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Cataclastic flow and semi-brittle deformation of anorthosite

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Abstract—A series of experiments on dry Bushveldt anorthosite (An_{75}, 350 μm grain size, 5% impurities) is carried out at 25–700°C, 500–1500 MPa pressures and 10^{-5} s^{-1} strain rate. The strength of the Bushveldt anorthosite remains pressure-sensitive throughout the applied *P–T* range while weakening occurs with increased temperature at a given pressure.

A transition from stick–slip to stable sliding occurs at 200–300°C and pressures of ≥500 MPa. Reduction in strength at 200–300°C, localized cataclastic flow, and lack of microscopic evidence of crystal-plastic deformation raises the possibility that the transition may be coincident with the propagation of a critical number of randomly distributed thermal cracks.

Uniform ductile flow occurs only at temperatures of 600 and 700°C, and 1000–1500 MPa pressures, coincident with the development of mechanical twinning, patchy and banded undulatory extinction and is likely to be due to semi-brittle deformation. Under these conditions, the deformation remains distributed to strains as high as 44%.

INTRODUCTION

THE low-temperature brittle–ductile transition in rocks in which localized fracture gives way to uniform cataclastic flow with increasing pressure is a porous-rock phenomenon (Heard 1960, Edmond & Paterson 1972, Hadizadeh & Rutter 1983, Hirth & Tullis 1989) and is not necessarily associated with the brittle–ductile transition zone (base of the seismogenic zone) in the Earth's crust. The same transition in non-porous rocks depends upon a combination of microfracturing and crystal-plastic deformation often referred to as semi-brittle deformation and requires elevated temperatures as well as pressure (Kirby 1980, Kirby & Kronenberg 1984, Chester 1989, Fredrich *et al.* 1989). The significance of this mixed deformation mechanism has recently been emphasized because it appears to be closely associated with the processes of the brittle–ductile transition in the Earth's crust which pertain to the rheological models for the lithosphere (e.g. Sibson 1984, Hobbs *et al.* 1986, Scholz 1988, Shimamoto 1989). In addition, evidence of mixed brittle and crystal-plastic deformation in quartzo-feldspathic rocks from middle to upper crustal shear zones has underscored the significance of the semi-brittle regime (e.g. Andrews 1984, Simpson 1985, Evans 1988, Hadizadeh *et al.* 1991). Experimental results indicate that the relative strength and mechanical behavior of rocks in the semi-brittle (intermediate) regime is, to a large extent, determined by micromechanical interactions and partition of strain between the brittle and the crystal-plastic components of deformation (Kirby & Kronenberg 1984, Fredrich *et al.* 1989, Shimamoto 1989). The experimental study reported here describes the variations in strength, with an analysis of the macroscopic behavior and the micromechanical details of cataclastic flow and semi-brittle deformation in anorthosite at elevated temperatures.

EXPERIMENTAL PROCEDURE

Bushveldt anorthosite, composed of approximately 95% plagioclase (An_{75}), 5% pyroxene and opaques with a *ca* 350 μm grain size was used as the experimental material. This rock has negligible porosity and contains much less than 1% weathering products. The plagioclase grains are dominantly tabular with abundant albite and pericline twins and sparse, healed microcracks.

Triaxial compression experiments were carried out at 500, 1000 and 1500 MPa pressure, 25–700°C temperature and a constant displacement rate of 10^{-5} s^{-1} on cylindrical samples 6 × 15 mm (5 × 13 mm for 1500 MPa tests) in dimension, in a modified Griggs solid medium machine described by Tullis & Tullis (1986). Sodium chloride sleeves (2 mm wall thickness) were used as the confining medium. The stress–strain curves were corrected for changes in cross-sectional area of the samples during deformation and for the elastic distortion of the loading column. Stepped graphite furnaces (thicker in the center) and Al_2O_3 end pieces were used in experiments at elevated temperature to reduce temperature gradients along the sample length to within 10°C. Samples were air-dried, jacketed in Cu (room temperature), Ag or Pt (200–700°C) and subjected to 5–30% (25–200°C) and 25–45% (300–700°C) axial shortening.

The longitudinal thin sections of the deformed samples were studied using a petrographic microscope.

