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Shear-zone geometries in experimentally deformed clays: the influence of water content, strain rate and primary fabric

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Abstract—In experimentally deformed clays, three parameters which influence the geometry of shear zones are water content, strain rate and the orientation of the shear zones with respect to any primary fabric. The shear zones are the main microstructures induced in the clays within the experimental conditions (triaxial compression at water contents between 20 and 35% w/w and strain rates between 10^{-4} and 10^{-8} s^{-1}). Small changes in water content produce a significant change in the appearance of shear zones: structures in wetter sediments are more complex and more numerous than those in drier sediments which tend to produce a small number of discrete planar shear zones. Strain rate is a far less important influence on shear-zone geometry. The orientation of the zones with respect to a primary fabric is also significant. Shear zones which are parallel to the fabric have a simpler geometry than zones which intersect the fabric at a high angle. Knowledge of these factors may help interpret the conditions within which shear zones formed in naturally-deformed soft sediments.

INTRODUCTION

SOFT-SEDIMENT deformation is now known to be common in a wide range of settings, and to produce a variety of microstructures. D.S.D.P. and O.D.P. cores recovered from active plate margins have shown features such as anastomosing faults and 'pseudo veins' (Lundberg & Moore 1981, 1986, Carson *et al.* 1982, Knipe 1986a,b), and microfaults and 'ductile shear zones' have been recognized both in slump sheets (Maltman 1987a) and mélanges (Cowan 1982). Some of these naturally occurring microstructures, particularly those in sediments from active margins, can be attributed to the compression of unlithified material. In order to improve knowledge of these microstructures and their production, compressional features have been investigated by experimentally deforming clays under known physical conditions, and examining any changes in the nature of the deformation microstructures which occur as a result of changing these conditions.

Much of the previous experimental work using clays has been concerned with either scale modelling (Tchalenko 1970, Hempton & Neher 1986), geotechnics (Morgenstern & Tchalenko 1967) or the replication of structures seen in rocks (Rutter & White 1979, Rutter *et al.* 1986). In this paper we describe the results from a series of 82 experiments aimed at reproducing microstructures which occur during ductile deformation in unlithified sediments. A variety of microstructures are generated during the experimental deformation, but by far the most important are the zones along which macroscopic displacement is concentrated. Under the microscope these zones appear to have maintained cohesion, and between crossed-polars the extinction position sweeps across the zones, indicating that they are ductile shear zones. Other structures such as crenulations and kink bands have also been described in experimentally deformed sediments (Maltman 1977), but these structures have been found in undeformed control specimens and hence are not considered in this study. Better understanding of the 'soft-sediment' shear zones should enable a distinction to be made between pre- and post-lithification features in rocks, and a more precise interpretation of the physical conditions operating during early deformation events.

EXPERIMENTAL TECHNIQUE

The experimental method used in this work is described by Maltman (1987b), and is therefore only briefly summarized here. Deformation is induced by triaxial compression ($\sigma_1 > \sigma_2 = \sigma_3$) of cylindrical specimens (100 mm long and 50 mm in diameter) contained in rubber sleeves. In all the experiments the principal bulk compressive stress (σ_1) was imposed parallel to the long axis of the cylinder. Ball clay has mainly been used in the experiments because it represents a good analogue to real argillaceous rocks, and deformation microstructures are well shown. The clay is first mixed with salt water to produce a slurry. In most of the experiments the slurry was artificially consolidated using a loaded piston–cylinder arrangement (see Maltman 1987b, fig. 1c). This generates a primary fabric perpendicular to the long axis of the cylinder, although some arcuation of the fabric results from sidewall friction (Fig. 1a). In practice it has

