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# VOLUME CHANGES DURING THE DEFORMATION OF ROCKS AT HIGH PRESSURES

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**Abstract**—Using a dilatometric method, volume changes were measured during straining to 20 per cent at confining pressures up to 8 kb, as well as during application and release of the pressure, in lithographic limestone, Carrara marble, sandstone, talc, graphite and sodium chloride. Dilatancy persists well into the ductile field but compaction tends to occur during straining at the higher pressures. In some cases, notably sandstone, compaction can be followed by dilation as straining continues. The stress–strain curves are shown to be significantly affected by the occurrence of volume changes because of the work done through them by the confining pressure. Therefore, an alternative flow parameter, defined as the total rate of doing work on the specimen with respect to strain, is considered to be a better guide in deducing from stress–strain behaviour the relative roles of cataclastic flow and intracrystalline plasticity as mechanisms of deformation. The brittle–ductile transition is seen as the pressure above which unstable propagation of microcracks no longer occurs, the transition to complete intracrystalline plasticity occurring at a higher pressure, if attained at all.

## INTRODUCTION

NON-ELASTIC volume changes can occur during the deformation of a rock without macroscopic fracturing being involved. They may reflect fine-scale fracturing, changes in pore structure or other internal structural changes in the rock. These changes are intimately associated with the mechanism of deformation, especially in the transition between brittle and ductile behaviour, as well as with the processes leading up to macroscopic fracture. The measurement of volume changes can therefore make an important contribution to our understanding of the details of the response of a rock to applied stress.

The first accurate measurements were made by BRIDGMAN [1], using a dilatometric method. In some rocks of low porosity he observed volume increases prior to fracture in uniaxial compression at atmospheric pressure. BRACE, PAULDING and SCHOLZ [2, 3] have made more detailed studies of volume changes prior to fracture in a number of rocks tested under high pressure, using a strain-gauge method. This and related work of Brace and co-workers has thrown much light on the microfracturing that precedes macroscopic fracture but its application has been mainly in the brittle field and at small strains.

Very few measurements have been made of volume changes during the larger strains that rocks can undergo in the ductile field at high pressures. Notable here is the work of HANDIN and co-workers [4, 5]. By measuring the movement of pore fluid in or out of the specimen in triaxial compression tests at constant pore pressure, they observed decrease in volume during deformation of rather porous limestone and sandstone and increase in volume, after an initial decrease, in a dolomite of lower porosity; at very low effective pressures, all specimens dilated. The highest effective pressure used was 1·5 kb. The same method was used by BRACE and ORANGE [6] at small strains and it is widely used in soil mechanics. It is limited in application by the requirements of adequate permeability and interconnexion of pores, requirements not met in many compact rocks as HANDIN *et al.* [5] showed in the case of a shale and BRACE and ORANGE [6] in marble.

In the present study, a dilatometric method has been used to measure volume changes during deformation in rocks at confining pressures up to 8 kb. The aim has been to throw further light on the mechanisms involved in the brittle to ductile transition and to help determine the relative contributions of cataclastic and crystal–plastic deformation mechanisms at pressures above the transition. This is of interest in view of the difficulty of achieving intracrystalline deformation in a polycrystalline aggregate if an insufficient number of active slip systems is available in the individual grains (cf. von Mises' requirement of five independent slip systems [7–9]). The implications of the von Mises' requirement for ductility in rocks are discussed elsewhere [10].

## APPARATUS AND EXPERIMENTAL METHOD

The measurements were made with a new device which fits into the high-pressure cylinder of a 10-kb room temperature deformation apparatus described elsewhere [11]. In principle, the jacketed specimen is enclosed within a fluid-filled bellows and volume changes in the specimen, which cause displacement of the fluid, are indicated by relative movement of the ends of the bellows. This dilatometric method, like that of BRIDGMAN [1], integrates the volume changes over the whole specimen. In this respect, it is similar to the pore fluid method but it has the advantage of being independent of the permeability of the specimen. It has the advantage over the strain-gauge method of not requiring elaborate preparation for each experiment and it is not restricted to relatively small strains.

The dilatometer is depicted schematically in Fig. 1 and in section in Fig. 2. The overall dimensions are $1\frac{1}{4}$ in. diameter and $5\frac{1}{2}$ in. length, set by the dimensions of the pressure

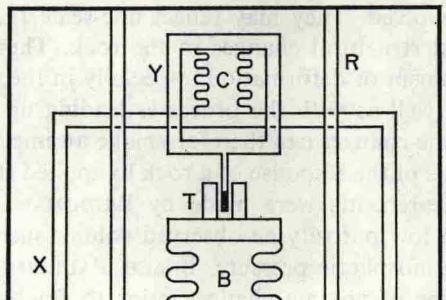

FIG. 1. Schematic arrangement of dilatometer.