American Journal of Science

FEBRUARY 1953

THE EFFECTS OF EXTRUSION AND SOME OTHER PROCESSES ON THE MICRO-STRUCTURE OF CLAY

J. H. WEYMOUTH AND W. O. WILLIAMSON

ABSTRACT. The micro-structures of plastically deformed fine-grained kaolinitic clay were studied optically in pyroxylin-backed films peeled from appropriate surfaces of the specimens. Planar parallelism, involving (001) of the aggregated clay-flakes, and linear parallelism revealed by the disposition of rutile and tourmaline prisms, were observable in extruded cylinders. The relations between these types of parallelism and the schlieren produced by using parti-colored clay are discussed. Shear-joints cut across the fabric indicated by the disposition of (001). They contained clay in which the arrangement of (001) allowed the relative movement of the walls of the joints to be deduced. Such deductions were made for extruded cylinders and for slabs subjected to rotational strain in a manner previously employed by Riedel. Attention is directed to analogies between the experimentally produced structures and those seen in naturally deformed rocks.

INTRODUCTION

The effect of flow on the orientation of clay-particles suspended in water has been investigated optically (Marshall, 1949, pp. 87-88). Popov (1944) has made an optical study of deformation in a clay-water system of greater consistency. Comparable study of deformed plastic clay has been neglected. However, the stripping of pyroxylin-backed films from the smoothed surfaces of appropriate specimens served to demonstrate the orienting effects which processing operations had on the feldspar, quartz and other nonplastic ingredients of ceramic "bodies"; the arrangement of the accompanying clay-flakes was not observed but should tend to conform with the disposition of these ingredients (Williamson, 1941). Later, the same technique was found to be applicable to a fine-grained "ball" clay. The micro-preparations of this clay, although obtained from dried specimens, revealed structures which had clearly been formed by deformation when the clay was still
plastic (Williamson, 1947a). Identical methods have been employed in the present investigation to extend the study then begun.

MATERIALS AND METHODS

The English "ball" clay used was not manifestly different from that studied earlier (Williamson, 1947a, 1947b). Its chemical analysis appears in table 1; mineralogical analysis by X-ray methods showed the presence of kaolinite with smaller amounts of illite and some quartz. The kaolinite and illite could not be differentiated when pyroxylin-backed clay-films were examined with the polarizing microscope; innumerable minute prisms of authigenic rutile and a few grains of quartz were, however, seen (cf. Williamson, 1947a). More detailed search should disclose further accessory mineral-species.

The rutile-prisms, although their maximum dimensions were considerably greater than those of the individual clay-particles, lay with a preferred orientation within the aggregates of parallel flakes. The c-axes of the prisms were parallel to the basal planes of the clay-flakes. Surfaces parallel to the basal planes of these flakes are mentioned frequently in later contexts and, for conciseness, are given the symbol (001).

Table 1

Analysis of Ball Clay Dried at 110° C.
(Analyst, Miss B. C. Terrell)

<table>
<thead>
<tr>
<th>Compound</th>
<th>Weight Percentage</th>
</tr>
</thead>
<tbody>
<tr>
<td>SiO₂</td>
<td>56.53</td>
</tr>
<tr>
<td>Al₂O₃</td>
<td>29.55</td>
</tr>
<tr>
<td>*Fe₂O₃</td>
<td>1.21</td>
</tr>
<tr>
<td>MgO</td>
<td>0.27</td>
</tr>
<tr>
<td>CaO</td>
<td>0.30</td>
</tr>
<tr>
<td>Na₂O</td>
<td>0.21</td>
</tr>
<tr>
<td>K₂O</td>
<td>1.50</td>
</tr>
<tr>
<td>H₂O</td>
<td>8.41</td>
</tr>
<tr>
<td>CO₂</td>
<td>nil</td>
</tr>
<tr>
<td>TiO₂</td>
<td>1.51</td>
</tr>
<tr>
<td>P₂O₅</td>
<td>0.05</td>
</tr>
<tr>
<td>Cl</td>
<td>Tr</td>
</tr>
<tr>
<td>F</td>
<td>Tr</td>
</tr>
<tr>
<td>SO₄</td>
<td>0.05</td>
</tr>
<tr>
<td>ZrO₂</td>
<td>Tr</td>
</tr>
<tr>
<td>MnO</td>
<td>Tr</td>
</tr>
<tr>
<td>BaO</td>
<td>0.03</td>
</tr>
<tr>
<td>V₂O₅</td>
<td>0.03</td>
</tr>
<tr>
<td>Cr₂O₃</td>
<td>0.01</td>
</tr>
<tr>
<td>C</td>
<td>0.17</td>
</tr>
<tr>
<td>B₂O₃</td>
<td>Tr</td>
</tr>
</tbody>
</table>

Total 99.75

*State of oxidation not determined.

