

## Deformation microstructures in experimentally deformed Maryland diabase

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**Abstract**—Experimentally deformed Maryland diabase has been examined using the transmission electron microscope in order to determine the mechanisms of deformation operative over a range of temperatures and pressures and thereby aid in the interpretation of polyphase flow data. Deformation mechanisms within the plagioclase and clinopyroxene of the diabase have been compared to those within monomineralic aggregates of these phases deformed at the same conditions. Both phases deform by microfracturing, mechanical twinning, and intracrystalline slip.

Data for the monomineralic aggregates show that plagioclase is stronger than clinopyroxene at  $<800^{\circ}\text{C}$ , but weaker at  $\geq 800^{\circ}\text{C}$ , for a pressure of 15 kbar and strain rate of  $10^{-6}/\text{sec}$ . Observations of the diabase are consistent with this result: at  $<800^{\circ}\text{C}$ , the plagioclase and pyroxene grains are about equally strained, whereas at  $\geq 800^{\circ}\text{C}$ , almost all of the sample strain is accommodated by the plagioclase, the more continuous phase.

### INTRODUCTION

MANY MECHANICAL models of tectonic processes within the oceanic lithosphere, such as extensional deformation in areas of rifting, have been based solely upon postulated flow properties of the asthenosphere below. The behaviour of the lithospheric plate, however, is an important consideration to modelling, as Tapponnier & Francheteau (1978) have shown for slowly accreting plate boundaries. Rheological constraints are therefore necessary for materials within both the asthenosphere and the lithosphere.

While experimental flow data for olivine, the dominant phase in the asthenosphere, are quite extensive (review by Goetze 1978), deformation studies of basaltic and gabbroic rocks have been limited, in part due to complications related to the deformation of polyphase aggregates. Exploratory studies (Griggs *et al.* 1960, Goetze & Brace 1972) have shown that the strengths of basalt, diabase, and gabbro are strongly dependent upon temperature from 25 to  $1000^{\circ}\text{C}$  at pressures of 5–6 kb as expected. More recently, Caristan & Goetze (1978) investigated the mechanical behaviour of Maryland diabase as a function of strain rate at a temperature of  $990^{\circ}\text{C}$  and pressures of up to 5 kbar. Although they suggest that the data follow a simple power law relation, they found that the stress exponent  $n$  increased from 3 to approximately 13 with increasing strain rate. For the purpose of extrapolation to natural conditions, such a power law is unsuitable since  $n$  is strain rate dependent. The flow law for diabase is more complicated in form since it depends upon the deformation of both plagioclase and pyroxene, whose individual flow laws are probably not equivalent.

In order to determine the flow relation for gabbroic rocks, the flow laws of the individual phases must be determined as well as their model percentages and geometrical arrangement. Such studies are currently under way (Shelton & Kronenberg 1978). Before mean-

ingful flow laws for the individual phases can be determined, however, it is necessary to outline the brittle to ductile transition and to determine the deformation mechanisms operative at various conditions within the ductile regime.

In this study, specimens of Maryland diabase, Adirondack anorthosite, and Sleaford Bay clinopyroxenite, experimentally deformed over a wide range of conditions, have been examined using the optical and transmission electron microscope (TEM), with the following aims:

- (1) To determine the deformation mechanisms operative within the two phases of the diabase.
- (2) To determine the relative contributions of the deformation mechanisms within each phase to the macroscopic strain.
- (3) To compare the microstructures of the two phases within the diabase with those found in clinopyroxenite and anorthosite deformed at the same conditions.

The direct observation of microstructures within deformed diabase, anorthosite, and clinopyroxenite should aid in the analysis of the experimentally determined flow law for gabbroic rocks and provide a basis for comparison with naturally deformed gabbros and basalts.

### EXPERIMENTAL PROCEDURES

#### *Starting materials*

Maryland diabase is composed of  $58 \pm 7\%$  clinopyroxene and  $36 \pm 6\%$  plagioclase, with 3% opaques and 3% chlorite. It has an ophitic texture with an average grain size of  $75 \mu\text{m}$  (Fig. 1). Both the clinopyroxene and the plagioclase show little evidence of previous deformation and contain very low dislocation densities ( $\leq 10^6 \text{ cm}^{-2}$ ). The pyroxene has a bulk composition of  $\text{En}_{46}, \text{Wo}_{38}, \text{Fs}_{16}$  as determined by electron microprobe analysis. Although

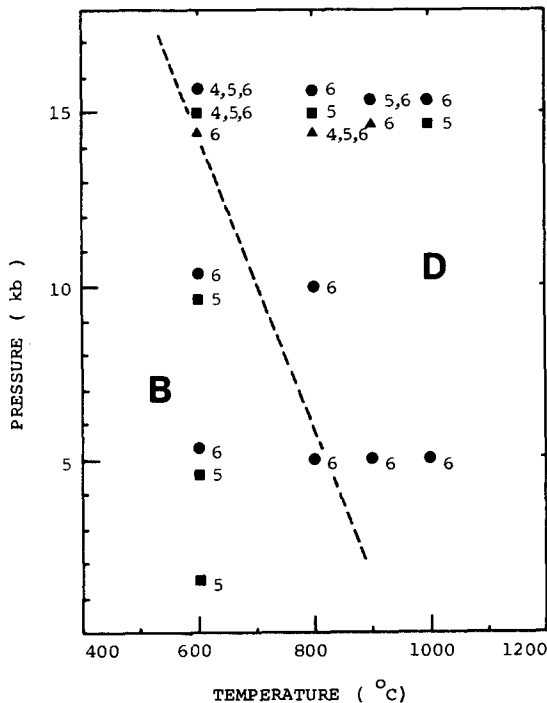


Fig. 3. Pressure-temperature diagram of deformation experiments performed on Maryland diabase (circles), Sleaford Bay clinopyroxenite (Kirby & Kronenberg 1978) (squares), and Adirondack anorthosite (triangles). The strain rates at which experiments were conducted are indicated;  $3 \times 10^{-4}$ /sec (4),  $3 \times 10^{-5}$ /sec (5), and  $3 \times 10^{-6}$ /sec (6). The dashed line marks the position of the brittle to ductile transition at a strain rate of  $10^{-6}$ /sec and the brittle (B) and ductile (D) fields are indicated.

it appears homogeneous on the optical scale, TEM observations accompanied by electron diffraction patterns indicate that it is exsolved to augite and pigeonite (Figs. 2a & b). The plagioclase contains broad albite twins (Figs. 2c & d) and electron microprobe analysis indicates that it has a composition of  $An_{71}, Ab_{27}, Or_{02}$ . Diffraction patterns of untwinned regions (Fig. 2e) include 'e' satellite reflections but contain no 'b' reflections. The diabase plagioclase is therefore of the 'e' structure type (Smith 1974, p. 199); no Boggild or Huttenlocher intergrowths were observed by electron imaging.

Sleaford Bay clinopyroxenite is a pure polycrystalline salite with a composition of  $En_{40}, Wo_{48}, Fs_{11}$  and an average grain size of 0.6 mm. Its bulk composition is similar to that of the diabase pyroxene; however, it contains no exsolution lamellae. It has been described in greater detail by Kirby & Christie (1977).

