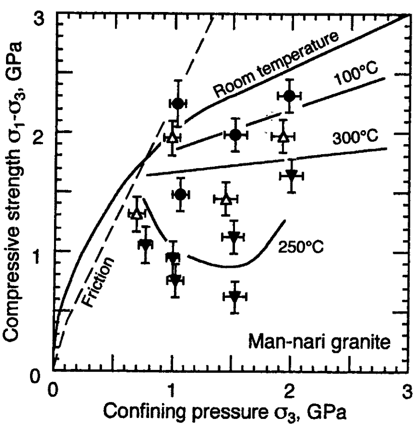

Fig. 1 Comparison of strength of dry Man-nari granite as a function of confining pressure at room temperature, 100°C (solid circle), 250°C (open triangle) and 300°C (solid triangle). Data in the high-pressure type are only plotted. The broken line shows the frictional strength by Byerlee (1978).

Experiments were conducted using a cubic press (Shimada, 1981) and a sample assembly previously described (Shimada, 1992) that was modified slightly as shown in Fig. 2. The modification consisted of removing strain gauges, jacketing the rock specimen with thin platinum tubing, and using three pairs of thermocouples. Temperature was monitored by a thermocouple at the center part of the specimen, and two other pairs were used (one fed to the anvil surfaces and the other from the anvil surface) to make sure of temperature measurement even if the monitoring one is damaged during a run. The uncertainties of temperature measurement due to the gradient in the sample area of the above assembly were, for example, ± 7°C at 250°C and ± 14°C at 500°C monitored temperature. A soft-fired (800°C) pyrophyllite sleeve of 15 mm outer diameter was used in the pyrophyllite cube to prevent pyrophyllite from dehydrating (cf., Matsushima et al., 1967).

Cylindrical rock specimens were with 16 mm in length and 8 mm in diameter, as used in previous studies (Shimada, 1981, 1992; Shimada and Cho, 1990). The starting material was Man-nari granite with a porosity of 0.7% and a grain size of ~1 - 3 mm. This rock is composed of 38.7% quartz, 29.7% orthoclase, 26.9% plagioclase, 1.7% hornblende and 3.0% biotite by modal analysis, and no alteration in minerals was seen optically.

The completed assembly was set up in the cubic press after vacuum-drying for more than 24 hours at 110°C. Confining pressure was first increased to a value lower than the expected one by ~100 MPa, the temperature was then slowly raised to the expected value monitored by a chromel/alumel thermocouple, and finally the confining pressure was increased to the desired value of 1500 MPa. These conditions

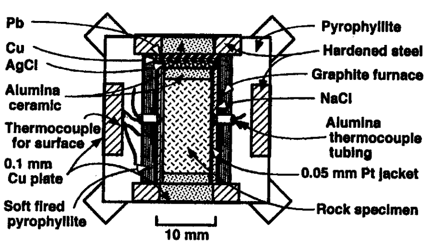

Fig. 2 The sample assembly designed for rock specimens of 8 mm in diameter and 16 mm long in a cubic press for high temperature experiments in this study.

were maintained for a few hours. Differential stress was then applied to the rock specimen in a fixed rate of advancement of anvils for axial loading (upper and lower ones in Fig. 1) of 1.7×10^{-4} mm s^{-1} (corresponding to an averaged strain rate of approximately 2×10^{-6} s^{-1} for the rock specimen) by using a computer-aided automatic-control loading unit. After the fracture was reached, or occasionally the stress or displacement corresponding to the room-temperature strength was reached, the differential stress was first decreased at the run temperature, then the temperature was decreased slowly to room temperature. Finally, the confining pressure was decreased to ambient condition. AE was measured by means of PZT with a resonance frequency of 1 MHz (Yukutake, 1982; Shimada, et al., 1983).

The unloaded rock specimens were mounted with acryl monomer and epoxy resin. Each specimen was then cut in several pieces parallel to the axial stress direction and perpendicular to the main fault plane if it was recognized on the surface. A thin section was prepared from one of cut specimens for optical microscopy. A second one was polished, ion-milled and sputter-coated with 20 nm of gold for scanning electron microscopy (SEM). From a third one, a specimen for transmitting electron microscopy (TEM) is also being prepared, although TEM work have not been completed and are not described here.