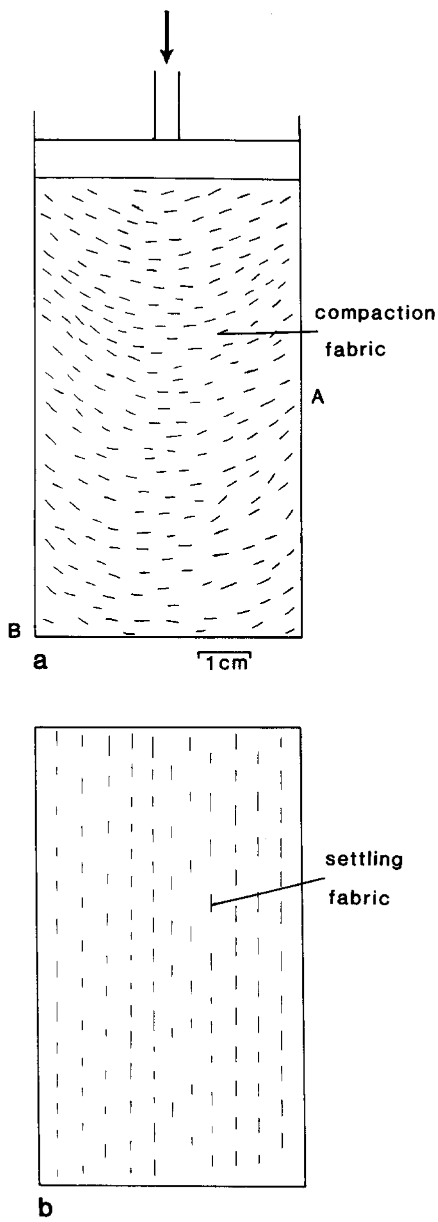


Fig. 1. Primary fabrics in specimens prior to deformation. (a) Specimen prepared using a piston–cylinder arrangement which produces an arcuate horizontal fabric due to edge effects. (b) Specimen prepared by gravity-settling and partial drying. Specimen is then cut to have a vertical primary fabric.

not been possible to produce consolidated specimens with a perfectly planar horizontal fabric. The effects of varying strain rate and water content on the appearance of shear zones have been investigated using specimens produced in this way. The deformation apparatus allows variation in strain rate over four orders of magnitude, and water content can be varied by changing the degree of consolidation.

For 11 of the tests the clay was consolidated by gravity-settling and partial drying of the slurry, producing an underconsolidated specimen (see Maltman 1987b, fig. 1a). These specimens are large enough to allow cutting in such a way that any primary settling fabric is parallel to the long axis of the cylinder (Fig. 1b). By using these specimens, together with those having the arcuate fabric mentioned above, it has been possible to investigate the effect on the shear zones of different orientations of primary fabric.

During experiments the stress–strain paths were monitored using a pressure transducer connected to a microcomputer via a suitable interface. Deformation microstructures have been examined petrographically in thin-section, after impregnation of the deformed wet sediment with Carbowax 8000.

DEFORMATION BEHAVIOUR

Shear-zone development in deforming clays has been discussed by Maltman (1987c). In the present work, deformation was seen to be initially accommodated by the bulging of the specimen until failure occurred at a bulk shortening strain of between 8 and 12%. After this, deformation was largely restricted to a narrow shear zone. Figure 2(a) shows the stress–strain paths from a series of experiments with various water contents in which the strain rate was kept constant. The data demonstrate that small differences in water content can produce a large difference in both the peak and residual strengths. Figure 2(b) shows the stress–strain paths for specimens with almost constant water contents and a variety of strain rates. Because of the lack of any pattern, and because it is difficult in practice to prepare specimens with an identical water content, it may well be that the small diversity in stress–strain behaviour is due to subtle differences in water content. From this comparison alone it appears that water content is far more important than strain rate in controlling the deformation behaviour of wet clay.

Microscopic observation of the induced shear zones shows that there is a large diversity in their overall appearance (Fig. 3). In some cases they are discrete planar zones, whereas in other specimens the zones anastomose and splay in an intricate pattern to form a network which is here termed a shear-zone array. The main purpose of this study is to investigate the effect of varying the water content, the strain rate and the angle between the shear zone and the primary fabric on the overall style of deformation microstructures. The results of varying these parameters are discussed separately below. Although no two specimens will show exactly the same deformation microstructures, the overall trends reported below are consistent with all the data.

Water content

A series of constant strain-rate triaxial experiments ($\dot{e} = 2.3 \times 10^{-5}\ s^{-1}$) has been undertaken using specimens with water contents between 19 and 35% w/w. Under normal consolidation conditions, and assuming an average sediment density of 2 g cm^{-3}, this range of water contents corresponds to a burial depth between 0 and 400 m. Figure 4(a) shows line drawings of the shear-zone arrays in these experiments. There is a striking variation in shear-zone geometry even for relatively small differences in water content. Specimens with a low