RESULTS

Fracture and stick–slip

The deformation at room temperature is characterized by sudden fracture followed by stick–slip behavior at all applied pressures with peak stresses that generally increase with increasing strain (Fig. 1a). Sharp, through-going shear fractures with continuous layers or pockets of loose gouge develop in all cases. The density of cleavage cracks in grains adjacent to the main shear fracture increases with increasing pressure but diminish rapidly away from the fracture at all pressures.

An experiment at 1000 MPa pressure was conducted with Pb as the confining medium by replacing the entire mid-section of the sample assembly (Tullis & Tullis 1986) with a hollow cylindrical piece of Pb. The stress–strain curve (curve marked Pb in Fig. 1a) shows that while the fracture stress of the rock remained within the average for room temperature tests with NaCl confining medium, the rock did not harden during the stick–slip deformation. The hardening behavior in samples tested with NaCl medium probably reflects the transmitted rigidity of the pressure vessel wall during post-failure dilation of the specimen. No significant microstructural difference is noted with this change in confining medium.

Deformation at 200–500°C

A mode of failure transition occurs in anorthosite at temperatures of 200–300°C, recognized by the disappearance of stick–slip behavior from the stress–strain curves (Figs. 1b–d). The sample deformation, however, remains localized throughout this temperature range at all applied pressures. The deformation occurs by cataclastic flow in well-defined gouge zones at 300°C and 500 MPa pressure while it proceeds by sliding on a combination of anastomosing bands of gouge and a conjugate system of cleavage cracks at 500°C and 1500 MPa pressure (Fig. 2a–c). Although the transition is associated with a reduction in strength for a given pressure, optical microscopy reveals no definite grain-scale crystal-plastic deformation features.

The described transition in anorthosite differs from the reported brittle–ductile transition in porous rocks (e.g. Schock *et al.* 1973, Hadizadeh & Rutter 1983, Shimada 1986, Hirth & Tullis 1989) in that: (1) it requires elevated temperature as well as pressure; and (2) the deformation results mainly from stable sliding within a gouge-filled fracture zone rather than from distributed cataclastic flow. It is interesting to note that, at this *P–T* range, the mechanism of deformation is entirely cataclastic flow. Thus we have described a transition from fracture to cataclastic flow, but, due to the localized nature of the flow, the transition may not be classified as a brittle–ductile transition (Rutter 1986).