3. Results and discussion

3.1 Temperature dependence of the strength

The results are listed in Table 1. Figure 3 shows the obtained strength as a function of temperature. Open symbols indicate the runs, in which one or two large AE events (sometimes together with an audible snapping sound) were observed accompanied by a stress drop ranging from 4 to 93 MPa or an abrupt jump of anvil displacement, just after a peak stress, taken as the strength, was attained. Hatched symbols indicate the runs in which neither AE event nor stress drop was observed but the load-displacement curve broke significantly toward the displacement axis, namely the yield strength.

The observed AE activity was identical to that of the high-pressure type fracture mentioned in the previous section. The fault feature in each specimen after the run was also of the high-pressure type (Fig. 4),

Table 1 Temperature dependence of strength for dry Man-nari granite in the regime of the high-pressure type fracture

Run	Confining pressure σ_3, MPa	Temperature, °C	Compressive strength $\sigma_1 - \sigma_3$, MPa	Comments*
RMG-19	1510 ± 90	24 ± 1	2270 ± 140	40°; H
RMG-34	1530 ± 90	93 ± 6	1990 ± 140	45°; H
RMG-61	1500 ± 90	153 ± 7	2060 ± 130	45°; H
RMG-67	1500 ± 90	178 ± 8	1690 ± 130	45°, 30°†; H
RMG-60	1500 ± 90	198 ± 9	1140 ± 130	45°; H
RMG-50	1530 ± 90	246 ± 10	630 ± 140	45°†; H
RMG-59	1510 ± 90	246 ± 11	1130 ± 140	45°†; H
RMG-75	1500 ± 90	258 ± 13	900 ± 130	45°; H
RMG-63	1510 ± 90	283 ± 9	710 ± 130	45°†, 30°†; H
RMG-62	1510 ± 90	295 ± 11	1420 ± 130	45°†, 30°†; H
RMG-69	1500 ± 90	332 ± 13	1180 ± 130	45°†, 30°†; H
RMG-68	1520 ± 90	361 ± 14	1050 ± 130	45°, 30°; H
RMG-64	1510 ± 90	402 ± 14	1380 ± 130	40°†, 45°†, 30°†; H
RMG-65	1500 ± 90	433 ± 18	1200 ± 130	45°†, 40°†, 30°†; H
RMG-66	1520 ± 90	487 ± 18	1000 ± 130	45°, 30°†; H
RMG-74	1510 ± 90	503 ± 21	1220 ± 130	45°†, 40°†, 30°†; N
RMG-70	1490 ± 90	537 ± 23	1020 ± 130	45°†; H
RMG-71	1490 ± 90	609 ± 38	630 ± 130	45°†, 30°†; N

* Crack angles to the compressive stress direction. H denotes the run where the high-pressure type of AE activity was observed accompanied by stress drop. N denotes the run where neither AE nor stress drop was observed.

† Short length cracks.