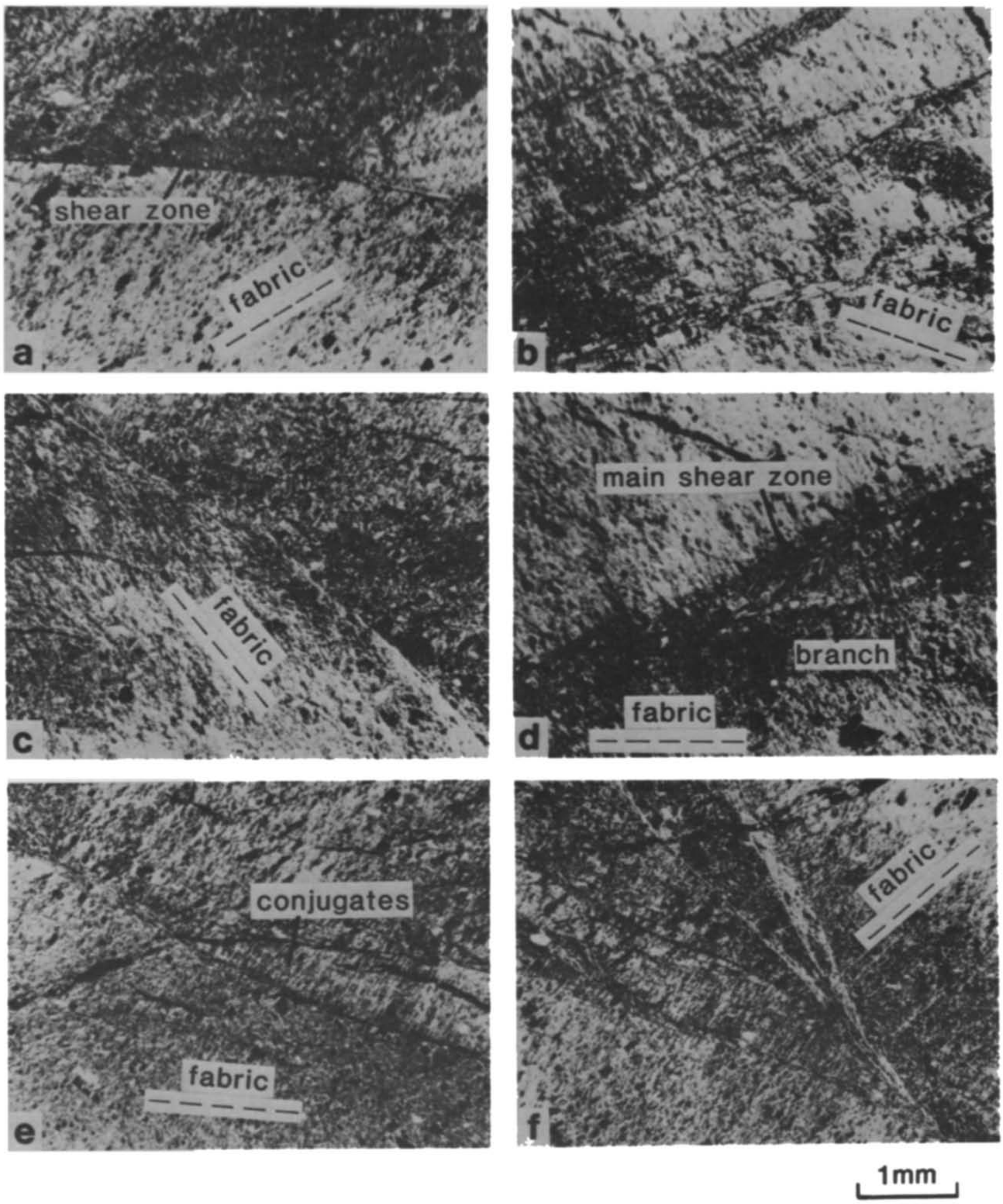


Fig. 3. Microscopic appearance of shear zones. Note how in all cases deformation is restricted to a well-defined zone and the material outside this zone remains relatively undeformed. Primary fabric direction is as shown. (a) Discrete shear zone in specimen with a water content of 21.3% (corresponding to burial to about 350 m). Total width of deformation zone is <100 μm. (b) Network of shear zones in a specimen with a water content of 34.5% (corresponding to a near-surface sediment). Deformation occurs in a zone approximately 8 mm wide. (c) Discrete shear zone developed sub-parallel to the primary fabric. (d) Splays developed in a shear-zone array which is at about 30° to the primary fabric. These splays typically appear to 'chase' the fabric and develop as the angle of shear zone to fabric increases. (e) Branching of a shear zone due to an increase in its angle to the primary fabric. Note the sigmoidal conjugates which are developed between the two branches. (f) Complex shear-zone array seen where the deformation zone is nearly perpendicular to the fabric.