Adirondack anorthosite is made up predominantly of labradorite ( $An_{56}, Ab_{42}, Or_{02}$ ) and has an average grain size of 0.6 mm. Individual grains contain albite growth twins and show straight extinction between crossed nicols. Unlike the diabase plagioclase, however, plagioclase grains of the anorthosite contain two sets of Boggild lamellae forming a tweed structure on the TEM scale.

#### Deformation experiments

Constant strain rate experiments were performed on Maryland diabase, Adirondack anorthosite (Shelton & Kronenberg 1978) and Sleaford Bay clinopyroxenite

(Kirby & Kronenberg 1978) in a Griggs type apparatus using NaCl and NaF as confining media. Diabase and anorthosite samples were dried on a hot plate at  $150^{\circ}\text{C}$  and clinopyroxenite samples were vacuum dried at  $120\text{--}150^{\circ}\text{C}$ . Specimens were then placed in silver or platinum jackets in order to reduce thermal gradients and to chemically isolate specimens from the confining media.

Maryland diabase experiments were performed at pressures of 5–15 kbar, temperatures of  $600\text{--}1000^{\circ}\text{C}$ , and strain rates of  $10^{-4}\text{--}10^{-6}$ /sec. The experimental conditions for all three materials are shown in Fig. 3.

#### Specimen preparation

Two standard petrographic thin sections were prepared from each sample, one for optical study and one for the TEM. Brass rings 3 mm in diameter were mounted at the sample center, near the thermocouple position. These specimens were then cut from the sections and thinned by ion bombardment. Initial difficulties associated with the different thinning rates of plagioclase and pyroxene were overcome by gluing nickel grids (75 mesh) to the rings before thinning. Specimens were examined in bright-field using a JEM-7 instrument operating at 100 kV.

## RESULTS

The macroscopic brittle to ductile transition for Maryland diabase has been determined as a function of temperature and pressure at a constant strain rate of  $3 \times 10^{-6}$ /sec. In addition, the conditions at which microcracking, mechanical twinning, and dislocation glide and climb are operative have been determined for both plagioclase and clinopyroxene. The relative amounts of strain within the plagioclase and clinopyroxene of the diabase have been evaluated by microstructural comparisons with the respective monomineralic aggregates. The brittle to ductile transition will be treated briefly in the next section, followed by discussions of the intracrystalline slip mechanisms within plagioclase and clinopyroxene at high pressure.

#### Brittle to ductile transition for Maryland diabase

The transition from macroscopic faulting to homogeneous sample shortening is represented schematically for a strain rate of  $3 \times 10^{-6}$ /sec in Fig. 3. For the purpose of discussion, experiments performed over a range of pressures at  $600$  and  $800^{\circ}\text{C}$  are selected.

At  $600^{\circ}\text{C}$ , macroscopic faults develop in diabase deformed at confining pressures up to 10 kbar. At 15 kbar, samples show homogeneous shortening and deform by intracrystalline slip within the pyroxene and penetrative microfracturing of the plagioclase.

At  $800^{\circ}\text{C}$ , diabase specimens deformed at 5 kbar confining pressure contain through-going faults. At  $\geq 10$  kbar, samples are uniformly shortened and show little evidence of microcracking; both pyroxene and

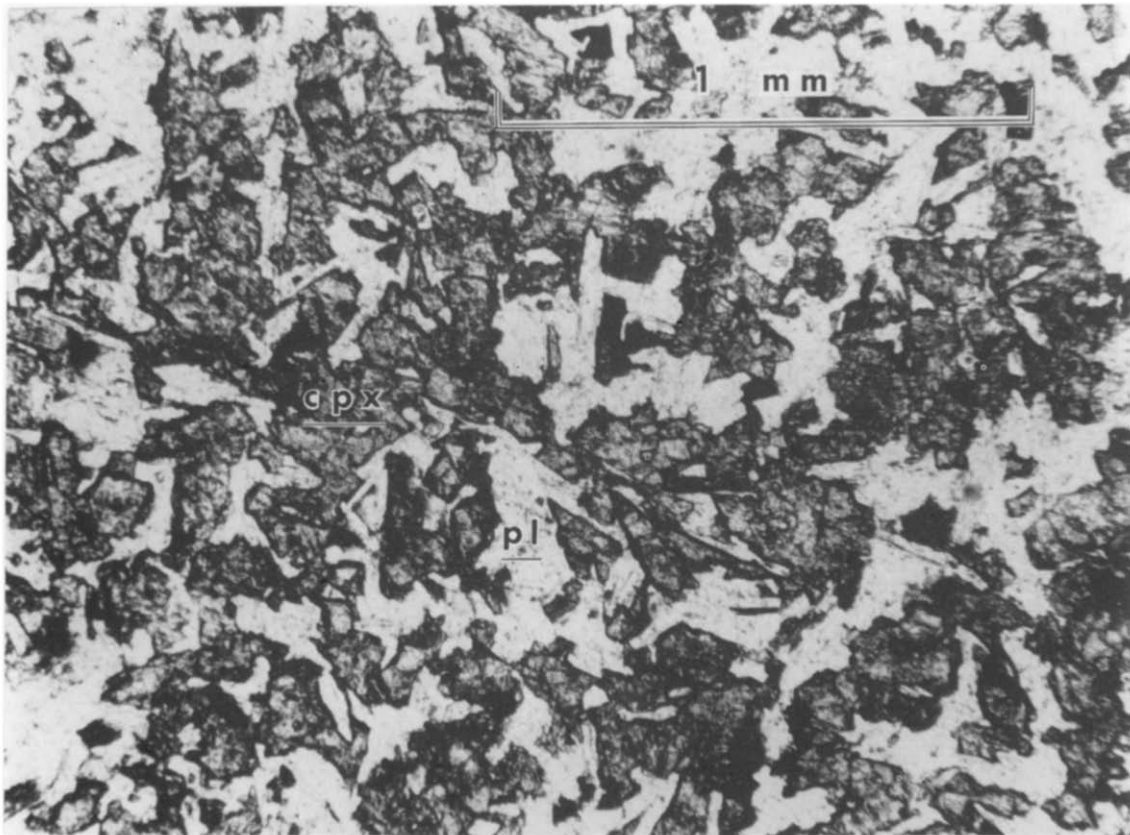


Fig. 1. Optical micrograph of undeformed Maryland diabase. It is made up of  $58 \pm 7\%$  clinopyroxene,  $36 \pm 6\%$  plagioclase, 3% opaques and 3% chlorite. The grain size is approx.  $75 \mu\text{m}$ . Laths of plagioclase 'pl' and relatively equant clinopyroxene 'cpx' grains define an ophitic texture.