The deformed specimens were dried, cut, smoothed and peeled in the manner described (Williamson, 1947a) but a new mixture, giving stronger films, was employed. This contained 10 gm. of
pyroxylin dissolved in a solvent consisting of acetone 100 ml., amyl acetate 45 ml., butyl acetate 15 ml., ethyl acetate 15 ml., castor oil 0.75 ml.; additional solvent was added if necessary.

The pyroxylin-films, peeled from the dried specimens, were remarkable for bringing away with them clay-layers resembling in thickness the usual type of petrological micro-section and similarly amenable to study with the polarizing microscope. The specimens contained minute clay-flakes which were usually arranged with their basal pinacoids in common orientation; thus were produced the (001) planes mentioned above. Films stripped from surfaces parallel to (001) should include flakey aggregates of clay-particles. This was true, but films were prepared as ready from surfaces perpendicular to (001). In such films the clay appeared microscopically as massive aggregates, with a fallacious appearance of monocrytallinity, which behaved optically like sections of large kaolinite-crystals cut parallel to the c-axis. In reality, each aggregate was built of minute clay-flakes lying perpendicularly to the surface of the film with their basal pinacoids in approximate parallelism; the mutual boundaries of these flakes were not perceptible. That the aggregates have such a constitution is indicated by table 2 which shows that most individual clay-flakes have maximum dimensions much smaller than the thickness of the stripped film which is commonly not less than 30-40 microns.

**Table 2**

Grain-size Analysis of Clay
(method of Andreasen)

<table>
<thead>
<tr>
<th>Percentage weight less than 25 micron equivalent spherical diameter</th>
<th>97.0</th>
</tr>
</thead>
<tbody>
<tr>
<td>&quot;</td>
<td>96.0</td>
</tr>
<tr>
<td>&quot;</td>
<td>90.8</td>
</tr>
<tr>
<td>&quot;</td>
<td>81.1</td>
</tr>
<tr>
<td>&quot;</td>
<td>74.9</td>
</tr>
</tbody>
</table>

The clay-films, still on their pyroxylin-backing, were mounted in Canada balsam in the usual way and then examined with the polarizing microscope. Parallelism of the constituent clay-flakes was observable by noticing the tendency for the field to extinguish in certain positions of the stage and to show maximum illumination at 45° thereto. In kaolinite c approximates to X and directions normal to c to Y or Z; thus orientation in the
micro-preparations was readily deducible by conventional methods and particularly by use of the sensitive tint plate.

THE EFFECTS OF EXTRUSION ON MICRO-STRUCTURE

Introduction.—The extruder was a hollow cylinder of brass, 12.5 mm. in internal diameter, closed at one end by a circular plate which was part of a piston. This piston moved forward by air-pressure and forced the contents of the cylinder through a brass die at the other end. The die commonly employed had a shoulder which presented a tapering surface to the cylindrical reservoir. A circular aperture 6.5 mm. in diameter in the center of this surface led to a cylindrical exit canal, 16 mm. long, co-axial with the reservoir (fig. 1).

![Diagram of extruder with alternate white and colored discs in process of extrusion. Diagonal shear-joints are occasional in the reservoir-filling but abundant in the extruded column. The complex system of shear-joints in and near the shoulder of the die is not depicted. Drastic rearrangement of the fabric has occurred at A and A' where spaces had existed between the reservoir-wall and the edges of the discs. At B is the type of region photographed in plate 2, figure 1.]

When the reservoir contained a continuous piece of plastic clay, the pressure from the piston caused a redistribution of the water-content of the filling (Riedel, 1929a). This effect was not obvious where the filling was a collection of individual discs as in the experiments to be described.

Movement of the piston was stopped when the contents of the reservoir had been only partly expelled. After the clay had dried in place, the unextruded residue remained attached to the extruded column. Clay-films from appropriate surfaces allowed the fabric of the entire deformed mass to be deduced. Description of this fabric will be attempted under the headings: (1) the unextruded residue; (2) the extruded column; (3) the zone of maximum deformation in which the clay is involved during its approach to and passage through the die.
(1) The unextruded residue.—The initial filling consisted of circular discs which had their broad surfaces in contact, their edges against the reservoir-wall, and their axes co-axial with the reservoir. These discs were built of aggregated clay-flakes which had (00l) parallel to the broad surfaces. They were made by the process of single-surface casting already described (Williamson, 1947a) or by a process of double-surface casting developed subsequently. In some experiments alternate discs were dyed with methylene blue.