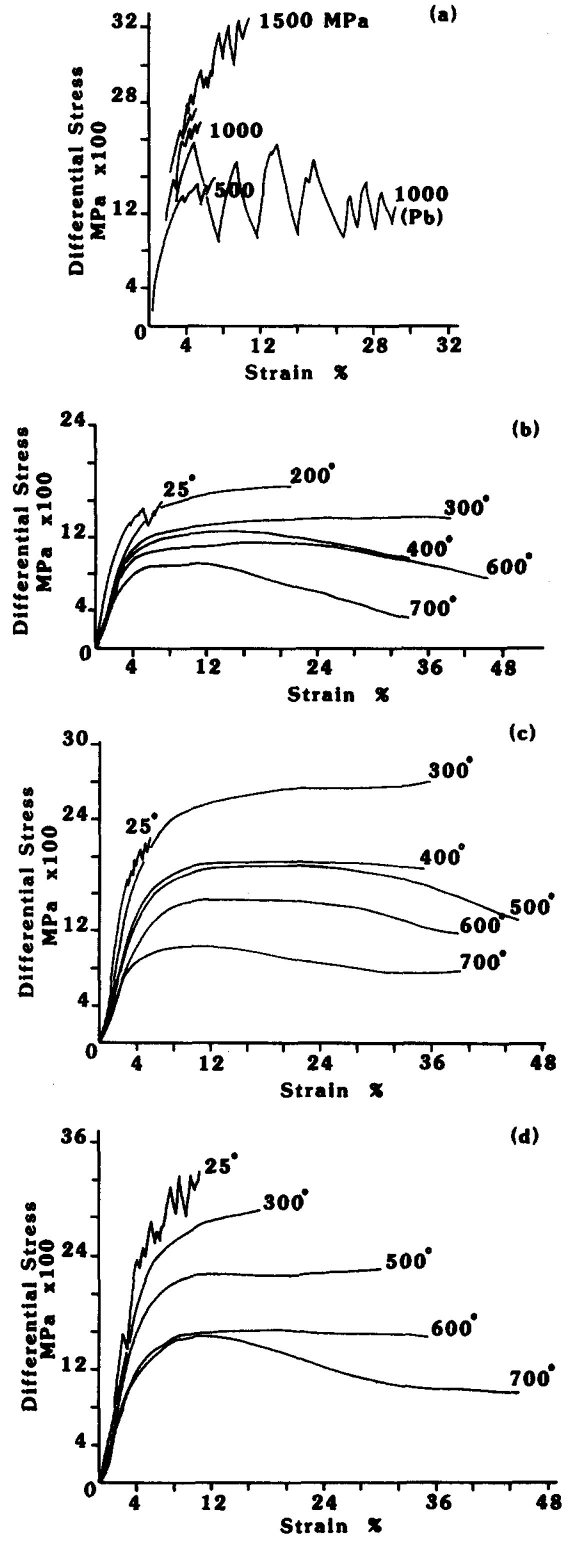

Fig. 1. Stress–strain curves. (a) Deformation at room temperature. Confining pressures are indicated on each curve. The curve marked Pb shows the result of a test with a lead confining medium. (b) Tests at elevated temperatures (values given beside each curve) and 500 MPa pressure. (c) Tests at elevated temperatures and 1000 MPa pressure. (d) Tests at elevated temperatures and 1500 MPa pressure.

High-temperature deformation (600–700°C)

(a) *Localized deformation at low pressure.* At 500 MPa pressure (Figs. 1b–d) deformation is stable and localized in a shear zone (Fig. 2d). Similar mechanical

