FIG. 8. Results for sodium chloride: (a) stress–strain curve, same within limits of scatter for $0 \cdot 25, 0 \cdot 5, 1, 2, 6$ and 8 kb; (b) equivalent stress–strain curves for $0 \cdot 25$ and 8 kb calculated from total work done on specimens; (c) relative volume change vs strain, same within limits of scatter for $0 \cdot 25, 0 \cdot 5, 1, 3, 6$ and 8 kb; (d) complete history of volume changes.

initial application of the pressure [Fig. 8(d)], since the final porosity of the specimens was in all cases less than $0 \cdot 1$ per cent, as determined by density measurements. Thus, the small initial porosity was effectively eliminated by the combined effects of confining pressure and deformation at all pressures and the changes in volume during pressure release were purely elastic.

## DISCUSSION

### General

The experiments have shown that the deformation of rocks can be accompanied by sub-stantial volume changes even in the range of macroscopically ductile behaviour, thus con-firming and extending previous observations [3, 5]. These volume changes are large compared with elastic effects and must be attributed to changes in the pore structure or grain arrangement or to the development of internal cracking. They may be of either sign, so presumably there are competing processes of compaction and dilation, especially where initial porosity is present. We shall first discuss some general aspects of the observations, then consider in more detail the interaction between volume changes and stress–strain properties, and finally attempt to draw conclusions about the mechanisms of deformation.

There is no obvious general correlation between the brittle–ductile transition and any particular aspect of the volume-change behaviour, such as change from dilation to com-paction or the disappearance of non-elastic volume change. Thus, in the simplest case of Carrara marble, dilation can still accompany deformation above the brittle–ductile tran-sition and it is not until much higher pressures that constant-volume deformation at zero porosity is achieved, like that in a ductile metal. However, there is some correlation between

volume change during deformation and the pressure-sensitivity of the stress–strain curve. Where the latter is low, as for limestone and marble at the highest pressures and for sodium chloride at all pressures, the occurrence of volume change during deformation is minimal, probably only involving the elimination of some residual porosity.

The marked dilation of most materials during pressure release can be related to earlier observations on the increase of length during pressure release [16]. The limestone, marble and sandstone used here resemble fairly closely the corresponding materials used in the earlier work and it is probably valid to make rough comparisons. Thus, the total dilation during pressure release from 6 or 8 kb after deformation in these three materials is approximately 9, 6 and 12 per cent, respectively, while the total length increase during similar pressure release is $4 \cdot 5$, 4 and 4 per cent (based on original lengths for valid comparison). It follows that the pressure-release effects in the calcite aggregates is expressed predominantly as an increase in length, especially in the case of the initially more compact marble, whereas the dilation of sandstone is more nearly isotropic. This is consistent with the special mechanism, involving the plastic and elastic anisotropy of the grains, postulated for the calcite aggregates [16] and with the absence of these factors in sandstone. In the latter, the dilation during pressure release presumably results mainly from a general loosening of the granular structure under the influence of contact stresses set up during deformation at the high pressure and differing from those resulting simply from applying hydrostatic pressure. The cement may also play a part since its behaviour may be like that of talc. The absence of similar pressure-release effects in the sodium chloride specimens also appears consistent since sodium chloride differs from calcite in being isotropic in its linear compressibility and more nearly isotropic in yield stress, while in no way resembling the model of an assemblage of hard particles which may to some extent represent the sandstone.

*Interaction of volume change and stress–strain properties*

In seeking to elucidate the mechanism of deformation of a material, account is often taken of the degree of resistance that it offers to deformation and of the way in which this changes with the nature and amount of the deformation and with changes in pressure and temperature. In tests where only one principal stress is non-zero ('uniaxial tests'), it is sufficient to specify this stress as measuring the resistance to deformation and so attention is directed to the stress–strain curve itself. However, under more general states of stress no single applied stress component is an adequate measure of the resistance of deformation. Instead, what is likely to be more relevant is the increment of work needed per increment of deformation.

In particular, in the 'triaxial test' the differential stress does not in general represent the rate at which work is being done within the specimen because of the work associated with volume change under the confining pressure. Assuming that the specimen axis is a principal axis of strain, the total work $dW$ done on the specimen per unit volume during an increment of axial strain $d\epsilon_1$ in the triaxial test can be written [5, 17] as

$$dW = (\sigma + p)d\epsilon_1 + 2\,pd\epsilon_3$$

or

$$dW = \sigma d\epsilon_1 + pd\epsilon_v.$$

Here $\sigma$ is the differential stress ($\sigma_1 - \sigma_3$ in conventional notation), $p$ is the confining pressure ($\sigma_3$), $d\epsilon_3$ is the increment in radial strain and $d\epsilon_v$ is the increment in volumetric strain; we adopt the convenient sign convention that compressive stresses and strains are positive and