Sandstone [Fig. 5(b)]. As for the lithographic limestone, the apparent work hardening shown by the σ vs ϵ_1 curves is strongly affected by the $p(d^2\epsilon_{vp}/d\epsilon_1^2)$ term, the $\sigma_w{}^*$ vs ϵ_1 curves showing a sharper bending over and an earlier reaching of peak strength. There is also a more marked decline in strength with increasing strain beyond the peak (this would be even more accentuated if the extra increase in cross-sectional area due to barrelling were allowed for).

Talc [Fig. 6(b)]. In this case, the stress–strain curves are not greatly modified by allowing for volume-change effects, the increased pressure sensitivity shown in the $\sigma_w{}^*$ vs ϵ_1 plot being the most noticeable effect.

Graphite [Fig. 7(b)]. Volume changes are very important in graphite [15]. In particular, the apparent work hardening shown by the σ vs ϵ_1 curves is largely a volume-change effect, very little being shown in the $\sigma_w{}^*$ vs ϵ_1 curves except at small strains.

Sodium chloride [Fig. 8(b)]. Although the small volume changes that occur at each pressure are roughly equal, the $p(d^2\epsilon_{vp}/d\epsilon_1^2)$ term increases with pressure. Thus the $\sigma_w{}^*$ vs ϵ_1 curves reveal a small pressure sensitivity in the stress–strain behaviour which had been obscured in the σ vs ϵ_1 curves by the volume-change effect (for clarity, only the 0·25 and 8 kb curves are shown, the curves for other pressures falling in between).

Mechanisms of deformation

Intragranular deformation by the crystallographic gliding processes, slip and twinning, which accounts for the high ductility under ordinary conditions of such materials as polycrystalline copper or silver chloride, is known to be important in many rocks (see, for example, GRIGGS and HANDIN [20], CARTER *et al.* [21] and RALEIGH [22]). On the other hand, the deformation of rocks such as poorly-cemented sandstones often clearly involves the relative movement of grains, a process well-known in soils and usually referred to as flow of a 'granular material'. Such a process is thought also to play a part in the deformation of compact rocks where the available intragranular plasticity is inadequate, but it will have to be associated with widespread fracturing along grain boundaries and within grains ('microfracturing') so as to make possible the relative movement of the grains or their fragments; the term 'cataclastic flow' is used to refer to this combination of processes. Therefore, following GRIGGS and HANDIN [23], and ruling out change of shape by diffusional mass transport in the present context, we may expect the deformation of any rock to be accomplished by some combination of intragranular plasticity and cataclastic flow. The relative contributions of the two types of mechanism in a particular rock might be determined by detailed microscopic study but this is complicated by the additional changes in the rock during pressure release. Here we attempt to draw some conclusions from the volume change and stress–strain observations made during deformation at high pressure, using the following premises:

1. Volume change. When the initial porosity is zero, intracrystalline plasticity can be assumed to involve no volume change since, except under low-pressure creep conditions, any change from accumulation of crystal defects will be smaller than is measurable here, whereas in cataclastic deformation volume inevitably increases in order to accommodate the relative movement of grains or their fragments. However, when there is initial porosity, some ambiguity enters in the interpretation of volume changes. Dilatancy will usually indicate a component of cataclastic deformation if an effective confining pressure is present, otherwise unnecessary work would be done against the confining pressure (an exception to this may sometimes arise when an inadequacy of slip systems under von Mises's require-

ment for ductility can be compensated by heterogeneity of deformation involving the pores [10]). On the other hand, inelastic decrease in volume during deformation is not, in itself, uniquely diagnostic of either intracrystalline plasticity or cataclastic flow.

2. Pressure sensitivity. On present evidence [19, 24, 25] the resistance to intracrystalline gliding depends only slightly on pressure compared with the substantial pressure dependence in cataclastic flow introduced by the macroscopic friction involved. This difference should help to identify the predominant mechanism of deformation. However, in interpreting the observed stress–strain curves, the work involved in volume change under pressure must first be allowed for as above. The value of $\tan \psi_w^* = d\sigma_w^*/dp$ at some particular strain ϵ_1 can then be taken as an index of the pressure sensitivity of the deformation processes themselves. At the extremes, pure intracrystalline plasticity can be expected to give a $\tan \psi_w^*$ of less than $0 \cdot 1$, commonly of the order of $0 \cdot 01$, while purely cataclastic deformation will give a $\tan \psi_w^*$ of the order of 1 or more for materials of average frictional properties ($\tan \psi = 1$ corresponds to $\tan \phi = 0 \cdot 35$).

The *sodium chloride* evidently deforms entirely by intracrystalline plasticity in view of the low-pressure sensitivity of its stress–strain curve ($\tan \psi_w^* = 0 \cdot 02$) and the lack of dilatancy; the small compaction results from elimination of porosity without involving significant cataclasis. Presumably slip on cube or other non-(110) planes is involved since the normally-active (110) planes comprise only two independent slip planes, far short of the von Mises requirement of five (cf. the case of MgO [25]).

The behaviour of *Carrara marble* also lends itself to fairly clear interpretation because of the low initial porosity. The dilatancy and the substantial pressure dependence in compression tests at all pressures up to about 4 kb indicate that cataclastic flow is an important part of the deformation mechanism and that it has a predominating influence in determining the character of the deformation up to 2 kb ($\tan \psi_w^*$ greater than 1 at most strains in this pressure range). Only at pressures above 5 kb does the deformation appear to approximate pure intracrystalline plasticity ($\tan \psi_w^* = 0 \cdot 05$ or less). This is probably because, although calcite has enough independent slip systems to satisfy von Mises's condition, the resolved shear stress for slip is relatively high [26] and so only at the highest pressures is it always easier than propagation of microfractures. The easily-produced twinning is inadequate for a general deformation [10] and so in itself does not determine the level of the stress–strain curve. Thus, although the macroscopic brittle–ductile transition in Carrara marble is around $0 \cdot 5$ kb, the transition to full intracrystalline plasticity is not completed until at least 4–5 kb at room temperature. The decrease in volume during deformation above 4 kb is presumably collapse of porosity that does not involve widely-distributed cataclasis.

In the *lithographic limestone*, the situation is complicated by the larger initial porosity. Although dilatancy is absent in compression tests above about 2 kb, the pressure sensitivity suggests that cataclastic flow largely determines the level of the stress–strain curve up to at least 4 kb and still plays some part up to 8 kb ($\tan \psi_w^*$ greater than 1 up to 4 kb and still not less than $0 \cdot 5$ at 8 kb). The compaction during deformation, especially in the 2–4 kb range, therefore presumably represents a partial removal of initial porosity while retaining enough free volume to accommodate the cataclastic processes; some porosity is still retained after 20 per cent deformation at 8 kb. The higher levels of the stress–strain curves and the greater difficulty of achieving full intracrystalline plasticity than in Carrara marble are probably mainly related to the finer grain size but possibly also to differences in purity. It should be emphasized that in neither material can we estimate the actual fractions of total strain contributed by the two types of processes, as distinct from discussing the degree