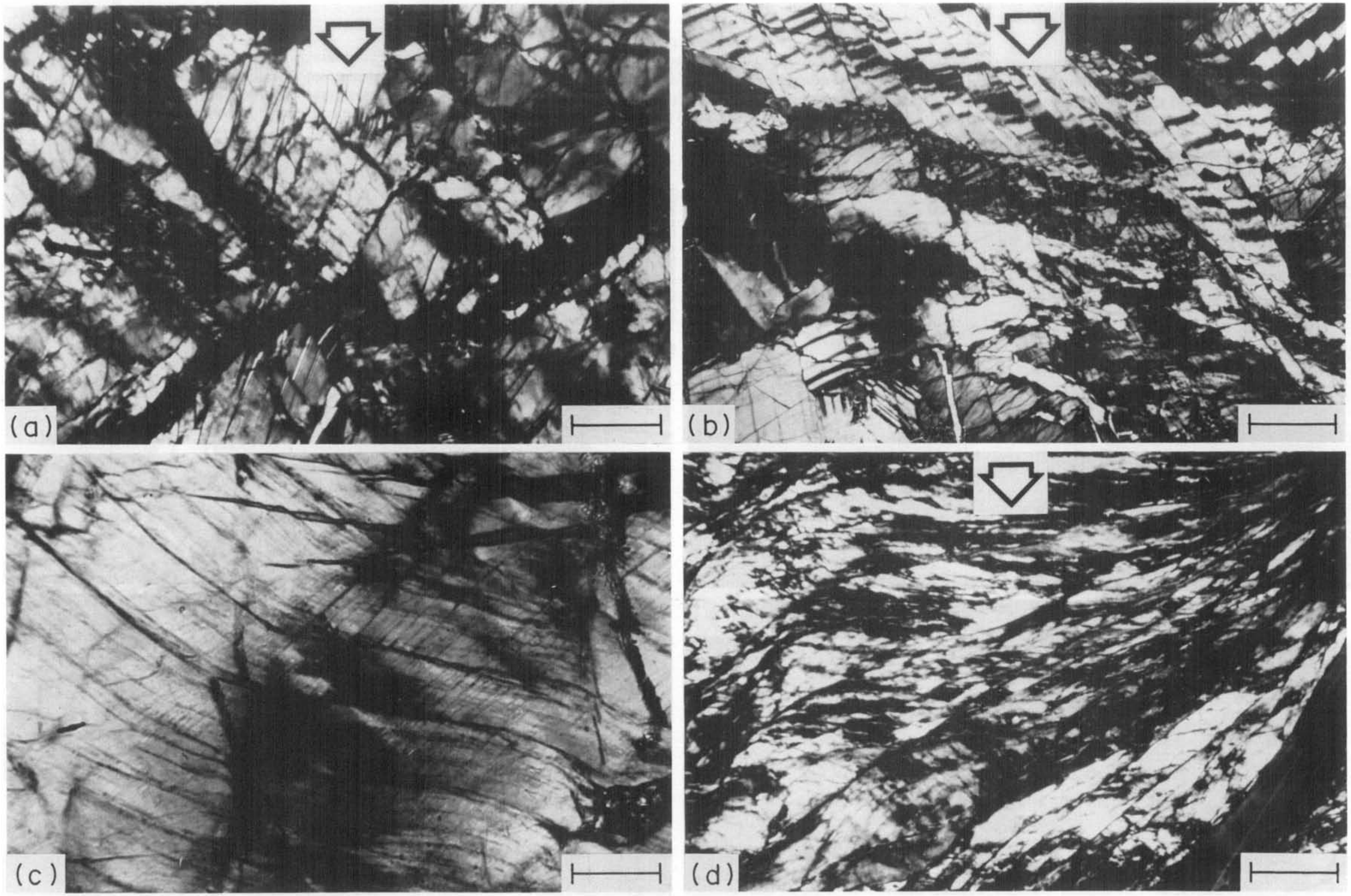

Fig. 2. Optical micrographs of typical deformation features in Bushveldt anorthosite specimens. Large arrows indicate the σ_1 direction. All images photographed in crossed polarized light. (a) Deformation at 200–500°C, 500 MPa pressure. Note well-defined conjugate gouge zones (center of the specimen). Scale bar = 500 μm. (b) Shear zone typical of deformation at 300–500°C, 1000–1500 MPa pressures. Note the role of cleavage cracks and less deformed grains surrounding the zone. Scale bar = 500 μm. (c) Close up view of a grain within the shear zone shown in (b). Broad kink in set of widely-spaced cleavage cracks is produced by step slips in the tightly-spaced conjugate set. Note patchy extinction at the bend. Scale bar = 40 μm. (d) High-temperature (600–700°C), low-pressure (500 MPa) shear zone. Note elongated grains separated along cleavage cracks. The dark band on the side produced during sectioning. Scale bar = 250 μm.