Friction between the filling and the reservoir-wall was reduced by an oil-film; however, drag at this wall sufficed to cause the broad surfaces of the discs to become feeably convex in the direction of flow. The original fabric had been slightly re-arranged so that (00l) was in approximate parallelism to the newly curved surfaces. A more drastic re-arrangement had occurred at some points against the wall where, in zones up to ca. 0.5 mm. across, (00l) was now subparallel, not perpendicular, to the wall-surface (A and A' in fig. 1). The effect was most marked where small gaps, since filled by plastic flow of the clay, had existed between this surface and the edges of the discs. The appearance, in some unextruded residues, of regularly repeated zones characterized by an orientation differing from that of the general fabric was also indicative of localized deformation; these zones showed where imperfect contacts had once existed between the broad surfaces of adjacent discs.

Ill-defined systems of shear-joints were commonly seen. In planes containing the axis of the unextruded clay-cylinder they appeared as two sets of traces which intersected at about 90° and made angles of ca. 45° with the trace of (00l) in the fabric which they traversed. Subsequently, they are termed “diagonal shear-joints.” They are considered to follow the curved surfaces of cones or of semi-ellipsoids in the manner deduced below for similar structures in the extruded columns themselves.

In films normal to the shearing-surfaces, the diagonal shear-joints appeared as continuous thin strips of clay with an optically positive elongation subparallel to the length of the strip; thus (00l) was oriented in the shearing-planes. It is shown later that (00l) commonly lies at a small angle to these planes.

1 The term “semi-ellipsoid” is used throughout for convenience of description but has no necessary mathematical implications.
The diagonal shear-joints developed during the compression of the reservoir-contents which accompanied extrusion; their formation was assisted by frictional effects at the metal walls, and possibly by the collapse of cavities which had existed in the ill-compacted clay.

(2) The extruded column.—The diameter of the dried column was ca. 5.5 mm. The structures revealed by films taken from the surfaces indicated by A, B and C in figure 2 will be considered in order:

A. A plane containing the axis of the column.—Extrusion has caused most of the clay-flakes to turn through angles up to 90° so that (001) now tends to be parallel to the axis of the column; the degree of parallelism is intensified towards the curved surface. Along the axis itself, however, are regions wherein the flakes, by maintaining their original disposition, still lie with (001) perpendicular to this axis. Such regions contain

![Diagram](image)

Fig. 2. Extruded cylindrical column. Key diagram to show the surfaces A, B and C from which clay-films were stripped.

residues which have escaped the shearing, involving slip on (001), which occurred during the passage through the die. Laterally they develop into trains of flakes which curve back towards the die-mouth until (001) becomes parallel to the surface of the column (figs. 1, 3). Where the reservoir had been filled with white and blue clay-discs, alternately arranged, the regions of residual orientation were found to be associated with the apices of the semi-ellipsoidal color-bands which appeared in the extruded column; these color-bands or schlieren have their convex sides directed away from the die-mouth. Such color-bands, usually in clay extruded from the "pugmills" of the ceramic industries, have been depicted but details of their microstructures are lacking (Richardson, 1939; Williamson, 1941; Haefeli and Amberg, 1949; cf. Pearson, 1944, fig. 89 for results from extruded metals). When clay-columns from pugmills are
dried, they may show preferred cracking in directions which are potentially those of the schlieren described above; freezing of the columns develops a pattern of ice-films which follows the same directions (Davenport, 1951; Haefeli and Amberg, 1949). Such phenomena prove the existence of systematically arranged planes of weakness. Comparably, the columns of the present experiments developed hair-cracks on drying or contained localized films showing very intense shearing by slip on (001); these cracks and films curved in sympathy with the color-bands and were commonly found at the boundaries between bands of different colors.