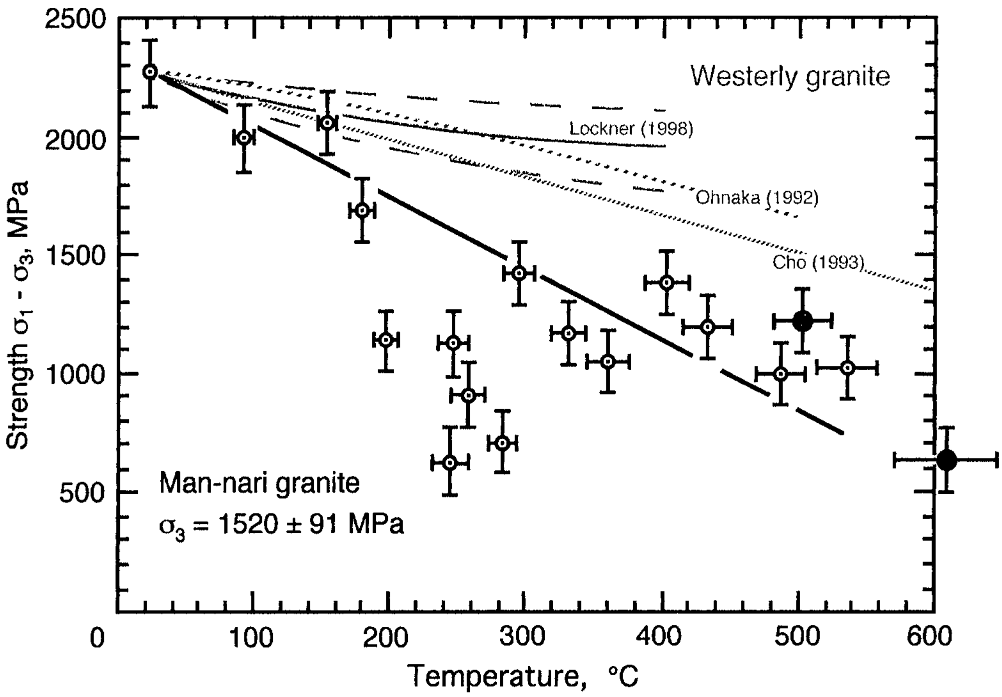

Fig. 3 Temperature dependence of strength for Man-nari granite at a confining pressure of 1500 MPa in the high-pressure type fracture regime. Open and hatched symbols indicate the runs with and without AE events accompanied by a stress drop, respectively. The gray lines indicate previously determined temperature dependence for Westerly granite. The solid line indicates a linear fit for the data, excepting those between 200° and 280°C on Man-nari granite.

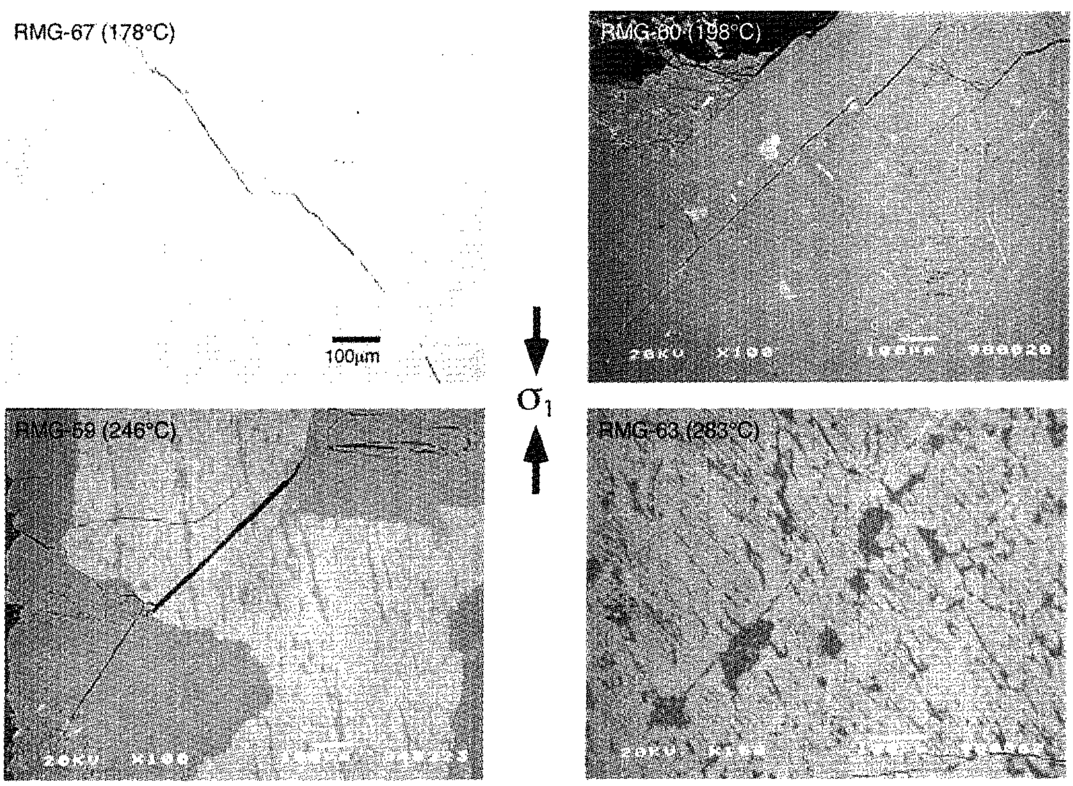

Fig. 4 Typical examples of SEM micrographs (backscattered electron images) of the high-pressure type cracks at a confining pressure of 1500 MPa. The direction of the compressive stress is vertical.

although a through-going fault was not observed excepting in a room-temperature run but small length faults or cracks oriented at 45° in elevated-temperature runs.