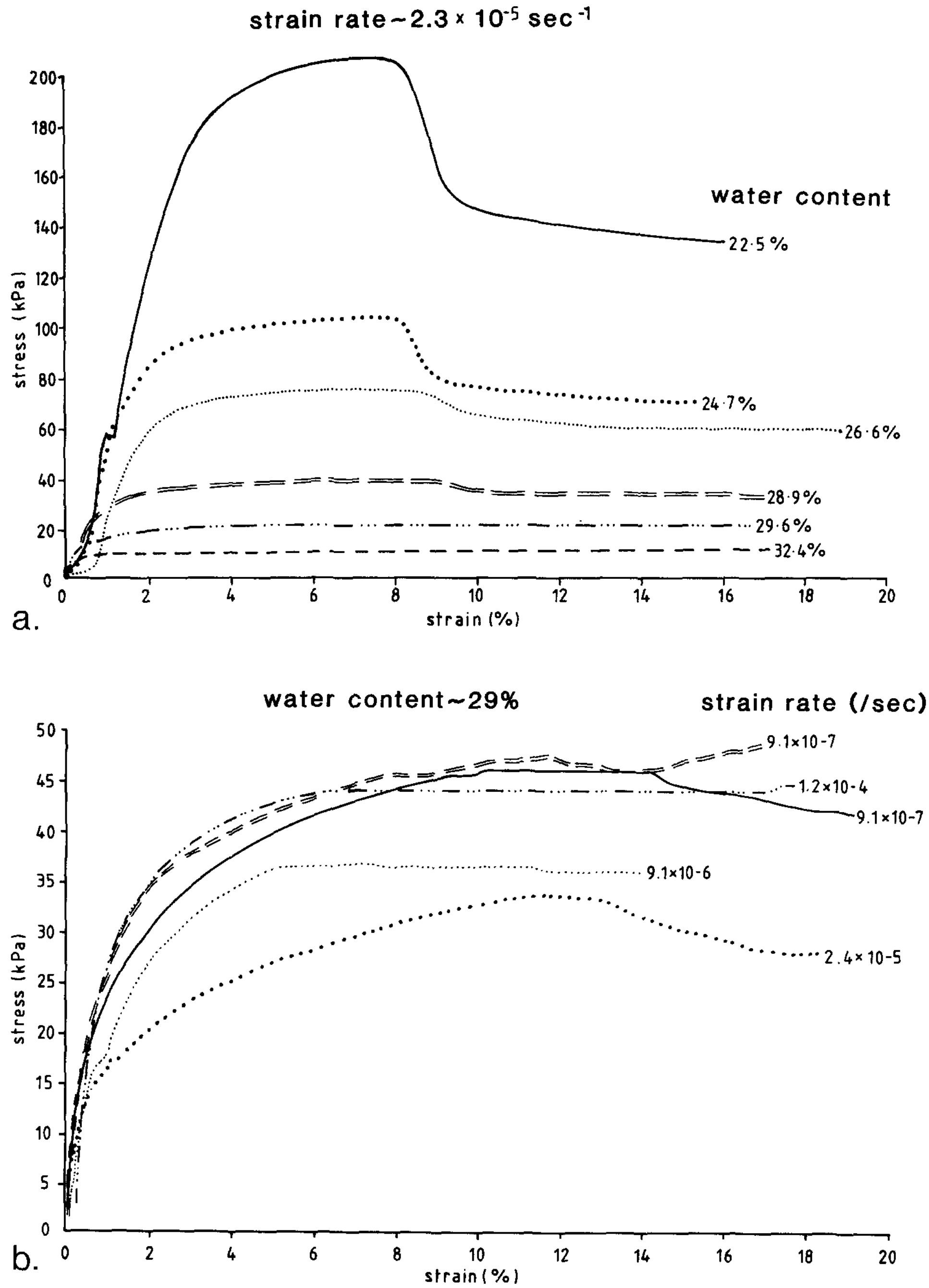


Fig. 2. Representative stress–strain curves to show the behaviour of the deforming clay under differing experimental conditions. (a) *Water content*. There is a large variation in both peak strength and residual strength with changing water content. Experiments performed at a constant strain rate of $2.3 \times 10^{-5}\ s^{-1}$. (b) *Strain rate*. In contrast to (a), there is little variation in the shape of the stress–strain curves with strain rate. Experiments performed at an almost constant water content of 29%

water content (<25% w/w) contain narrow, discrete shear zones and the deformation is restricted to these narrow zones (e.g. Fig. 3a). Wetter specimens (>30% w/w) contain shear-zone arrays with a more complex appearance. Deformation is still essentially accommodated by discrete shear zones, but these form a braided pattern which can occupy a wide zone (up to 10 mm across). Splays and anastomosing of shear zones are very common in these complex zones and the deformation gives the impression of being chaotic (Fig. 3b). There is a range between the two extremes described, and small changes in water content can have a marked effect on the appearance of the shear zone.