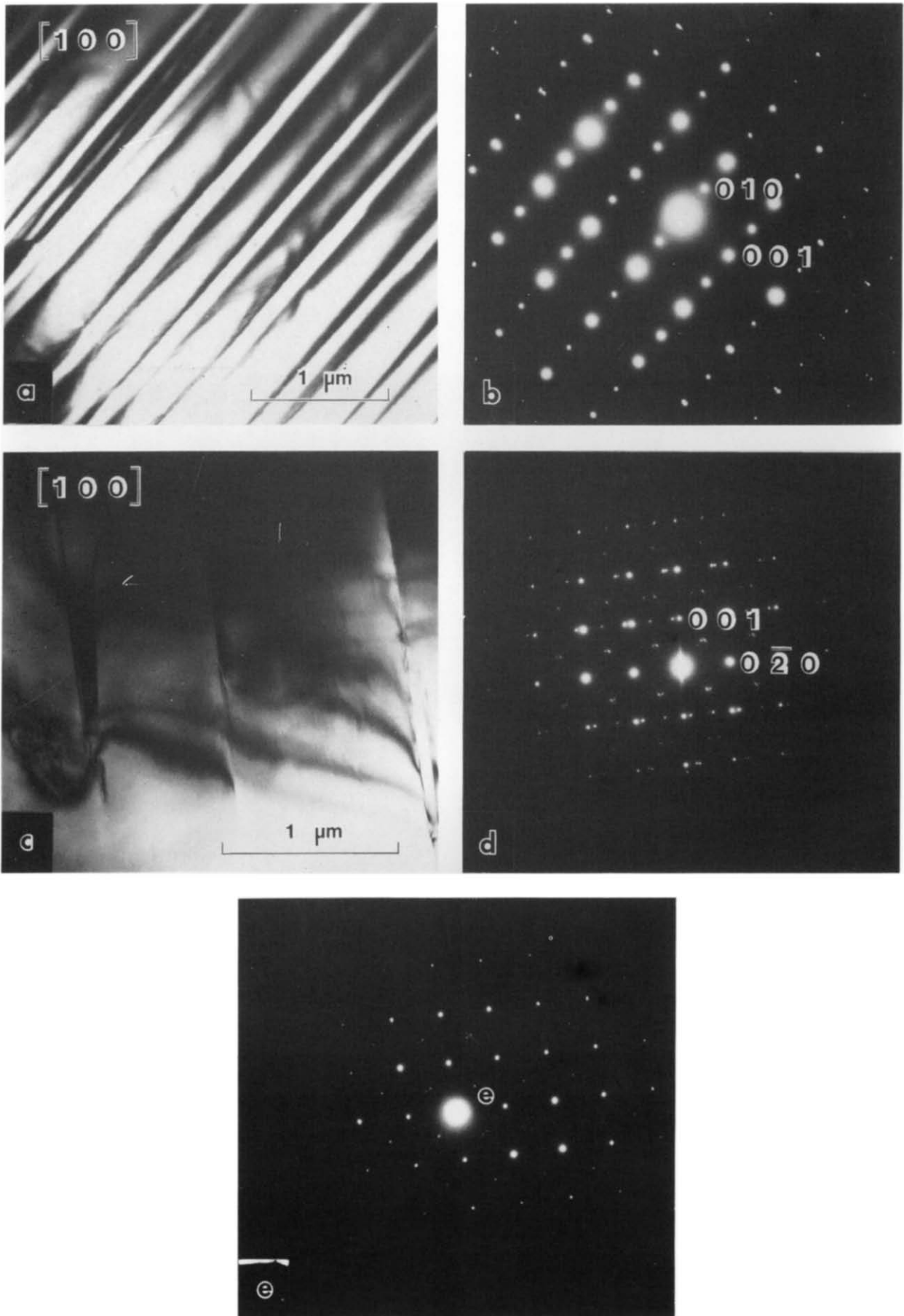


Fig. 2. Electron micrographs of undeformed Maryland diabase. (a) The clinopyroxene is exsolved on (001) to augite and pigeonite as inferred from the bulk composition and using (b) the accompanying diffraction pattern. (c) The plagioclase contains broad albite twins as indicated by the image and by (d) the accompanying diffraction pattern. (e) Diffraction pattern taken from an untwinned region of the plagioclase exhibits 'e' reflections but no 'b' reflections.

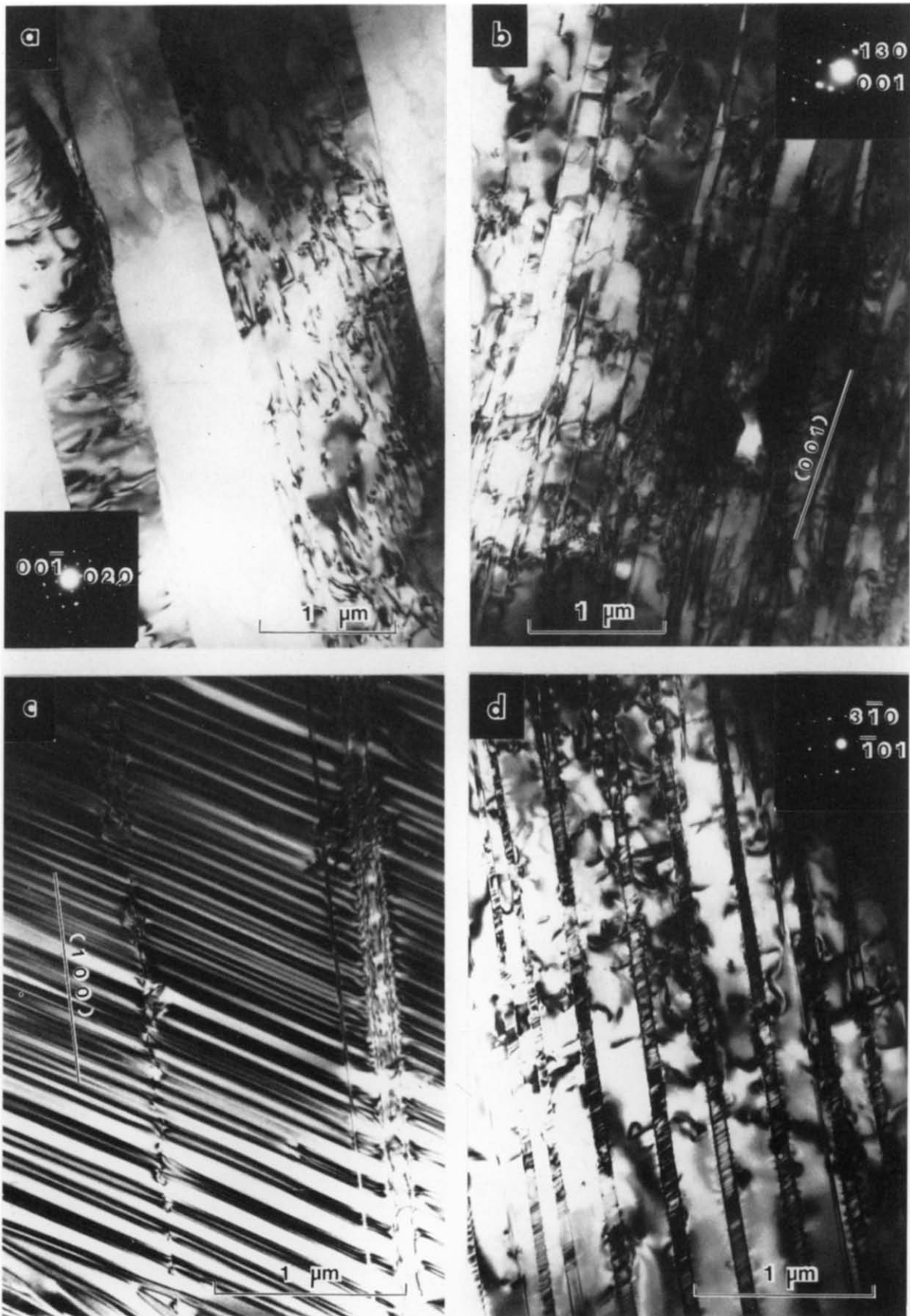


Fig. 4. TEM micrographs of twins in plagioclase (a & b) and clinopyroxene (c & d). (a) Albite twins in plagioclase of the Maryland diabase. (b) Mechanical pericline twins in the Adirondack anorthosite. (c) Mechanical (100) twins in clinopyroxene of the Maryland diabase shear the original (001) exsolution lamellae. (d) The boundaries of (001) mechanical twins (nearly vertical) coincide with those of the original exsolution lamellae of the diabase pyroxene.