The strength shown in Fig. 3 decreases with increase of temperature but it is unusually low around 250°C. Temperature dependence of strength has been studied, for example on Westerly granite, by many authors (Griggs et al., 1960; Stesky et al., 1974; Tullis and Yund, 1977; Wong, 1982), although they measured strength at rather large temperature intervals, e.g., every 100°C. The temperature dependence of strength varies strongly with confining pressure. By normalizing it with the strength at room temperature under a fixed confining pressure, on the other hand, Ohnaka (1992), Cho (1993) and Lockner (1998) have expressed the temperature dependence of the above strength data on Westerly granite by an empirical relationship independent of confining pressure (by a combination of hyperbolic and exponential functions of temperature, by a linear relation to temperature with slope of -7.1×10^{-4} K^{-1} and by a linear relation to reciprocal temperature with slope of 74.1 ± 41.7 K, respectively). Their temperature dependences are shown by gray lines in Fig. 3, using a room-temperature strength of 2070 MPa at 1500 MPa confining pressure on Man-nari granite. The results for Man-nari granite show a similar tendency to those for Westerly granite below 200°C and above 280°C, although the temperature dependence is slightly greater, the linear fit being -1.3×10^{-3} K^{-1} (the solid line in Fig. 3).

The strength values between 200° and 280°C deviate significantly from the above relationship and are very low, with a minimum at around 250°C. The effect of dissociated water from hydrous minerals in granite such as biotite and hornblende or from pyrophyllite of pressure medium could not have occurred at these temperatures. The decomposition temperatures of biotite, hornblende (e.g., Wyllie, 1977) and