The regions of residual orientation, associated with the axis of the column, were discontinuous; they alternated with other regions in which (001) was approximately parallel instead of

![Diagram](image)

**Fig. 3. Diagrammatic axial section of extruded column showing regions of residual orientation. All broken lines represent traces of (001) but dyed clay is indicated by closer shading. In the "nose" of dyed clay a region of residual orientation is bounded on one side by a hair-crack. This region, on the other side, trespasses into the white clay. Difficulties in drawing have led to certain traces of (001) being represented as making acute angles with, instead of being parallel to, the traces of the curved surface of the column.**

perpendicular to the axis. Residual orientation was particularly evident where, prior to extrusion, there had been contacts between the faces of contiguous clay-discs. Adjacent discs showed differences in ease of deformation, associated with differences in water-content, and the location of regions of residual orientation depended on this fact as is illustrated in plate 1, figure 1. Here the more deformable blue clay is seen to have plunged forward as "noses" ahead of the less deformable white clay. In these noses (001) is largely reoriented parallel to the axis.
of the column. On the concave side of each nose is a region of residual orientation which continues into the convex part of the adjacent arc of white clay (fig. 3). In some examples the region extends completely across the arc and trespasses into the nose of blue clay which follows. The average water-contents of discs used to produce a specimen showing slightly less differential deformation of the color-bands than is visible in plate 1, figure 1 were: white discs 27 per cent, blue discs 29 per cent.

Diagonal shear-joints were obvious; they were filled with clay which had (001) approximately parallel to the shearing-planes (plate 1, fig. 2). Such shear-joints were not relics of those seen in the reservoir-filling because the fabric which they traversed had been produced from that of the filling by a process of nonaffine deformation. Their traces were straight lines or lines which curved slightly in sympathy with the curvature of the color-bands. The rearrangement of the clay-flakes during extrusion was increasingly drastic from the axis to the outside of the column (fig. 3). Thus the formation of those shear-joints which are now visible necessarily post-dated most of this rearrangement. This surmise was confirmed by examining regions where the joints crossed the color-bands at large angles, i.e., near the exterior of the column. The boundaries between the blue and the white bands were repeatedly faulted by minute movements along the shearing-surfaces which intersected them (plate 2, fig. 1).

It remains to consider the form in space of the shear-joints. In microscopical preparations stripped from planes containing the axes of cylinders the shear-joints appeared as two sets of straight or slightly curved traces intersecting at about 90° and making angles of approximately 45° with the surfaces of the cylinders. The traces maintained this disposition irrespective of how the plane of section was rotated about the axis of the cylinder. Thus they represent the curved surfaces of cones or semi-ellipsoids having axes coincident with the axis of the cylinder. Two sets of such cones or semi-ellipsoids must be postulated; the apices of one set are directed away from the die-mouth and of the other set towards it.

B. A plane perpendicular to the axis of the column.—When the film stripped from such a circular section was examined with the sensitive tint plate, it split up into four equal sectors which
Fig. 1. Photograph of axial section through reservoir-filling, zone of maximum deformation, and extruded column (fig. 1). “Noses” of the more deformable dyed clay are visible.

Fig. 2. Photomicrograph of shear-joints in axial section of extruded column. One of the two sets of joints is more perceptible. (Crossed Nicols X 60.)
Fig. 1. Photomicrograph showing faulting of schlieren by shear-joints in an area such as B in figure 1. (Crossed Nicols X 120.) Some of the field is in extinction. The boundary between the white and the dyed clay is indicated by the broken lines joining A to B. The faulting made visible by the arrangement of these lines was associated with movement along two sets of shear-joints of which one, not in extinction, is perceptible.

Fig. 2. Photomicrograph of shear-joints produced in Riedel's experiment, cf. fig. 7. The line of junction of the boards is parallel to the length of the photograph (Crossed Nicols X 63.)
were colored either blue or orange; pairs of opposite sectors showed the same color. Towards the center of the column the sectors were less distinct and the blue and orange colors became more irregular in their distribution. The general arrangement of the colors indicated a fabric in which (001) of the clay-aggregates followed the curved surface of the column but, away from this surface, took up other positions.

Circular sections across columns containing schlieren exhibited alternate rings of blue and white clay concentrically arranged about the axis of the column and increasing in thickness as the axis was approached.

The shear-joints were not discernible. This accords with their postulated form in space (see above) which suggests that here they would be represented by circular traces concentric with the point of emergence of the axis of the column. The disposition of (001), being identical with that in the surrounding fabric, would not permit these traces to be distinguished optically.