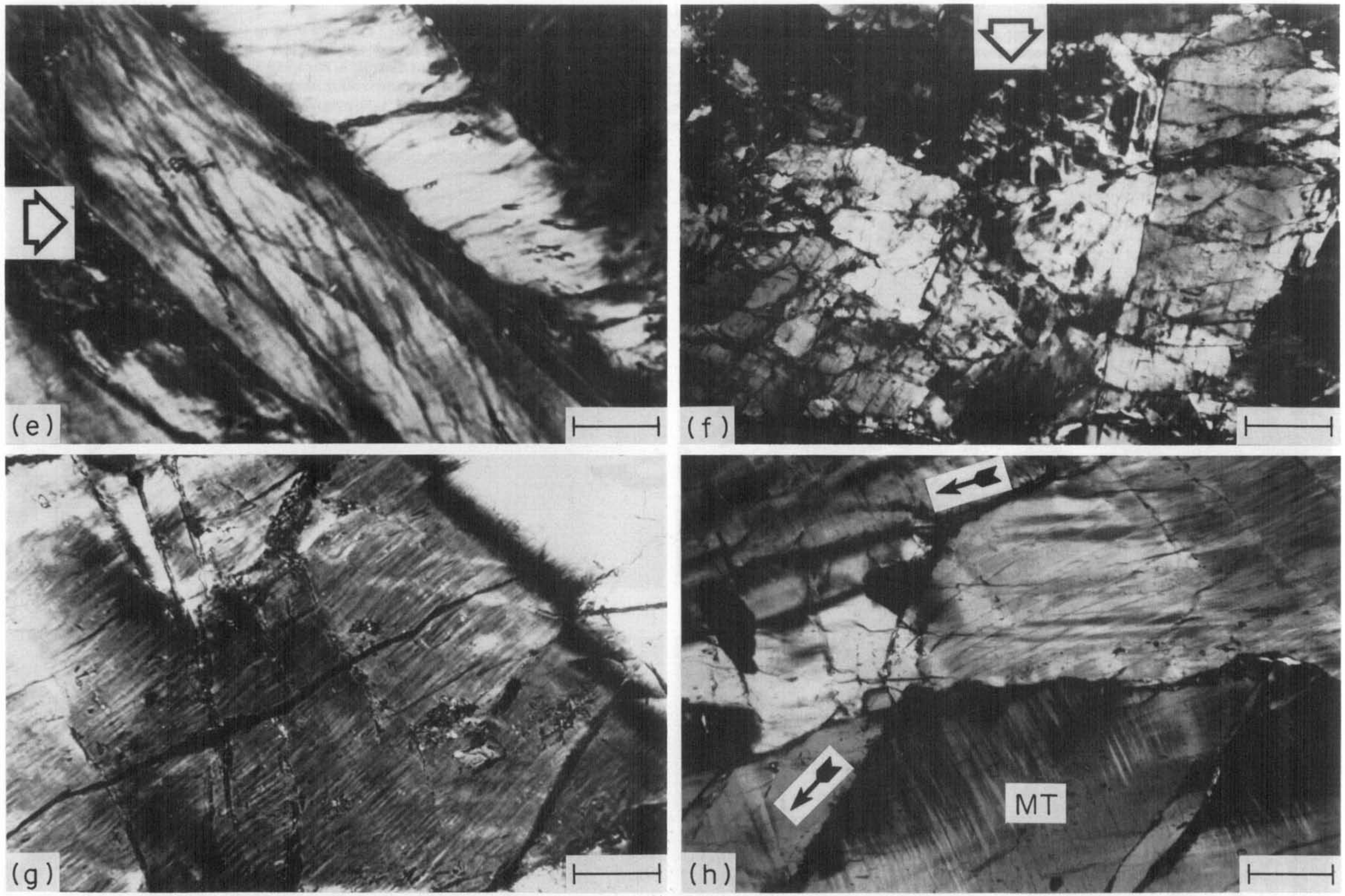

Fig. 2 *continued*. (e) Close up view of a highly deformed fragment within zone shown in (d). Continuous elongation is achieved by slip on cleavage cracks. The dark areas are filled with submicron gouge particles. Scale bar = 40 μm. (f) Uniformly distributed cataclastic flow at 600–700°C, 1000–1500 MPa pressures. Scale bar = 100 μm. (g) Close up view of part of a grain from (f). Note patchy extinction and features resembling 'slip lines' of Marshall & MacLaren (1977). 45% strain. Scale bar = 40 μm. (h) Close up view of grains in microstructure described in (f), showing mechanical twins (MT) and banded extinction (arrows). Scale bar = 40 μm.

behavior and microstructural features were reported by Shelton *et al.* (1981) and Tullis & Yund (1987) in Hale albite and by Tullis & Yund (1977) in Westerly granite deformed at 700°C and 500 MPa pressure. In the shear zone (*ca* 1 mm wide), remarkable stretching of grains is achieved apparently through a 'deck of cards' shearing mechanism in which tightly-spaced cleavage cracks provide the slip surfaces (Fig. 2e). The internal deformation of grains is complemented by some slip at the grain boundaries as indicated by the curvature of cleavage cracks within the grains. Away from the shear zone, grains are relatively undeformed with crack densities and distributions very similar to those seen at 200–300°C. Heavy undulose extinction and some mechanical twins (similar to those shown in Fig. 2h) are developed close to the margins of the shear zone while most of the pre-existing twins within the shear zone are highly bent and appear to be 'erased'.

(b) *Uniform cataclastic flow.* At 1000 and 1500 MPa pressures, localized cataclastic flow gives way to distributed deformation predominated by intense grain-scale microfracturing, often on cleavage planes (Fig. 2f). Under these conditions the deformation remains distributed to strains as high as 44% and the stress–strain curves consistently indicate strain softening behavior at 700°C. Strong patchy (Fig. 2g) and banded (Fig. 2h) undulatory extinction are present, probably due to fine mosaics of intragranular microcracks (Marshall & McLaren 1977). Mechanical albite and pericline twins with characteristic narrow, wedge-shaped lamellae (Vance 1961, Vernon 1965, Borg & Heard 1969) are frequently observed, terminating against grain boundaries or microfractures (Fig. 2h). Permanent mechanical twins were experimentally produced in plagioclase (An_{55}) single crystals at 500°C and 500 MPa pressure by Borg & Handin (1966) while Borg & Heard (1970), experimenting with a wide range of plagioclase compositions, reported that no such twinning occurs below 800°C. Broadly-kinked lamellar features (Fig. 2g), similar to those described by Marshall & McLaren (1977) as slip lines in An_1 plagioclase, were produced at large strains. Electron microscopy of the slip lines by Marshall & McLaren (1977) revealed that they were bundles of microcracks parallel to (010) cleavage planes. Thus, while cataclasis is the predominant mode of strain accommodation, the presence of mechanical twins indicate the onset of semi-brittle mechanisms at this *P–T* range.