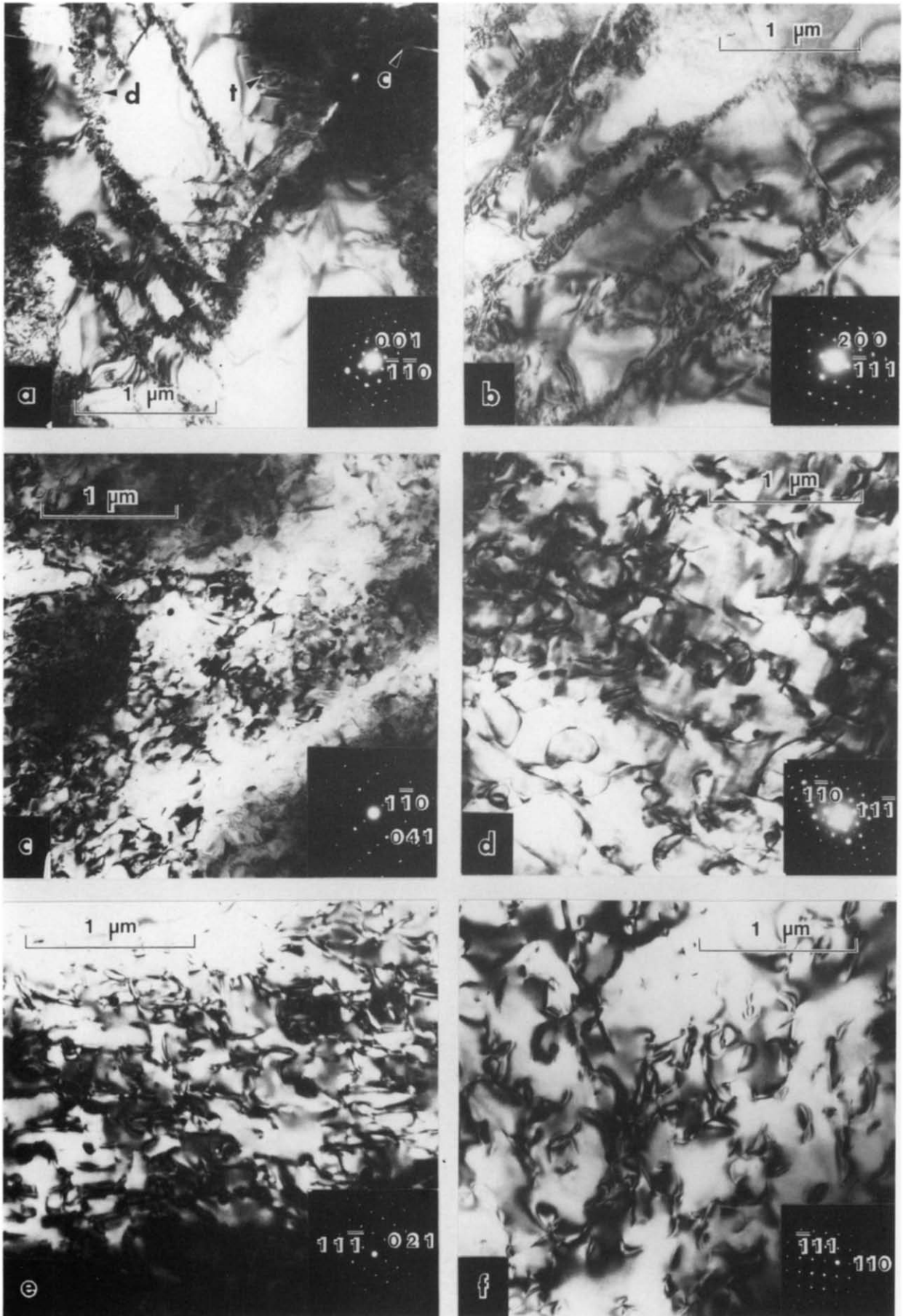


Fig. 5. TEM micrographs of plagioclase grains of Maryland diabase (a, c, e) and Adirondack anorthosite (b, d, f) at temperatures of 600–900°C. (a) Plagioclase in a sample of Maryland diabase deformed at 600°C, 10 kbar, and  $3 \times 10^{-6}$ /sec. The intracrystalline strain is inhomogeneous with dislocations clustered along narrow zones 'd'. Microcracks 'c' are common and some regions contain mechanical twins 't'. (b) Adirondack anorthosite sample deformed at 600°C, 15 kbar, and  $3 \times 10^{-6}$ /sec. Dislocations form highly strained planar zones, similar to those of plagioclase in Maryland diabase. (c) At 800°C, the dislocation density in the plagioclase of Maryland diabase is far more uniform and is extremely high ( $10^{10}$ – $10^{12}$   $\text{cm}^{-2}$ ). (d) The microstructure of Adirondack anorthosite deformed at 800°C is similar to those of the diabase plagioclase. The dislocation density ranges from  $10^9$  to  $10^{10}$   $\text{cm}^{-2}$ . (e) The dislocation density in plagioclase of Maryland diabase specimens deformed at 900°C is considerably lower ( $10^9$   $\text{cm}^{-2}$ ) and more uniform than at 800°C. (f) Adirondack anorthosite deformed at 900°C, 15 kbar and a strain rate of  $3 \times 10^{-6}$ /sec contains relatively low, homogeneous dislocation densities ( $10^8$   $\text{cm}^{-2}$ ).