C. The curved surface of the column or a parallel surface close beneath it.—Many flakey clay-aggregates appeared. The extent of their surfaces, contrasted with the much smaller dimensions suggested by the grain-size analysis (table 2), showed that they were built of minute units not distinguishable microscopically. Their irregular extinction, more obvious in the larger aggregates, may be symptomatic of their composite nature. The flakey aggregates tended to lie with the maximum diameters of their surfaces parallel to the length of the column; the optical sign of this elongation was positive. Similar aggregates, described previously, were thought to have been synthesized during processes of plastic deformation (Williamson, 1947a). They can be formed also by casting (op. cit.) and thus were identifiable in films stripped from planes parallel to the broad surfaces of the discs used for filling the reservoir (see above). Their optical behavior could be explained in part by the presence of minute flakes which had their basal pinacoids in parallel arrangement and, in addition, a tendency for their a- and b-axes to be in common alignment. Montmorillonite is known to form aggregates with such a structure (Hauser and Le Beau, 1938: 1939: Hauser, 1951, personal communication). The optically positive elongation along the major diameters of the surfaces of the present aggregates suggests the further supposition that
the b-axes of the constituent crystalline units have a preferred orientation in this direction. It is hoped to study these polystyrene flakes in more detail.

The diagonal shear-joints were not certainly identified, probably because the angles which they made with the surfaces studied were too acute.

The existence of minute prisms of authigenic rutile, arranged preferentially on (00l) of the clay-aggregates, was mentioned earlier. The prisms, although they maintained this arrangement during the deformation of the clay, had now acquired a distinct parallelism aligned with the axis of the extruded column; the existence of a second lineation in (00l) at right angles to the first, although feasible, was not obvious on mere inspection (Cloos, 1946, p. 12). The lineation marked by the rutile-prisms was followed also by infrequent prisms of blue-green tourmaline. This tourmaline, although prismatic, was flattened in (00l) of the containing aggregate; it appeared to be authigenic. The most robust crystal noticed presented a prismatic surface 0.30 x 0.05 mm.; most of the rutile-prisms were, however, below 0.14 mm. long and had length: breadth ratios in excess of 10:1. The linear parallelism of the rutile and tourmaline was effected by slip on (00l) in their clay-mineral host.

The descriptions given under A, B and C show that the structure of the column was essentially similar to that deduced for a cylinder of electrical porcelain, extruded from a pugmill, by noting the disposition of the nonplastic ingredients alone (Williamson, 1941, fig. 8; cf. fig. 2 of the present communication).

(3) The zone of maximum deformation.—The reservoir was filled with discs of blue and of white clay, alternately arranged, and extrusion from it was arrested when only about half of the contents had been expelled. A film was stripped from a plane which contained the axis of the reservoir-cylinder and of the extruded column. Because these two axes were aligned, the film corresponded to a plane of symmetry cutting the zone of extreme deformation in which the clay was involved during its approach to and passage through the die. The color-bands, which hitherto were arched only slightly in the direction of flow, were seen to have moved forward more rapidly in the axial, as against the lateral regions, in the vicinity of the die (cf. Pearson, 1944, fig. 89 for a comparable occurrence in the
extrusion of tin). Thus were initiated the semi-ellipsoidal color-bands found in the extruded column. The clay-flakes continued to lie with (00l) parallel to the boundaries between the color-bands, both in the zone of maximum deformation and in the extruded column of which this zone is the precursor. This arrangement is analogous to that seen in flow-banded igneous rocks where tabular crystals lie with their major surfaces in the planes of the schlieren.

In the zone of maximum deformation (00l) rotated through angles up to 90°. This rotation did not represent a revolution of undeformed clay-aggregates on their own axes but was the result of progressive slip on (00l). The angle of 90° was attained only where the zone of intense shearing, adjacent to the tapering shoulders of the die, contributed to the border-zone of the clay-stream entering the cylindrical canal that led to the exit; this border-zone ultimately formed the outside of the extruded specimen, i.e., that region where (00l) was most nearly parallel to the axis of the column. On the contrary, axially lying structural elements underwent a minimum of deformation (Pearson, 1944, p. 101) and hence could survive in the column as the regions of residual orientation already described.

The structures produced where the die had square instead of tapering shoulders differed from those described in only one important particular. The shoulders contained stagnant regions demarcated from the mobile clay by narrow belts in which intense shearing had aligned (00l) in general accord with the surface of separation. In the dried clay this surface was often followed by actual hair-cracks. Similar stagnant regions developed in clay subjected to extrusion from Riedel's apparatus (Riedel, 1929a, plate 8); they have been depicted also for extruded metals (Pearson, 1944).