DISCUSSION

Transition from stick–slip to stable sliding

The disappearance of sudden stress drops from the stress–strain curves at 200–300°C, is due to stable sliding on gouge-filled fault zones rather than a distributed flow. The cataclastic flow associated with the development of a gouge zone above a certain pressure is found to be one of the factors that stabilizes frictional sliding along experimental fault zones (e.g. Engelder *et al.* 1975, Logan 1978). The form of stress–strain curves in this case reflects mechanical stability, supporting the suggestion (Tse & Rice 1986) that a transition from unstable to stable sliding is not necessarily associated with a change in grain-scale deformation mechanism. The significance of the observation here is that the stable sliding of dry anorthosite faults at $10^{-5}\,s^{-1}$ strain rate, is possible only at an elevated temperature.

The main microstructural difference between room temperature and 200–300°C temperature faults in anorthosite is the presence of well-defined gouge zones in tests at the higher temperatures. How the elevated temperatures augment the development of gouge zones and effect the stable sliding in anorthosite is not clear. The two previous experimental studies of the mechanism of frictional sliding and fault stability of rocks at elevated temperatures are not conclusive as to the micromechanics and nature of the transition in the 200–500°C temperature range (Stesky 1978, Lockner *et al.* 1986, both using granite as the testing material). In the absence of microscopic evidence for crystal-plastic deformation we may consider the possible effects of microcracking due to thermal expansion anisotropy of plagioclase (Bruner 1979) at elevated temperatures. Fredrick & Wong (1986) have shown that heating Westerly granite to temperatures above 100°C produces significant numbers of grain boundary cracks and, at temperatures above 250°C, a sharp increase in the rate of intragranular cracking occurs. If such results can be broadly extrapolated to anorthosite, it is expected that a large number of randomly distributed thermal microcracks distribute deformation and inhibit the coalescence of axial cracks that usually lead to an unstable shear failure in non-porous rocks at high pressures and room temperature (Hirth & Tullis 1989). Consequently, through interaction of shear and tensile cracks in the incipient fault zone, sufficient microcrack porosity will be created to allow cataclastic flow to operate. The proposed mechanism, however, remains speculative since the density, proportion and types of thermal cracks in monomineralic rocks such as anorthosite are likely to be different from Westerly granite. Also data regarding the effects of pressure on thermal cracking in anorthosite is lacking.

Semi-brittle deformation

The data on pressure sensitivity of strength (Fig. 3a), coupled with microstructural observations indicate that in anorthosite, microfracturing, comminution and grain-scale friction play a significant role in accommodating strain up to 700°C. The strength–temperature plot (Fig. 3b) does not reveal any significant abrupt change in mechanical behavior, although as expected, there is a gradual weakening of anorthosite with increased temperature and, the weakening appears to be more pronounced at higher pressures (Fig. 3b). Tullis & Yund (1987) found that Hale albite ($Ab_{98}An_1Or_1$, 150 μm grain size) undergoes a transition from cataclastic flow to a 'transitional regime' at 700°C, and pressures

≥1000 MPa. In anorthosite, the appearance of mechanical twins at 600°C indicates a lower temperature for the onset of semi-brittle deformation although, in agreement with Tullis & Yund (1987), at this temperature the deformation is still localized at pressures below 1000 MPa. The predominance of brittle deformation at 600–700°C and hence the pressure sensitivity of deformation can be explained by the observation of Borg & Heard (1970) that only small amounts of strain can be accommodated by mechanical twinning. It may be concluded that anorthosite undergoes uniform ductile flow equivalent to low-temperature cataclastic flow of porous rocks (i.e. at temperatures below those required for crystal plastic flow of the rock) only through semi-brittle deformation mechanisms at relatively high pressures.