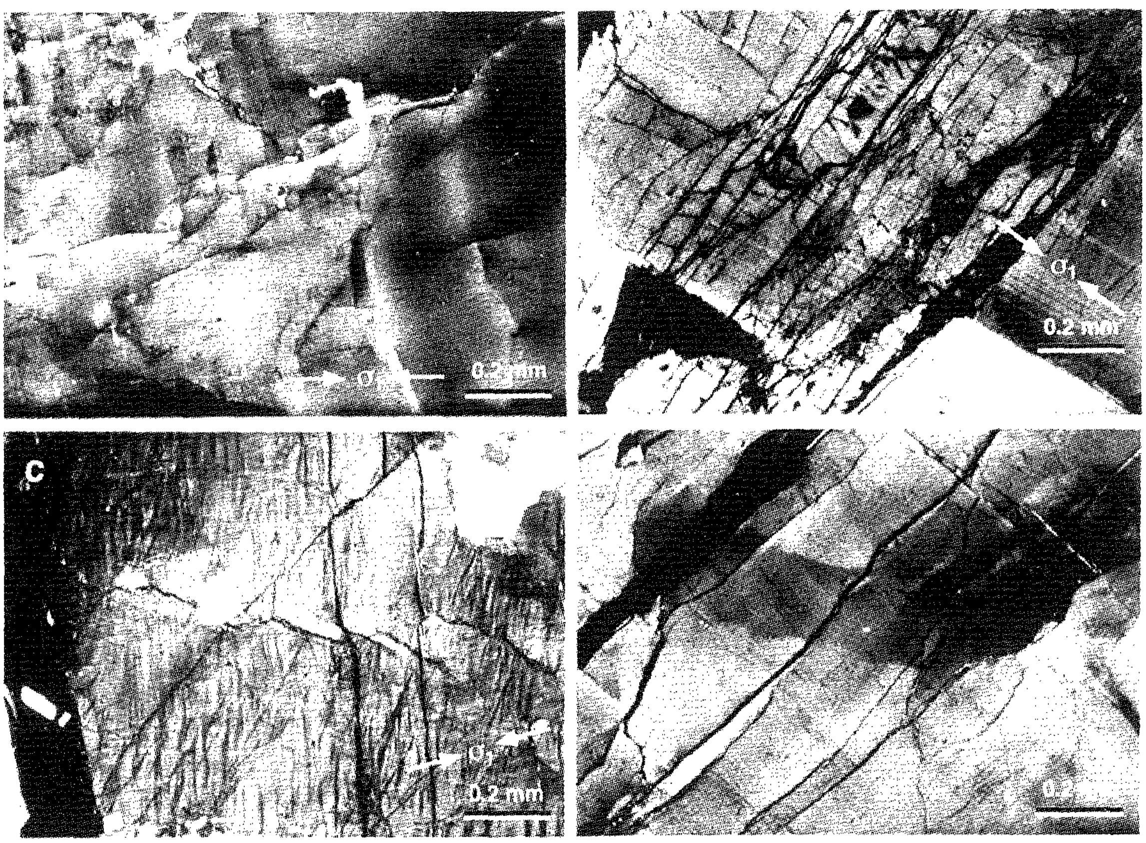

Fig. 5 Some examples of optical micrographs for Man-nari granite in the high-pressure type regime at a confining pressure of 1500 MPa. Crossed nicols. Arrowheads indicate the direction of the compressive stress. (a): Oriented microcracks and inhomogeneous extinction in quartz grain (RMG-60, 198°C); (b): Irregular microcracks and inhomogeneous extinction in plagioclase grain (RMG-63, 283°C); (c): Deformation lamellae in quartz grain (RMG-70, 537°C); (d): Subgrain in quartz grain (RMG-64, 402°C).

pyrophyllite (e.g., Matsushima et al., 1967) are 850°C, 1000°C and above 550°C, respectively at 1.5 GPa of pressure. Micromechanical studies showed a possible explanation of the unusually low strength in the above temperature interval.

3.2 Micromechanical studies

Micromechanical studies are briefly described here, since they were carried out only optically using thin sections from the specimens recovered after runs of 1500 MPa confining pressure. TEM studies will be described elsewhere.

Some examples of optical microscopy are shown in Fig. 5 and summarized schematically in Fig.6. Brittle faulting represented by localized shear fracture dominates up to 180°C. Intragranular fracture and patchy extinction in quartz grains are obvious above 100°C. Cleavage microcracks at around 200°C and several crack groups between 250° and 300°C are obvious in plagioclase grains. In addition to these brittle deformation factors, patchy extinction associated with oriented cracks is observed in quartz grains between 200° and 350°C, which may indicate that crystal plasticity in quartz starts at around 200°C. Inhomogeneous extinction with irregular microcracks in feldspar grains becomes obvious above 300°C, and feldspar grains exhibit more ductility at the higher temperatures with undulose extinction and more regular crack-related inhomogeneous extinction. Deformation lamellae in quartz grains become obvious with random orientation at 350°C, and are highly developed with orientation perpendicular to the compression stress direction at the higher temperatures. Subgrain formation in quartz grains appears above around 400°C.

The presence of fabrics such as patchy extinction, undulose extinction, deformation lamellae and subgrain formation are evidence for crystal plasticity governed by the dislocation motion (e.g., Tullis and Yund, 1987; Hirth and Tullis, 1992; Passchier and Trouw, 1996). The rock exhibited macroscopically brittle fracture behavior accompanied by occurrence