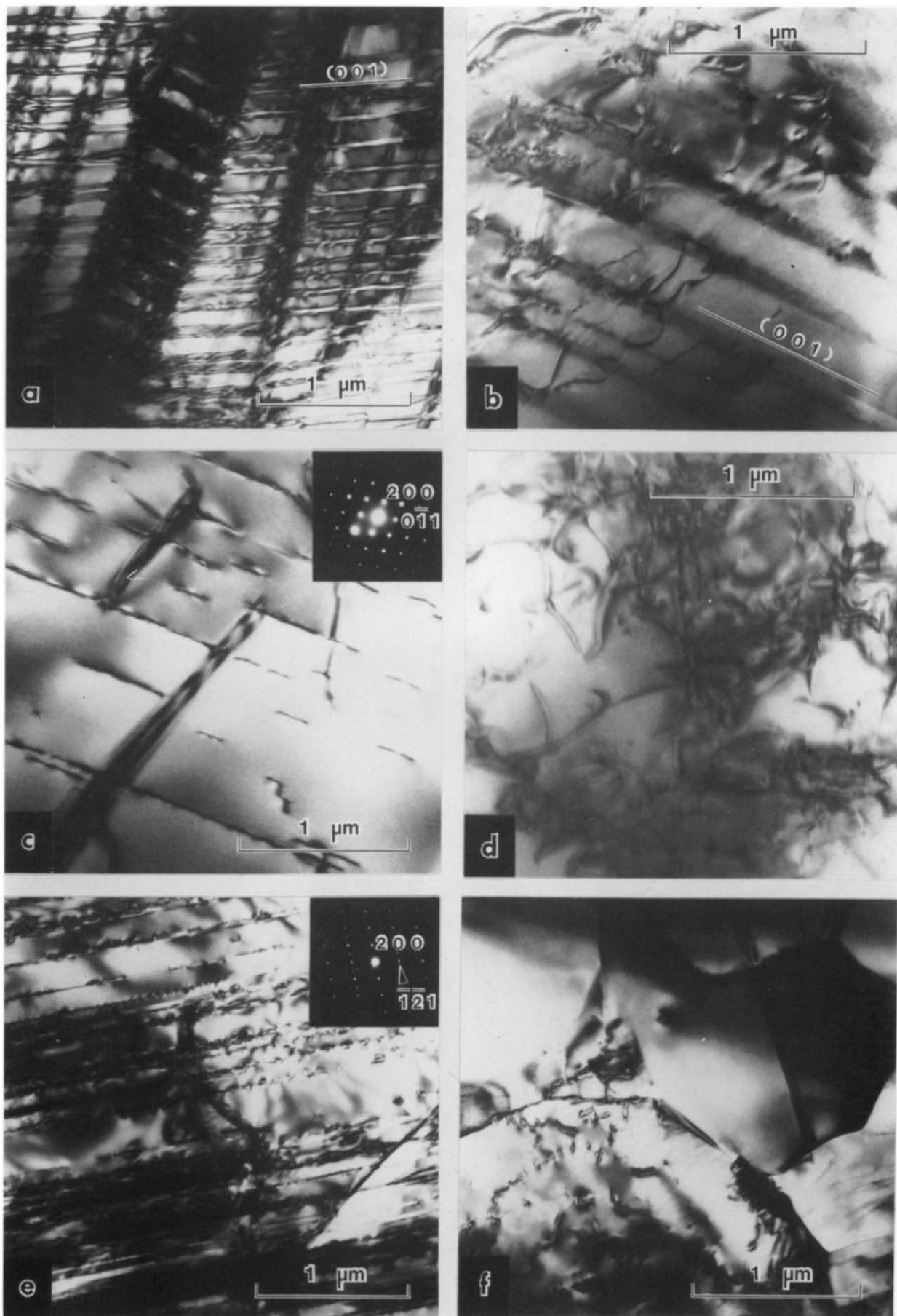


Fig. 6. TEM micrographs of clinopyroxene in samples of Maryland diabase (a, b, c, d) and Sleaford Bay clinopyroxenite (e, f). At  $\leq 800^{\circ}\text{C}$  pyroxene deforms by mechanical twinning and glide on (100). (a) The (100) mechanical twins shear (001) exsolution lamellae in pyroxene grains of Maryland diabase deformed at  $800^{\circ}\text{C}$ . (c) (100) dislocations in clinopyroxene of Maryland diabase deformed at  $600^{\circ}\text{C}$ , 15 kbar, and  $3 \times 10^{-6}/\text{sec}$ . (b) At  $1000^{\circ}\text{C}$  clinopyroxene of the diabase contains few mechanical twins. Instead, pyroxene grains contain dislocations on many slip systems (d). The microstructures in samples of Sleaford Bay clinopyroxenite deformed at the same conditions closely resemble those observed in pyroxene of Maryland diabase. (e) At  $600^{\circ}\text{C}$ , the clinopyroxenite contains (100) mechanical twins and (100) dislocations. (f) At  $1000^{\circ}\text{C}$  however, mechanical twinning is replaced by multiple slip. Unlike the pyroxene within the diabase, pyroxenite specimens contain recrystallized grains.

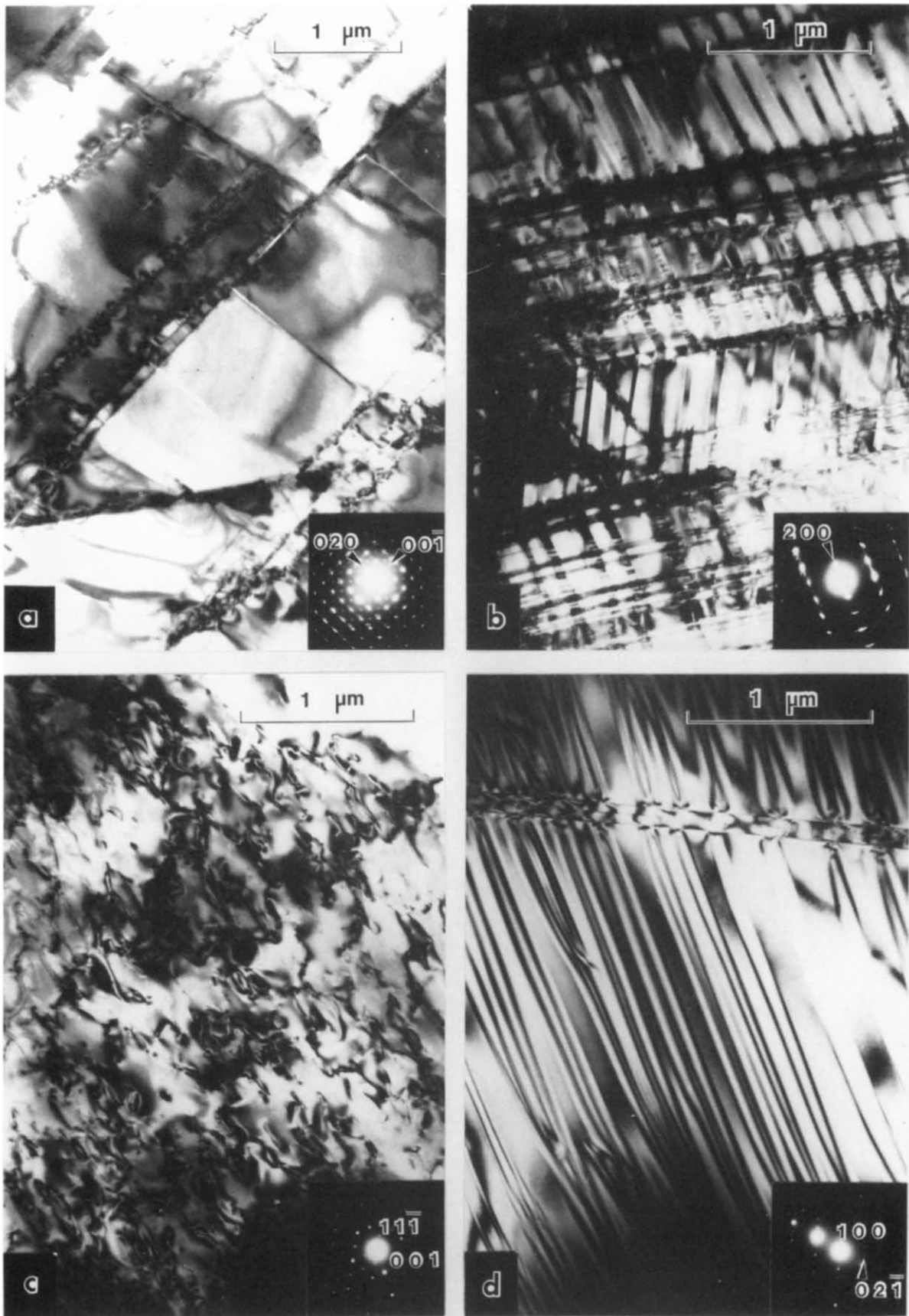


Fig. 7. TEM micrographs of plagioclase and pyroxene in Maryland diabase specimens deformed at 600°C (a, b) and 900°C (c, d). (a) At 600°C and 15 kbar, plagioclase contains microcracks and narrow zones of dislocations whereas (b) clinopyroxene contains few microcracks and abundant evidence for intracrystalline slip. (001) exsolution lamellae of the pyroxene are sheared by (100) mechanical twins (nearly horizontal). At 900°C however, the plagioclase deforms more than clinopyroxene. (c) The dislocation density of the plagioclase at 900°C is approx.  $10^9$  cm<sup>-2</sup> while (d) the clinopyroxene contains few twins and dislocation densities of  $10^7$ – $10^8$  cm<sup>-2</sup>.



plagioclase contain higher dislocation densities.