Strain rate

Experiments have been performed with an almost constant water content of 29% w/w, and various strain rates between 10^{-4} and $10^{-8}\ s^{-1}$. Line drawings of the shear zones formed during these experiments are shown in Fig. 4(b). In contrast to the corresponding diagram for water content, it appears that varying the strain rate between these values has an insignificant effect on the geometry of the shear zones. In all cases the overall width of the shear zones is approximately the same, as is their general complexity and appearance. In practice it is impossible to exactly duplicate water contents, and the

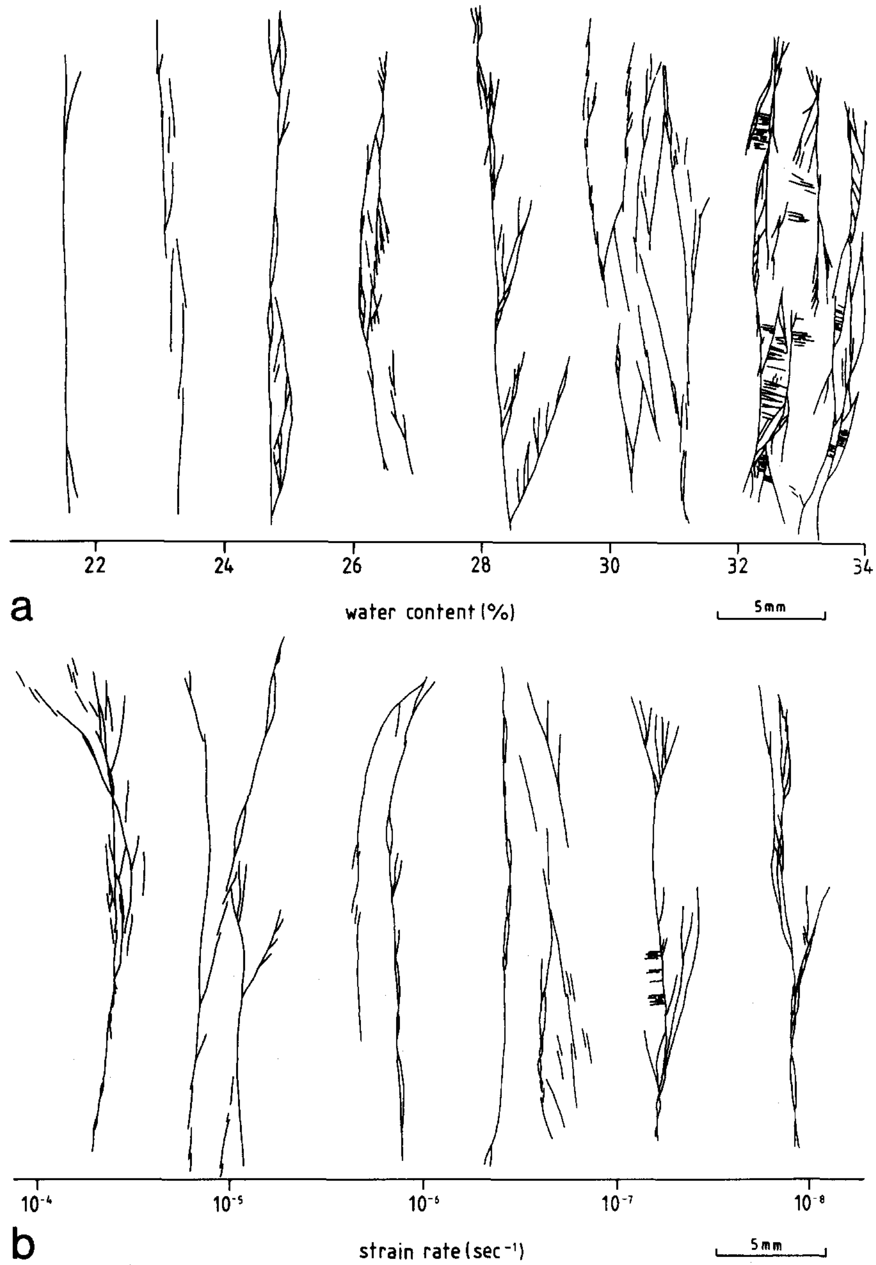


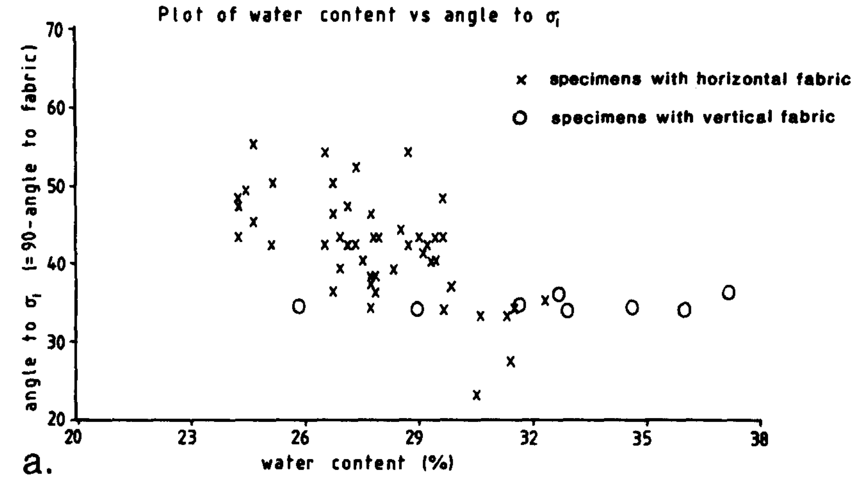
Fig. 4. Line drawings to show the large variation observed in shear-zone geometry. The vertical orientation of the zones is for comparison and bears no relation to their orientation within the specimen. (a) The variation in shear-zone appearance with changing water content. A small variation in the water content has a marked effect on the overall geometry of the shear zone. (b) The variation in shear-zone appearance with changing strain rate. There is no significant change in the style or width of the shear zones with a variation over four orders of magnitude in strain rate.

minor changes in water content which result have a larger influence on controlling shear-zone geometry than a variation over several orders of magnitude in the strain rate.

Primary fabric

