to which each controls the course of the stress–strain curve and, in fact, intracrystalline plasticity may contribute a large part of the total strain over much of the ductile field.

The high-pressure sensitivity of the stress–strain curves of the *sandstone* ($\tan \psi_w^* = 1–1\cdot5$) points to its deformation being mainly cataclastic flow, like that of a granular mass of quartz and felspar (cf. quartz sand [4]), with the matrix cement apparently not greatly modifying the behaviour. However, the volume-change observations suggest that the sandstone does not conform to the picture, often discussed in soil mechanics [27, 28], of approach to a critical void ratio in the deformation of a granular medium. Here the situation must be complicated by continual changes in structure associated with comminution of grains and subsequent readjustments in their packing, these effects being somehow reflected in the general tendency to dilatancy at larger strains, accompanied by strain softening, after the preliminary phase of compaction.

Graphite and *talc* are both aggregates of a platy mineral in which intracrystalline slip is probably restricted to the unique cleavage plane. Such slip is inadequate for homogeneous deformation in the aggregate, even if kinking is taken into account, and so additional accommodating mechanisms are required [10]. For the latter, non-basal slip is likely to be too difficult and so some cataclastic flow can be expected. In talc, there is probably a component of cataclastic flow in all cases since $\tan \psi_w^*$ is about 0·2–0·3 over the whole pressure range. In graphite, the situation is similar up to about 4 kb but at higher pressures $\tan \psi_w^*$ decrease to around 0·05. A possible explanation, which avoids postulating a marked decrease in coefficient of friction at high normal stresses or the activation of additional slip mechanisms, is that the deformation now occurs almost entirely by basal slip and that any incompatibility in strain from grain to grain is accommodated in the pore space, which is still appreciable compared with that in the talc at high pressures.

Extension tests

For the lithographic limestone at small strains, say below 5 per cent, the difference between the extension stress–strain curve at 6·5 kb and the compression curve at about the same pressure [Fig. 3(a)] can be mainly ascribed to the difference in work associated with volume change since the σ_w^* curves [Fig. 3(b)] more nearly coincide or even fall in reverse order (it must be borne in mind that the low precision of the derived curves, especially at low strains, permits only very approximate comparisons). The Carrara marble extension and compression curves [Fig. 4(a) and 4(b)], which are less influenced by volume changes at around 6·5 kb, nearly coincide at low strains in either plot. The large difference in mean stress between the extension tests and compression tests at the same confining pressure therefore evidently has little influence on the deformation processes at small strains at this level of pressure. However, the difference in mean stress does appear to be important at larger strains where for both materials the σ_w^* vs ϵ_1 curves in extension lack the intrinsic work hardening that appears in compression. This suggests that the cataclastic component in the deformation becomes more dominant in the extension tests as straining proceeds.

In neither material is the Mohr failure condition valid for the flow stress at a given strain since the Mohr envelopes for extension and compression tests will not coincide, irrespective of whether the early part or later part of the stress–strain curve is being considered. The Mohr theory predicts that the Mohr stress circle for an extension test with 6·5 kb as maximum compressive principal stress should coincide with that for a compression test with the same maximum compressive principal stress (this would be at about 1·7 kb confining pressure for the limestone and between 2 and 2·5 kb for the marble). However, the latter circle is always of smaller radius than the former, irrespective of whether σ or σ_w* is considered as flow stress. This means that, in effect, increase in the intermediate compressive principal stress σ_2 increases the level of the stress–strain curve in tests where the extreme principal stresses are in the vicinity of 2 and 6 kb, respectively.

BRITTLE–DUCTILE TRANSITION AND OTHER STABILITY ASPECTS

From the pressure-sensitivity of the flow stress and from the dilatancy, it is evident that the brittle–ductile transition is not simply a transition from macroscopic fracture to intracrystalline plasticity. Microcracking, known to be prevalent prior to macroscopic fracture [2, 29], must still be widespread and important above the transition [3]. The transition can therefore be said to be determined as the pressure above which microcrack propagation is stabilized at all strains, so that no individual microcrack or combination of them develops into a microscopic fracture. The stabilizing [30, 31] presumably results from factors such as plastic work ('plastic blunting'), the friction between sliding surfaces, or the difficulty of a crack crossing grain boundaries or other barriers such as other cracks. To describe the transition simply as the pressure at which 'the stress required to form a fault is equal to the stress to cause sliding on the fault' [32] does not bring out its essential nature. Rather, dealing with the transition in terms of stability or instability of crack propagation calls for concepts on the microscale analogous to those, such as critical strain energy release rate or critical crack size, developed in technical fracture mechanics [33, 34]; Bieniawski [35] has already applied some of these notions to rocks on the larger scale.

Another stability question is whether, when the pressure is above the transition, the deformation within a uniformly loaded specimen will be uniformly distributed or will tend to be concentrated within localized zones such as shear bands (cf. Lüders' bands in mild steel). This should be decided by Drucker's criterion of material stability according to which, in the absence of a geometrical instability such as necking, a material will deform in a stable manner if 'additional deformation requires positive work by the external agency' [36]. In the present situation where some of the work is involved in volume change, this criterion predicts distributed or stable deformation when the σ_w vs ϵ_1 curves show work hardening and localized or unstable deformation where they show work softening. Our observations are consistent with this. In particular, the sandstone seems to deform uniformly, apart from the barrelling due to end-constraints, while the σ_w vs ϵ_1 curve is rising, but localization of deformation sets in after the curve bends over—although the experiments are not very critical in establishing an exact correlation here.

A possible explanation, in the case of porous rocks, for the ductile-to-brittle transition with increasing pressure of the type described by Byerley and Brace [37] may also lie in an analogous effect if with increasing pressure the $\Delta v/v_0$ vs ϵ_1 curve develops a sufficiently marked upward curvature ($d^2\epsilon_v/d\epsilon_1{}^2$ negative) to produce an overall work softening in the σ_w vs ϵ_1 curve. The appearance of p in the $p(d^2\epsilon_v/d\epsilon_1{}^2)$ term in equation (2) leads to this term becoming more important at higher pressures even if $d^2\epsilon_v/d\epsilon_1{}^2$ is not changing markedly with pressure (note that it is only upward curvature of $\Delta v/v_0$ vs ϵ_1 that is relevant, not actual change from compaction to dilatation with increasing strain).

An alternative situation may arise, although not illustrated in our experiments, where there is volume change occurring such that $\Delta v/v_0$ vs ϵ_1 is concave downwards ($d^2\epsilon_v/d\epsilon_1{}^2$ positive). It is then possible for the σ_w vs ϵ_1 curve to show work hardening even though the σ vs ϵ_1 curve is falling. This could give rise to a situation where, in spite of a downward sloping stress–stress curve being observed, no localized shear develops, and so help explain