In general, it appears that the transition from microcracking to intracrystalline slip and twinning for plagioclase is primarily a function of temperature whereas this transition for clinopyroxene depends more strongly on pressure. At temperatures of  $\leq 600^\circ\text{C}$ , plagioclase deforms by microcracking over the entire pressure range tested. This is consistent with the results of Tullis & Yund (1977) for plagioclase feldspar in Westerly granite. In contrast, mechanical twinning and dislocation glide in clinopyroxene at high pressures appear to be temperature insensitive (Kirby & Kronenberg 1978) whereas the role of microfracturing becomes increasingly important at pressures of 10 kbar and below.

#### Plagioclase microstructures

Microfracturing in plagioclase of the diabase and the anorthosite is important both at low pressures ( $\leq 5$  kbar) for temperatures of  $600\text{--}800^\circ\text{C}$  and over the full range of pressures tested at temperatures  $\leq 600^\circ\text{C}$ . Microcracks form along (010) and (001) cleavage planes as well as planes having irrational indices. It is difficult to evaluate precisely the contribution of microcracking to the macroscopic strain since the unloading and quenching procedures may produce additional microcracks. However, a qualitative estimate may be made for samples deformed to approx. 20% strain in which microcracks are pervasive and dislocation densities are low ( $10^7\text{--}10^8\text{ cm}^{-2}$ ). This may be done by deducting the average microcrack density observed in high temperature samples deformed well within the ductile regime; here the microcracks are presumed to be due to unloading.

Mechanical twinning occurs over the full range of temperatures from 600 to  $1000^\circ\text{C}$ . Both albite and periclinal mechanical twins (Figs. 4a & b) appear to be more common within high temperature samples ( $T > 800^\circ\text{C}$ ), and for a given temperature are more abundant within the anorthosite. Since the starting materials contain albite growth twins, it is not always clear whether observed (010) twins are mechanical in origin. However, twins oriented approx.  $5^\circ$  from (001) are clearly the result of mechanical shear since no original periclinal twins were observed in either the diabase or the anorthosite.

Since the early experiments by Mügge & Heide (1931), much interest has been generated regarding the nature of mechanical twins and their relationship to the structural state of plagioclase. It has been shown that some mechanical twins in plagioclase are elastic (Starkey & Brown 1964; Marshall & McLaren 1977a). Thus the crystal may untwin when the load is removed, unless the degree of Si/Al ordering has been changed (Laves 1952; Starkey 1963; Borg & Heard 1969). Yund & Tullis (1980) have shown that the Al/Si disordering rates in albite are rapid in samples deformed at 800 to  $900^\circ\text{C}$  at 15 kbar, but slower at  $700^\circ\text{C}$  and immeasurably small at  $600^\circ\text{C}$ . Diffraction patterns of plagioclase grains in Maryland diabase contain 'e' reflections for specimens deformed at  $600^\circ\text{C}$ , but not at  $800\text{--}1000^\circ\text{C}$ . Higher disordering rates at

$\geq 800^\circ\text{C}$  may therefore explain the greater numbers of plagioclase twins observed in high temperature samples. In general, the observed twins in the plagioclase of Maryland diabase and Adirondack anorthosite may represent a fraction of the original, stressed twin population preserved by residual stresses within the samples or by disordering processes.

Dislocation glide occurs on many slip systems within the plagioclase of Maryland diabase at temperatures of  $600\text{--}1000^\circ\text{C}$  (Table 1). At  $600^\circ\text{C}$ , the strain within plagioclase grains is inhomogeneous and dislocations are clustered along narrow planar zones (Fig. 5a). These walls of tangled dislocations are often intimately associated with microcracks and are potentially related to the development of grain scale fractures. At  $800^\circ\text{C}$  (Fig. 5c), the dislocation density is extremely high ( $10^{10}\text{--}10^{12}\text{ cm}^{-2}$ ) and far more uniform than at lower temperatures. Tangled dislocations of many slip systems form a complex cellular structure in which individual dislocations are difficult to discern. At  $900^\circ\text{C}$  (Fig. 5e), the dislocation density is considerably lower ( $10^9\text{ cm}^{-2}$ ) due to higher recovery rates. Dislocation substructures similar to those within Maryland diabase specimens deformed at  $800^\circ\text{C}$  have been observed by Marshall & McLaren (1977b) within bytownite deformed experimentally at the same temperatures. Marshall & McLaren (1977c) have analyzed slip plane faults in these samples and deduced possible Burgers vectors.

The dislocation microstructures in Adirondack anorthosite closely resemble those of the diabase plagioclase deformed at the same conditions. At  $600^\circ\text{C}$  (Fig. 5b) the anorthosite contains moderate to high dislocation densities. The strain is inhomogeneous with dislocations concentrated along narrow zones, just as within Maryland diabase. At  $800^\circ\text{C}$  (Fig. 5d) dislocations are more regularly spaced and the strain is far more homogeneous. At  $900^\circ\text{C}$ , the dislocation density is generally lower and more homogeneous (Fig. 5f). For temperatures  $\geq 800^\circ\text{C}$ , dislocation densities within the anorthosite tend to be lower than in the plagioclase grains of the diabase samples deformed to the same sample strain.

Dynamic recrystallization occurs to a limited extent within the plagioclase of Maryland diabase specimens deformed to 18% or greater strain at temperatures of  $800\text{--}1000^\circ\text{C}$ . Small, strain-free grains,  $0.1\text{--}0.4\text{ }\mu\text{m}$  in diameter, are found within the regions of highest dislocation density ( $10^{10}\text{--}10^{12}\text{ cm}^{-2}$ ). Their form and occurrence are nearly identical to those of recrystallized grains within an experimentally deformed peristerite (Marshall *et al.* 1976). Adirondack anorthosite samples deformed to 17% strain at  $900^\circ\text{C}$  contain no recrystallized grains, due to the characteristically lower dislocation densities.

#### Clinopyroxene microstructures

Microfracturing in pyroxene of both Maryland diabase and Sleaford Bay clinopyroxenite occurs along (110), (001) and other irrational planes. The experimental procedure only allows qualitative conclusions about the

Table 1. Microstructures outlined for Maryland diabase, Adirondack anorthosite, and Sleaford Bay clinopyroxenite specimens deformed at a constant strain rate of  $3 \times 10^{-6}$ /sec and a confining pressure of 15 kbar.