Orientation of shear zones. In the various experiments the angle (α) between the shear zones and the long axis of the cylinder was found to differ. In most specimens the zones were sufficiently distinct and planar for their orientation to be measured. Figure 5 shows the variation in α with both water content and strain rate for specimens where the primary fabric is both vertical and horizontal. Whereas there is no obvious relationship between α and strain rate, there seems to be some correlation between α and water content for the specimens with a horizontal primary fabric. Specimens with high water contents generally have a lower value of α than drier specimens, which sometimes show angles (α) greater than the theoretical maximum of 45°. Differences in water content do not produce an observable difference in the amount of curvature seen in the primary fabric, so this factor cannot explain the diversity observed in the orientation of shear zones. In contrast there is apparently no dependence of α on water content for the specimens with a vertical primary fabric, and the values of α tend to be lower than those for specimens with similar water contents but a horizontal fabric.

The explanation is thought to lie in the intensity and



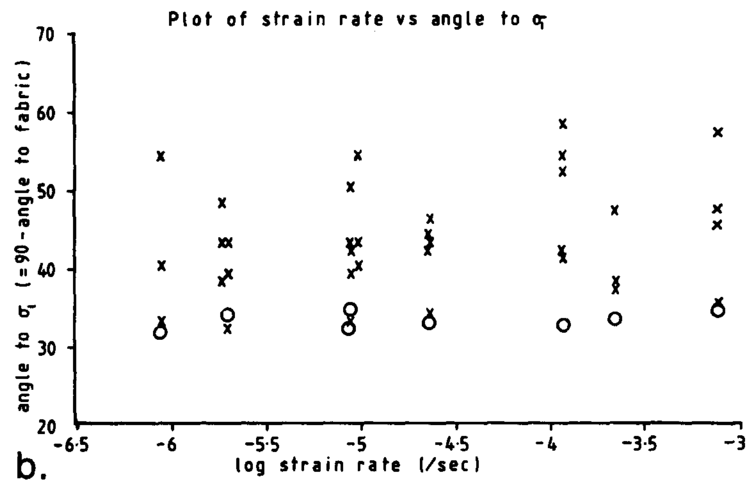


Fig. 5. Graphs to show the variation of the orientation of the shear zones with respect to σ_1. Readings are ±0.5°. For full discussion see text. (a) The variation in orientation of shear zones with varying water content. For a horizontal fabric, specimens with a low water content tend to develop shear zones at a higher angle to σ_1 than wetter specimens. No significant variation is observed in specimens with a vertical fabric. (b) The variation in orientation of shear zones with varying strain rate. In contrast to (a), no obvious trend emerges for both types of specimen.