In the stagnant regions produced by the present experiments the original orientation was still to be found, i.e., (00l) tended to be perpendicular to the axis of the reservoir-cylinder. The fabric was, however, crossed by a meshwork of diagonal shear-joints filled with the usual positively elongated clay-strips. These joints resulted from compression, which may have been particularly intense before the increasing pressure from the piston caused the adjacent clay to separate from the potentially stagnant regions and commence its flow through the die.
In specimens partially extruded through the various dies, the shear-joints, which had appeared only sporadically in the contents of the reservoir, became abundant in the zone of maximum deformation. These joints formed a pattern resembling that figured by van Iterson for the trajectories of maximum shear-stress in comparable circumstances (van Iterson, 1947, fig. 51; Salmang, 1951, fig. 22).

The intersecting sets of diagonal shear-joints, which were so obvious in the extruded column, became well developed only as the clay entered the straight canal leading to the exit orifice (fig. 1). Thus they were formed, as has been deduced already, after the more drastic rearrangement of the fabric had ceased. Similar joints were produced by extruding clay from the same reservoir but through other dies; these dies had tapering shoulders and cylindrical exit canals which were 9.5 mm. or 3.5 mm. in diameter.

The presence of such joints implied that the issuing clay-column had been subjected to lateral compression and axial extension. The validity of this hypothesis was proved by study of the clay-strips which filled the joints. These commonly had extinction-directions which made acute angles of up to 15° with the traces of the shearing-surfaces; these directions were shown optically to be the traces of (001). The disposition of the acute angles with reference to the shearing-surfaces was compatible with the arrangement of (001) shown diagrammatically in figure 4. This figure may be compared with that given by Hills (1943, fig. 18).

The shear-joints in certain dykes, although their form in space is different, are similar in origin to the present examples if they were formed by lateral compression, accompanied by extension of the dyke along its course (Balk, 1937, fig. 15). However, there is evidence that in some instances differential movement of the dyke-walls is involved (Blyth, 1950).
Extrusion on the Micro-structure of Clay

DIAGONAL SHEAR-JOINTS PRODUCED BY
OTHER TYPES OF DEFORMATION

Introduction.—Such shear-joints may be defined as those which cut across the fabric of the clay, as revealed by the parallel disposition of (001), and are themselves filled with clay-layers having (001) subparallel to the shearing-surfaces. Their presence in extruded clay led naturally to the reinvestigation of certain types of deformation described elsewhere to see if they had been overlooked. In addition, some novel types of deformation were attempted.

Slapped discs.—The preparation and fabric of these have been recorded (Williamson, 1947a). Further attention was directed to films stripped from planes parallel to the circular faces of the discs and limited by the edges. This was to discover if the markings on the edges, previously classified as cross-joints resulting from tension, were actually shear-joints. The evidence obtained suggested that the former designation was correct and was strengthened by the results of a new experiment. The edges of the discs were slotted radially and further spreading of the clay promoted by continuing the fabrication-process. The slots became V-notches pointing towards the centers of the discs. Thus tangential tension was operating in the manner previously assumed; indeed, the stress-conditions in a peripheral sector were like those shown diagrammatically by Cloos (1946, p. 28, fig. 7a).

Compressed discs (Williamson, 1947a).—The two sets of peripheral shear-joints were found to be open or to be filled with the typical oriented clay-layers. A few of the open joints were walled with oriented clay; here progressive movement had split the previously formed clay-filling.

Rolled rods.—The preparation of these, with a brief note on their micro-structure, has already been mentioned (Williamson, 1947b). The fabric, when examined in greater detail, resembled that stated by Knopf and Ingerson (1938, p. 151) to develop from rotational rolling. As was to be expected, it was not traversed by diagonal shear-joints. Certain surface-markings could, however, be equated with the ac cracks produced, according to these authorities, by tensile strain in a direction transverse to the rolling movement.
Repeated alternations of axial tension and compression were applied manually to the rods, as in the diagnosis of "backlash" (Macey, 1948; Williamson, 1947b). The clay sheared along systems of surfaces inclined to the axis in the manner mentioned by the two investigators cited. Microscopical study revealed that the shearing had produced typical diagonal joints, of which some were open but others were filled with the usual oriented clay-layers.

*Flexed slabs.*—These were of interest because they showed a measurable extension caused by slip along shearing-surfaces. Rectangular slabs, approximately 5 x 2.5 cm. by 0.5 cm. thick, were made by a process of double-surface casting which tended

![Diagram of flexed slab showing two systems of shear-joints represented by broken lines (diagrammatic).](image)

A. Axis about which slab was flexed.

B. Axis along which elongation occurred.

to orient (001) parallel to their rectangular surfaces. They were flexed onto a circularly curved surface 5.7 cm. in diameter and at once gently flattened. They were then flexed in the opposite direction and again flattened. This procedure constituted one cycle of deformation. The flexing was about an axis perpendicular to the length of the slab (fig. 5). After five cycles of deformation two systems of shearing-surfaces had become obvious: these intersected along lines parallel to the axis mentioned. Slip on these surfaces produced elongations of 3%-5% parallel to the lengths of the slabs.