T, °C	ADIRONDACK ANORTHOSSITE	MARYLAND DIABASE		SLEAFORD BAY CLINOPYROXENITE
		Plagioclase	Clinopyroxene	
600	Disloc. density mod. to high, inhomog. Disloc. in narrow zones. Cells. Microcracking. Few twins.	Disloc. density mod., inhomog. Disloc. concentrated in narrow zones. Microfractures (010) & (001) & irrational planes. Mechanical twins.	Mechanical twins (100) & (001). Slip (100) [001]. Few microcracks.	Mechanical twins (100) & (001). Slip (100) [001].
700				
800	Disloc. density high ( $10^9$ - $10^{10}$ cm <sup>-2</sup> ), homog. Twins (010) & (001).	Disloc. density very high ( $10^{10}$ - $10^{12}$ cm <sup>-2</sup> ) homogeneous. Cells. Twins (010) & (001). ReXl. grains rare.	Few twins (100) & (001). Disloc. density low ( $10^7$ - $10^8$ cm <sup>-2</sup> ).	Some mechanical twins (100). Moderate to high disloc. density ( $10^8$ - $10^9$ cm <sup>-2</sup> ).
900	Disloc. density mod. ( $10^8$ cm <sup>-2</sup> ), more homogeneous. Multiple slip. Twins (010) & (001).	Disloc. density $\approx 10^9$ cm <sup>-2</sup> . Multiple slip.	Disloc. density low to mod. Few twins (100) & (001).	
1000		Disloc. density mod. to high ( $10^8$ cm <sup>-2</sup> ). Multiple slip. Small, reXl. grains. Few cells. Few twins.	Disloc. density low to mod. ( $10^7$ - $10^8$ cm <sup>-2</sup> ). Multiple slip.	Multiple slip. Disloc. density $\approx 10^8$ - $10^9$ cm <sup>-2</sup> . Subgrain boundaries ReXl. grains.

Confining pressure 15 kb.  
Strain rate  $3 \times 10^{-6}$ /sec.

contribution of microfracturing to the total sample strain. Nevertheless, this mechanism seems to be more important at low pressures. At 600°C, microcracking occurs extensively at pressures of 5 kbar and continues to be important up to 10 kbar. At 15 kbar, few microcracks are observed at temperatures of 600–1000°C.

Mechanical twinning of clinopyroxene in Maryland diabase occurs on (100) and less commonly on (001) at temperatures of  $\leq 800^\circ\text{C}$  and a strain rate of  $3 \times 10^{-6}$ /sec. The (100) twins often contain twinning dislocations within their boundaries and shear the original (001) exsolution lamellae found within the diabase pyroxene (Fig. 4c). The boundaries of (001) twins are generally more complex in appearance and tend to coincide with those of the exsolution lamellae (Fig. 4d). The twinning elements and associated shear strains for both (100) and (001) twins have been determined (Raleigh & Talbot 1967) as have the detailed twin boundary structures (Kirby & Christie 1977). Mechanical twins and (100) dislocations are also common in the Sleaford Bay clinopyroxenite at temperatures of  $\leq 800^\circ\text{C}$  (Fig. 6e). Above this temperature, twins are less common and multiple slip appears to be the dominant flow mechanism, for both the pyroxenite and the pyroxene within the diabase.

Dislocation glide on (100) in the diabase pyroxene is common at temperatures of  $\leq 800^\circ\text{C}$  (Fig. 6c). Above this temperature, glide and climb of dislocations occur on many slip systems (Figs. 6b & d). The slip planes and slip vectors in this high temperature regime have not been

rigorously determined using the TEM; however, likely slip systems have been inferred by Kirby & Etheridge (in press) using petrographic techniques.

Microstructures of deformed Sleaford Bay clinopyroxenite (Figs. 6e & f) closely resemble those of the Maryland diabase pyroxene, with mechanical twinning and (100) slip at 600°C and multiple slip at 1000°C. The twin and dislocation densities, however, indicate that at temperatures of  $\geq 800^\circ\text{C}$ , the intracrystalline strain of the clinopyroxenite is higher than that of pyroxene grains in the Maryland diabase, for the same sample shortening.

Dynamic recrystallization occurs within clinopyroxenite samples deformed to 17% strain at temperatures of 900°C and above. In contrast, the pyroxene of Maryland diabase deformed to the same strain contains no recrystallized grains at temperatures of 900 or 1000°C, associated with the lower internal strains.

#### Microstructural comparisons

Optical and TEM observations indicate that the deformation of Maryland diabase at a pressure of 15 kbar and temperatures of  $\geq 800^\circ\text{C}$  is accomplished primarily by dislocation glide and climb within the plagioclase. Dislocation densities within plagioclase range from  $10^8$  to  $10^{12}$  cm<sup>-2</sup>, while the clinopyroxene contains very low dislocation densities ( $10^7$ - $10^9$  cm<sup>-2</sup>) and few mechanical twins (Figs. 7c & d). Microstructural comparisons with anorthosite and clinopyroxenite samples deformed to nearly the same macroscopic strains are consistent with

this result. Dislocation densities in Adirondack anorthosite are lower ( $10^8$ – $10^{10}$   $\text{cm}^{-2}$ ) and the cellular structure not so well developed, compared to plagioclase in the diabase. In addition, clinopyroxenite specimens contain more numerous mechanical twins and higher dislocation densities ( $10^8$ – $10^9$   $\text{cm}^{-2}$ ) than the pyroxene grains in the diabase. It should be added, however, that neither the plagioclase nor the pyroxene of Maryland diabase are chemically and structurally identical to the single phase aggregates. While we believe that these comparisons are applicable as first approximations, further studies may be required to determine the effects that both mineral chemistry and structure (i.e. ordering and exsolution) may have upon the deformation behaviour of plagioclase and clinopyroxene.

At  $\leq 600^\circ\text{C}$ , the deformation of Maryland diabase involves approximately equal strains of the plagioclase and clinopyroxene grains (Figs. 7a & b). At these lower temperatures, the microstructures found within the plagioclase in the diabase and the anorthosite are very similar. In addition, the microstructures of the pyroxene in the diabase and clinopyroxenite are more comparable at these conditions than at higher temperatures.

## DISCUSSION

Analysis of the microstructures of experimentally deformed Maryland diabase and its two monomineralic end members suggests that there is a transition in the relative strengths of plagioclase and clinopyroxene with increasing temperature at high pressure. This inference is confirmed by the strength data for the anorthosite and the clinopyroxenite (Shelton & Kronenberg 1978); anorthosite is stronger than clinopyroxenite at  $600^\circ\text{C}$ , but weaker at  $900^\circ\text{C}$ , for a pressure of 15 kbar and a strain rate of  $3 \times 10^{-6}$ /sec. Thus one can define two modes of deformation for the diabase: a low temperature mode in which the plagioclase is the stronger member and a high temperature mode in which the pyroxene is the stronger member.

### *Polyphase flow relation*

A simple power law of the form commonly used to describe the creep of monomineralic aggregates cannot be applied to polyphase rocks whose constituents have comparable volume fractions but different strengths. Previous attempts to do so have resulted in large variations in the apparent values of the activation energy  $E$  and the stress exponent  $n$  (Goetze & Brace 1972, Caristan & Goetze 1978, AveLallemant 1978). Flow laws for the individual phases must be determined and, combined with textural evidence, used to determine the contribution of each phase to the macroscopic strain.