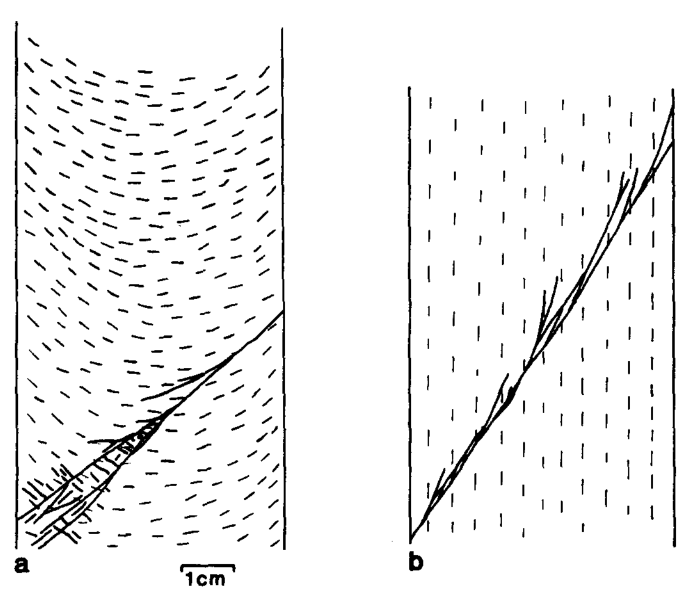


Fig. 6. Line drawings to show the typical geometry of shear zones developed in cylindrical specimens. (a) Arcuate fabric: a shear zone will intersect the fabric at a large range of angles (γ), the geometry of the zone depending on γ. (b) Vertical fabric: γ is constant, and shear zone has a consistent appearance throughout the specimen. Note the way that in both (a) and (b) splays are developed parallel to the fabric.

orientation of the primary fabric. More intense primary fabrics are produced in specimens which have been more consolidated (=low water contents), because of the greater alignment of the clay particles (Rieke & Chilingarian 1974). It is this alignment that appears to influence the orientation of the shear zones, in the specimens with a sub-horizontal fabric. The specimens with a vertical fabric are highly underconsolidated and only have a weak settling fabric which has not been intensified by artificial compaction. The fact that α for these specimens is apparently independent of water content suggests that the fabric intensity does not change with decreasing water content.

The experimental data indicate that the orientations of the shear zones do not correspond with those predicted by theories for isotropic media. α values of less than 45° are predicted by Coulomb–Mohr theory, because of the angle of internal friction, and by the Prandtl–Reuss theory adapted for geological materials (Aydin & Johnson 1983) if dilation is to be invoked as the initial deformation mechanism. Both the internal friction and the tendency for dilation would be expected to be greater for specimens which have been more consolidated, and hence drier specimens should exhibit a smaller angle between the shear zones and σ_1. However the opposite trend is observed, suggesting that the anisotropy due to the primary fabric is a significant factor, which overrides the theoretical orientations of shear in isotropic materials. In the experiments where the starting fabric was parallel to the long axis of the cylinder and hence parallel to σ_1, α values were about 30° for specimens with a water content of 25%, considerably lower than α for specimens with a similar water content and a horizontal fabric. This again suggests some fabric control on the orientation of shear zones. The role of anisotropy in controlling the orientation of shear planes with respect to σ_1 is well known in rocks with a well developed secondary fabric (Donath 1968, Cosgrove 1976), and the present work shows that the effect is also apparent in wet sediments.

Appearance of shear zones. The primary fabric also influences the appearance of the shear zones. As has been mentioned above, the horizontal fabric is arcuate due to edge effects associated with the piston–cylinder arrangement. In these specimens, a shear zone propagating from A to B in Fig. 1(a) therefore intersects the fabric at a variety of angles (γ), and this allows direct observation on a single shear zone or shear-zone array of how the geometry of the zone varies as a function of γ. Near point A, the shear zone will be parallel or sub-parallel to the primary fabric. It is likely that the shear zone is initiated here, because a parallel fabric will provide the least resistance to failure. The zone then propagates towards point B. Specimens with a vertical fabric (Fig. 1b) will have a constant angle γ, and it is not clear whether the shear zones propagate near A or B.