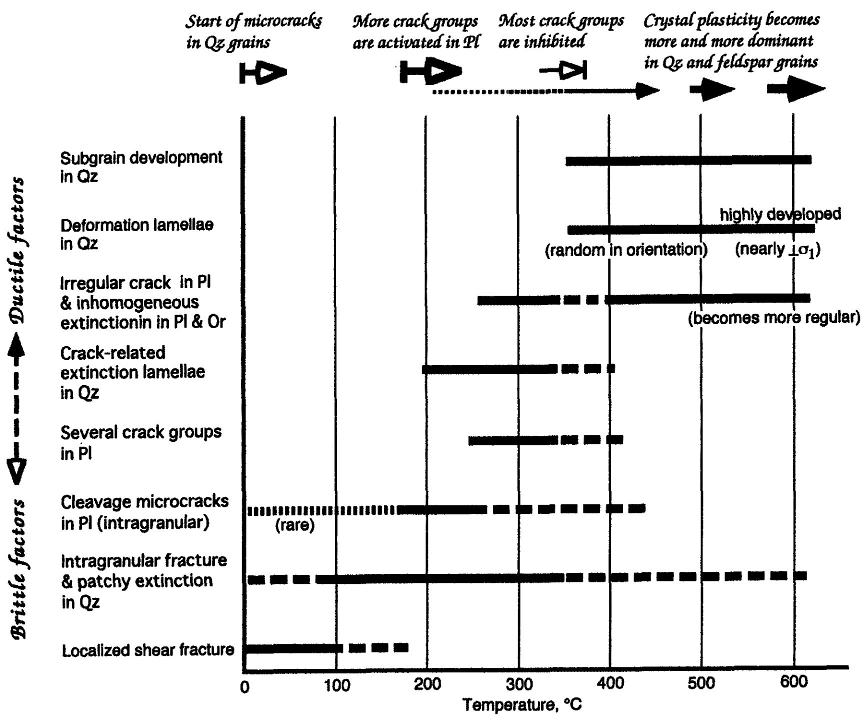

Fig. 6 Schematic summary of optical microscopy for Man-nari granite in the high-pressure type regime at a confining pressure of 1500 MPa as a function of temperature.

of AE events and stress drop up to 530°C as shown in Fig. 3. However, it deformed microscopically with several factors for crystal plasticity as temperature increased. A possible explanation for the unusual behavior of strength from the above microscopic observations is as follows: The fracture strength in the brittle regime decreases with increasing temperature due to the activation of crack formation caused by the property of composing minerals, loosening of grain boundary and so on; more crack groups are activated in feldspar grains as well as quartz grains in which crystal plasticity begins to coexist at around 200°C, which may have led to the weakening of the rock; the further hardening effect at around 300°C is possibly because the above low temperature deformation systems, e.g. cracking, are inhibited while crystal plasticity becomes dominant in quartz grains; crystal plasticity becomes increasingly dominant at higher temperature and begins in feldspar grains. Therefore, the temperature interval between 200° and 300°C is characteristic for this granite. Further studies as well as TEM studies are required to confirm such behavior for other, especially fine-grained rock.

4. Implication in the lithosphere strength

If we estimate lithosphere strength using these experimental results based on our previous assumption, that the high-pressure type fracture could be possible in the crust considering the size effect on rock strength, our previous model (Shimada 1993a, b) would be extensively modified. The pressure and temperature dependences of strength for large-size granite would be modified as shown in Fig.7. We do not, at present, have any idea how the strength decreases with increase of confining pressure for large-size granite specimens at 250°C, which is shown by a broken line with a question mark. Using this strength profile, the strength envelope in a granitic crust would be speculatively modified as shown in Fig.8, in which the heavy broken curve indicates the estimation proposed here. The adopted temperature profile (Goetze and Evans, 1979) is also shown. The conspicuous features of the strength envelope are the decreasing strength with increase of depth following the frictional regime or the constant strength region in the high-pressure type regime, the presence of a minimum value of strength, and the presence of a maximum value of strength followed by the brittle-ductile transition, resulting in the presence of a low-strength zone between 8 and 12 km depth. The boundary between brittle and ductile regimes is obscure and we do not have any idea how to estimate quantitatively the decrement and the minimum value of strength at present. Nevertheless, such a strength envelope has quite interesting implications for the brittle-ductile hypothesis for seismogenic zones.

The seismological evidence that earthquakes in the intraplate crust occur in such a manner that the activity increases with increase of depth and is cut off at a depth of 5 – 25 km depending on the thermal structure, and that large earthquakes occur commonly near the cutoff depth, has been explained well using the brittle-ductile model of crustal strength (e.g., Meissner and Strehlau, 1982; Sibson, 1984; Ito, 1990). This hypothesis has been extensively developed together with the studies on the thermal structure and reflective seismology in the crust (e.g., Ito, 1983,1999). This hypothesis is on the basis of the similarity between the previous simple strength envelope and the frequency-depth distribution of earthquakes (e.g., Meissner and Strehlau, 1982). This implies that the possibility of earthquake occurrence is higher at the depths where the strength of the crust is higher, or that the stronger part of the crust has the ability to generate more earthquakes.