An apparently analogous semi-brittle deformation in marble exhibits compaction and strain hardening with increasing pressure (Paterson 1958, Edmond & Paterson 1972, Fredrich *et al.* 1989). If it is assumed that the strain softening in anorthosite at 600–700°C reflects a volume increase, then lack of the expected strain localization (Edmond & Paterson 1972, Rudnicki & Rice 1975) remains unexplained. The contrasting semi-brittle deformation in marble and anorthosite is likely to be due to differences in micromechanics of brittle–plastic interactions and crystal structures of calcite and feldspar, and associated limitations on the crystal-plasticity of calcite at room temperature.

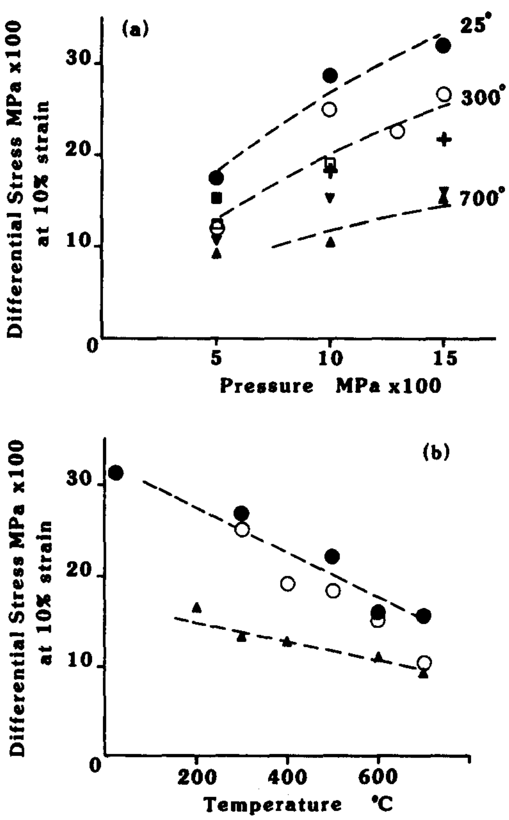

Fig. 3. (a) Plot of yield stress vs confining pressure. Fitted dashed lines roughly indicate the pressure sensitivity of strength over 25–700°C temperature range. Symbols: solid circles, 25°C; closed square, 200°C; open circles, 300°C; open square, 400°C; crosses, 500°C; inverted triangles, 600°C; upright triangles, 700°C. (b) Plot of yield stress vs temperature. Fitted dashed lines indicate rates of weakening with increased temperature at lowest and highest pressures. Symbols: solid circles, 1500 MPa; open circles, 1000 MPa; triangles, 500 MPa pressure.

Implications

In fault zone models with a significant transitional layer (Hobbs *et al.* 1986, Scholz 1988, Shimamoto 1989) the strength and behavior of rocks deforming by semi-brittle mechanisms is of considerable importance. Our results suggest that stable deformation could take place throughout a transitional layer, over a wide range of conditions, predominantly by distributed semi-brittle deformation at greater depths and localized cataclastic flow at lower pressures and temperatures. It needs to be noted that the presence of quartz as a major rheological component, slow natural strain rates and stress corrosion cracking in the presence of water are likely to introduce significant complications if these results are to be extrapolated to nature. For example, lack of substantial thermal cracking due to slow temperature changes, crack healing due to slow strain rates, and availability of fluids in the crust, may inhibit the development of cataclastic flow, as suggested here.

CONCLUSIONS

The main conclusions of this experimental study are as follows.

(1) Bushveldt anorthosite deforms by sudden fracturing at room temperature and exhibits stick–slip behavior at pressures up to 1500 MPa. It undergoes a mode of failure transition at about 300°C, 500 MPa pressure. The transition is characterized by stable slip on narrow, well-defined gouge zones rather than by distributed cataclastic flow. Optical microscopy reveals no definite evidence of crystal-plastic deformation in the 200–500°C temperature range and samples deform by localized cataclastic flow, assisted by cleavage cracking, at all pressures.

(2) Anorthosite undergoes uniform ductile flow equivalent to low-temperture cataclastic flow of porous rocks (i.e. at temperatures below those required for crystal-plasticity of the rock) only through the operation of semi-brittle mechanisms at relatively high pressures.

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