Figure 6(a) shows a typical shear zone in a specimen with a horizontal arcuate fabric and a water content of 29% w/w. Where γ is small (near point A) the shear zone exhibits a relatively simple appearance characterized by minimal anastomosing and splaying, and the deformation is restricted to this narrow zone (Fig. 3c). As the shear zones propagate, γ increases and this is associated with an increase in the complexity of the shear zone geometry. It seems that shear zones may 'chase' the fabric (Fig. 3d) to produce splays which deviate from the main shear-zone orientation. In other cases splays do not develop, but the main shear zone splits into two or more sub-parallel branches with sigmoidal conjugate shears sometimes developed between them (Fig. 3e). An increase in γ is commonly accompanied by an increase in the width over which deformation is accommodated. As the shear zone propagates further, γ increases even more, and the shear zone becomes still more complicated. The width over which the deformation is accommodated increases further and braiding becomes more common, to produce a network of closely spaced discrete shear zones (Fig. 3f). Where the shear-zone array and the fabric are sub-perpendicular (which commonly occurs close to point B), high-angle closely-spaced conjugate shear zones locally develop in close proximity to a single shear zone. These conjugates are typically sigmoidal and sub-parallel to the primary fabric. Therefore, a continuous shear zone in one specimen may vary in style and in width merely due to a change in γ.

Figure 6(b) shows a typical shear zone in an unconsolidated specimen with a vertical primary fabric and a water content of 29% w/w. No arcuation of the primary fabric is produced by the method of preparing this kind of material. In contrast to the variation in shear-zone style described above, the appearance of the zone remains approximately constant all the way across the specimen. There is only a small amount of anastomosing, but splays commonly develop parallel to the weak settling fabric. Although the weak fabric does not appear to control the orientation of the shear zones, it does seem to influence the overall appearance. The splays shown in Fig. 6(a) and (b) are parallel to the fabric, and hence have different senses with respect to σ_1. They are not therefore in the standard mechanical orientations of tension, shear, etc., but must be responding to the orientation of the anisotropy. Natural sediments will not generally have an arcuate primary fabric, but shear zones may be developed in a variety of orientations. Diversity in the appearance of these zones may well be associated with differences in their orientation with respect to a primary fabric. Therefore, this effect has to be considered before any interpretations can be made about water content differences at the time of failure in natural sediments.

CONCLUSIONS

An experimental approach has been used to explore the influence of three physical factors on the geometry of shear zones that arise during the deformation of argillaceous sediments. The experiments are intended to be close analogues of natural deformation, and the results enable a more informed interpretation to be applied to shear zones which are observed in natural materials that are suspected to have been deformed prior to lithification. The appearances of shear zones described in this paper contrast with those of microstructures known to result from deformation of rocks (e.g. Rutter *et al.* 1986), and hence their recognition in nature indicates pre-lithification deformation. The main conclusions of this study are listed below.

(1) There is a large variation in the range of possible pre-lithification deformation conditions (e.g. strain rate, burial depth, consolidation state), but the appearance of shear zones which arise during such deformation helps place constraints on these conditions.

(2) Water content is far more important than strain rate in controlling shear-zone geometries in wet sediments. Differences of a fraction of a per cent in water content can have a greater influence on the nature of deformation than differences of several orders of magnitude in strain rate. In natural examples, assuming normal consolidation, broad complex shear zones would correspond to deformation in near-surface sediments such as open cast slumps, whereas more discrete geometries would correspond to deformation at depth in the sedimentary column.

(3) The orientation of shear zones in experimentally deformed sediments is influenced by the anisotropy of the primary fabric. It is this latter effect which appears to be responsible for producing failure planes in excess of 45° to σ_1. Even wet sediments with water contents in excess of 25% can develop an anisotropy intense enough to influence the orientation of shear zones within the material. Hence this phenomenon is not restricted to rocks with a strongly developed secondary fabric.

(4) The angle between any primary fabric and deformation-induced shear zones is an important influence on controlling shear-zone appearance. An increase in the angle produces an effect similar to increasing the water content. Hence, when trying to place constraints on the water content at the time of failure in natural sediments it is important to take into account the angle the shear zone makes with the primary fabric.

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