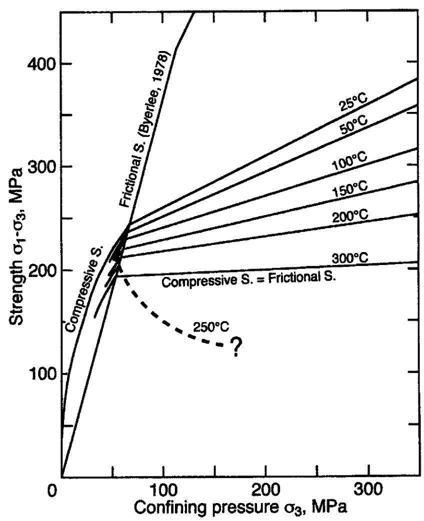

Fig. 7 Estimated pressure and temperature dependence of strength for large-size granite. Modified from Shimada (1993a).

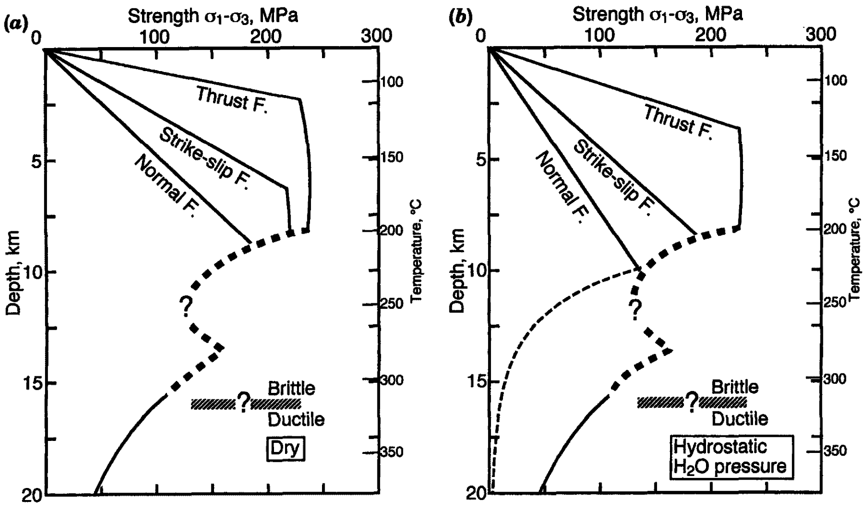

Fig. 8 Estimated strengths in a granitic crust as a function of depth for thrust, strike-slip and normal faulting. (a) Dry crust, (b) wet (hydrostatic pore-water pressure) crust. Calculations are based on Byerlee's (1978) friction law and the strength for the high-pressure type fracture in the brittle regime, and on the steady-state creep laws (using a strain rate of 10^{-14} s^{-1} and the creep parameters of dry granite (Kirby and Kronenberg, 1987). The creep strength for wet granite is also shown as a broken curve. The geotherm used is T (K) = 350 + 15z (km) (Goetze and Evans, 1979). The heavy broken curve is the estimation proposed here (original model: Shimada, 1993a, b).

Our model of the strength envelope with a minimum as shown in Fig. 8 could provide an alternative explanation: Earthquakes could occur or nucleate more easily where the strength is low. A similar model for a frictional strength profile with a strength minimum has been proposed assuming near-lithostatic pore pressure in the deeper crust (Streit, 1997). However, a very high pore pressure such as near-lithostatic is regarded as enigmatic, from the hydrofracture constraint (Scholz, 1992, 1996). Our model has a strength minimum even in dry conditions.

Acknowledgements

We are very grateful to I. Saida and A. Nakagawa for their technical supports. This work was supported in part by a Grant-in-Aid for Scientific Research (B) (No. 09440159) from the Ministry of Education, Science, Sports and Culture of Japan.

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要　旨

乾燥花崗岩に対し封圧 1500 MPa下での３軸試験が，細かい温度間隔で 600℃まで，平均ひずみ速度 2×10^{-6} s^{-1} で行われた。実験は，圧縮強度が摩擦強度に等しくなるときに起こる，高圧型破壊領域で行われた。強度は温度の増加とともに減少し，250℃近くでは異常に低下した。微細機構観察から，この強度の異常な低下は，温度の増加につれて，クラック群の卓越からその抑制と結晶塑性の卓越への変化であることが示唆された。この結果は，地殻の地震発生層の脆性－延性仮説に対する新しい解釈を与える：すなわち，地震は強度が低いところでより発生あるいは核形成し易いことを示唆する。

キーワード：高封圧，高温，花崗岩，強度，リソスフェアの強度，脆性－延性仮説