Microscopically the shear-joints were seen to be unusually wide and to be filled with oriented clay-layers. Some joint-fillings were so robust that they appeared as ramifying streaks, in which (001) was approximately parallel to the walls and was marked
by rutile-prisms which had maintained their tendency to lie in this plane. The streaks enclosed tiny fragments of the matrix in which the general fabric of the slab was still preserved.

**Rotationally strained slabs.**—Various investigators have caused shear-joints to form in plastic clay while they were elucidating, by analogy, certain natural deformation-mechanisms which have affected rocks; the micro-structures of the clay in or near these shear-joints have not been recorded. To remedy this deficiency, an experiment made by Riedel (1929b) was repeated in a modified form. A slab of clay ca. 6.5 x 4.0 cm. by 2-3 mm. thick was cast in a manner which oriented (001) parallel to the two major faces of the slab. The slab was placed symmetrically across the junction between two horizontal wooden boards (fig. 6). One board was then displaced for a short distance in a direction parallel to its line of junction with its neighbor (cf. Hills, 1943, figs. 21 and 88). This movement produced a rotational strain in the clay-slab adherent to the boards. The results of this strain were investigated by allowing the slab to dry and examining a clay-film stripped from a horizontal surface about 1 mm. above the line of junction of the boards. Two sets of vertical shear-joints were visible (plate 2, fig. 2). The major set was arranged en echelon at an angle

![Fig. 6. Rotational strain of clay-slab lying across the junction between two boards, with shear-joints indicated (diagrammatic).](image-url)
of a few degrees to the line of junction of the boards. The less well-developed set was at angles of 80°-90° to the first. The clay-strips in both sets of joints extinguished at angles of up to 15° with reference to the traces of the shearing-surfaces; this extinction-direction was, as usual, the trace of (001). The arrangement of the extinction-angles was compatible with the dispositions of (001) indicated diagrammatically in figure 7: this figure may be compared with those given by Turner (1948, fig. 39a and b).

THE ORIENTING MECHANISM IN DEFORMED CLAY

If the nomenclature of petrofabric analysis is adopted, the specimens described may be classified as: (1) non-tectonites which showed depositional orientation marked by parallelism of (001), i.e., cast discs or slabs; (2) tectonites, i.e., specimens deformed by extrusion or other processes.

The oriented fabrics produced, for example, by extrusion resulted from componental movements which were essentially not the external rotation of the clay-aggregates but the slip of their constituent flakes along (001). The existence of such an effect was implicit in earlier descriptions of the fabric of "slapped" discs (Williamson, 1947a, p. 650 ff.). The effect is reminiscent of the mechanism postulated by Sander, in contrast to Schmidt, to explain the rearrangement of mica during the natural deformation of rocks (Knopf and Ingerson, 1938, pp. 166-167; Turner, 1948, pp. 270-274). The slip in clay-aggregates is, however, not along glide planes in a crystal-lattice but occurs within the water-layers which separate the opposing (001) surfaces (Williamson, 1951). However, certain dried montmorillonitic films slip on (001), in a manner more directly analogous to that postulated for mica by Sander, when they are hammered in a special way (Hauser and Le Beau, 1939).

The fillings of the diagonal shear-joints had a fabric which truncated that of the host except in a few examples where there was a curving transition between the orientations of (001) in the two fabrics. The extreme fineness of most of the clay-particles doubtless enhanced their ability to slip into and reorient themselves along shear-joints, even where the movement along such joints had been very slight; thus was produced
a clay-strip which commonly appeared to be demarcated from the differently oriented matrix.

The joint-fillings, as seen in sections normal to the shearing-surfaces, showed an extinction which, although commonly sharp, was rarely parallel to the traces of these surfaces; the extinction-direction, which was the trace of (00l), made a small angle with them. The implication is that differential movement of the walls of the shear-joints, although not usually adequate to align (00l) parallel to these walls, sufficed to leave (00l) at a small angle to them. A similar structure is seen in the slip-zones of the Melibokus granite which contain inclined but parallel biotite-flakes (Knopf and Ingerson, 1938, plate 4, fig. 1); mimetic crystallization of biotite appears to be involved in contrast to the actual slip of clay-flakes recorded in the present experiments. It is interesting to find that, according to Allen

![Diagram](image-url)

Fig. 7. Traces of (00l) in shear-joints of Riedel's experiment. AA' line of junction of the boards. (Diagrammatic, cf. fig. 6 and plate 2, fig. 2).