In general, the macroscopic strain rate ( $\dot{\epsilon}_{\text{sample}}$ ) for a polyphase rock such as the diabase will be a function of the strain rates of the individual phases ( $\dot{\epsilon}_{\text{plag}}$ ,  $\dot{\epsilon}_{\text{cpx}}$ ) and their respective volume fractions  $V_{\text{plag}}$ ,  $V_{\text{cpx}}$ :

$$\dot{\epsilon}_{\text{sample}} = V_{\text{plag}} \dot{\epsilon}_{\text{plag}} + V_{\text{cpx}} \dot{\epsilon}_{\text{cpx}} \quad (1)$$

The strain rates  $\dot{\epsilon}_{\text{plag}}$  and  $\dot{\epsilon}_{\text{cpx}}$  depend upon the respective strengths of plagioclase and clinopyroxene and may be strongly influenced by grain to grain contacts. If the phases are interspersed on a fine scale, as for fine grained engineering alloys, intracrystalline deformation mechanisms may be inhibited, resulting in a high resistance to sample deformation. Polyphase aggregates consisting of relatively coarse grains, however, may deform without any mechanical interactions between the phases (Chen & Argon 1979). In this case the same deformation mechanisms operate in the composite as in single phase specimens, and the polyphase constitutive equation may be derived from relations governing flow of the individual phases.

Since the deformation microstructures in plagioclase and pyroxene of Maryland diabase closely resemble those observed in the anorthosite and pyroxenite, the flow laws determined for the monomineralic specimens may be applied to determine  $\dot{\epsilon}_{\text{plag}}$  and  $\dot{\epsilon}_{\text{cpx}}$  within the diabase. If thermally activated power laws are presumed for both phases individually, then expression (1) can be written:

$$\begin{aligned} \dot{\epsilon}_{\text{sample}} &= \sum_{i=1}^2 V_i \dot{\epsilon}_i \\ &= \sum_{i=1}^2 V_i A_i \sigma_i^n \exp(-E_i/RT), \end{aligned} \quad (2)$$

where the subscript  $i = 1, 2$  refers to the two phases and  $\sigma_i$  is the average deviatoric stress imposed upon the  $i$ th phase. If the phases are distributed inhomogeneously, as for strongly layered rocks, the average deviatoric stresses will in general be unequal ( $\sigma_1 \neq \sigma_2 \neq \sigma_{\text{sample}}$ ) and the geometrical arrangement of the individual phases must be analyzed (Gurland 1958). Such an analysis must include textural evidence to determine which phase if any forms a stress supporting framework. If, on the other hand, the phases are homogeneously dispersed within the rock, the polyphase flow strength can be estimated by equating the deviatoric stresses ( $\sigma_1 = \sigma_2 = \sigma_{\text{sample}}$ ) and applying the experimentally determined values  $A$ ,  $n$ , and  $E$  for each component. Chen & Argon (1979) have derived a steady state flow law for this case, generalized to three-dimensional stress.

### *Contributions to macroscopic strain for the diabase*

The plagioclase of Maryland diabase forms a stress supporting framework surrounding dispersed, equant pyroxene grains (Fig. 1). The average deviatoric stresses imposed upon the two phases are therefore not equivalent. Microstructural observations of samples experimentally deformed at  $3 \times 10^{-6}$ /sec confirm that the strains in the two phases are not equivalent: at temperatures  $\geq 800^\circ\text{C}$  the plagioclase is weaker than the clinopyroxene and deforms more, whereas at lower temperatures plagioclase is stronger than pyroxene and both phases deform approximately equally. This deviation from a simple summation of strains is related to the optically

texture of the rock and may therefore be characteristic of gabbroic rocks in general.

Further deformation experiments and textural analysis are needed in order to determine an accurate flow law for Maryland diabase. Once the values of  $A$ ,  $n$ , and  $E$  for each component are determined, it will be necessary to analyze the texture of the diabase before and after the experiments and to determine the way in which the flow laws for plagioclase and clinopyroxene are combined. The resulting relation must then be tested directly with the mechanical data for the diabase. These studies, which are currently under way, should provide a flow relation which may be applied to naturally deformed gabbros and basalts, assuming the deformation mechanisms in nature are the same.

#### *Naturally deformed plagioclase and clinopyroxene*

Studies of naturally deformed plagioclase and clinopyroxene verify the importance of microfracturing, mechanical twinning, and especially dislocation glide and climb at conditions found within the lithosphere. Microstructures developed within the experimental samples closely resemble those found in deformed metamorphic rocks of upper greenschist to almandine-amphibolite facies.

Optical studies of naturally deformed plagioclase indicate that microcracks on (001) and (010) are important at low pressure (e.g. Debat *et al.* 1978). The importance of microcracking in plagioclase, however, has probably been overestimated due to confusion between cataclastic textures and those resulting from dynamic recrystallization (Bell & Etheridge 1973). Naturally deformed plagioclases often contain thin lamellar twins (Vernon 1965, Capedri 1970, Lawrence 1970, Vernon 1975) of both the albite and pericline laws, as well as kink bands and undulose extinction (Seifert 1965, Sturt 1969, Vernon 1975). TEM studies have shown that dislocation densities within naturally deformed plagioclase commonly approach those produced experimentally within the plagioclase of the diabase (up to  $10^{12} \text{ cm}^{-2}$ ), forming a complex structure (Lorimer *et al.* 1974). Small recrystallized grains, 1–10  $\mu\text{m}$  in diameter, have been observed in the regions of highest strain (White 1975), just as in the experimental samples, and have been recognized in rocks from upper greenschist facies (Marshall & Wilson 1976) to granulite facies (Vernon 1975).

Investigations of microstructures developed in naturally deformed clinopyroxene have been limited. However, both mechanical twinning and glide on (100) have been described for crustal rocks (Raleigh & Talbot 1967, Leung 1970) and twinning, glide, and recrystallization have been reported for clinopyroxene from kimberlite nodules (Borley & Suddaby 1975).

#### SUMMARY

For the experimental strain rate of  $3 \times 10^{-6}$ /sec, there is a reversal in the relative strengths of the two phases in the diabase at roughly 700°C, with plagioclase weaker

than pyroxene at higher temperatures but stronger at lower temperatures. For the much slower geologic strain rates, however, this transition will occur at lower temperatures. Thus at conditions for which gabbroic rocks are ductile, plagioclase will constitute the weaker, interconnected phase, and the deformation behaviour of gabbroic rocks in the lithosphere will most closely depend on the deformation of the constituent plagioclase.

Deformation within the lower temperature regime, where plagioclase is stronger than pyroxene, may occur in shock metamorphism. Although the strain within shock loaded materials is extremely heterogeneous, studies of lunar breccias indicate that mechanical twinning and dislocation glide have occurred extensively within both plagioclase and clinopyroxene (Wenk 1970, Christie *et al.* 1973, Nord *et al.* 1975). This same behaviour is observed in the lower temperature deformation regime of the experimentally deformed diabase.

It appears that the same general deformation mechanisms operative within the experimentally deformed Maryland diabase are important in plagioclase and clinopyroxene naturally deformed within the lithosphere. Thus we infer that a polyphase flow relation which is determined from experimentally deformed pure phases and an analysis of the texture of the polyphase rock may be applicable to basalts and gabbros deformed at geologic strain rates.

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