(1945), clay-minerals themselves were oriented in certain fissure-fillings by processes of mimetic crystallization.

The structure of dykes described by Blyth (1950) also invites comparison; these dykes, although intruded into unshered country rocks, showed vertical shearing-surfaces parallel or at a small angle to their walls. This phenomenon was ascribed to relative movement of the bounding walls in a direction parallel to their course. The orientation of (00l) in the clay joint-fillings might, at first sight, be assumed to correspond to that of the shearing-surfaces in the dykes, because of the similar formative mechanism. Comparison of figures 4 and 7 with various figures given by Blyth shows, however, that the acute angle made by (00l) with the direction of movement of the adjacent bounding wall of clay points in a direction opposite to that of the corresponding acute angle made by the shearing-surfaces and the direction of movement of the associated dyke-wall; this apparent anomaly appears to have been explained by Blyth himself (1950, p. 415, esp. fig. 11).
The production of systems of shear-joints in plastic clay could be symptomatic of a lattice-like structure which is, however, imperfect. On this hypothesis, clay-particles separated by water-films tend to take up positions in a force network such that potential energy is reduced to a minimum. Many particles fail to secure such positions and hence slip is more readily initiated in their vicinity. Macey, in particular, has elaborated such ideas (Williamson, 1951, esp. p. 18 and refs. cit.).

In conclusion it may be recalled that van Iterson (1947) has emphasized the inapplicability of the term "slip-planes," i.e., the "shear-joints" of the present context, to certain structural discontinuities which accompany plastic flow. However, slip-planes were undoubtedly produced during our experiments (cf. plate 2, fig. 1).

SUMMARY

A fine-grained kaolinitic clay was deformed plastically and the resulting micro-structures investigated by a technique in which coherent films were stripped from smoothed clay-surfaces. Particular attention was given to fabrics produced by extrusion-processes in which a cylinder was forced through a die to form a second cylinder narrower than but coaxial with the first. The original cylinder was built of contiguous discs in which were clay-aggregates having (00l) arranged at right angles to its axis. In the extruded cylinder (00l) had turned through angles up to 90° from its original position but this was not caused by external rotation of the clay-aggregates. It resulted from cumulative slip along (00l) in which the interstitial water between the clay-flakes was involved. The use of an alternation of stained and unstained clay-discs caused semi-ellipsoidal color-bands to develop in the resulting extruded cylinder. The disposition of (00l) was co-planar with the boundaries of these schlieren. In the outer layers of the cylinder was seen a linear parallelism to the axis; this was marked by minute prisms of rutile and tourmaline which lay on (00l) of the clay-minerals and thus in the planes of the schlieren.

Diagonal shear-joints crossed the fabric of the extruded cylinder. They contained clay-layers having (00l) at a small acute angle to the shearing-surfaces. The arrangement of the acute angles was compatible with the formation of the cylinder by a process of lateral compression and axial elongation. Simi-
lar shear-joints were produced by a variety of other deformation-processes. Differential movement of the walls of the joints produced the structures found in the clay-layer between these walls; comparison is made with similar structures in dykes.

The formation of sets of shear-joints in plastic clay accords with the hypothesis that the clay-particles, separated by water, are arranged as a lattice in which many fail to achieve positions of minimum potential energy; hence are found regions in which shearing is more readily initiated.

ACKNOWLEDGMENTS

We are indebted to Miss B. C. Terrell for a chemical analysis, to Mr. A. Frostick for a grain-size determination, and to Mr. A. J. Gaskin and Dr. G. F. Walker for the preparation and interpretation of X-ray diffraction photographs. It remains to thank Dr. A. R. Alderman and Dr. W. Boas for their helpful criticism.

The work described in this paper was carried out as part of the research program of the Division of Industrial Chemistry of the Commonwealth Scientific and Industrial Research Organization, Box 4331, G. P. O., Melbourne, Australia.

REFERENCES


Haefeli, R., and Amberg, G., 1949. Struktur und Schwinduntersuchungen an Ziegeleitonen: Schweizer. Tonwaren-Industrie, vol. 52, no. 1, pp. 4-7; no. 2, pp. 4-7; no. 3, pp. 4-7; no. 4, pp. 4-6; no. 5, pp. 7-10; no. 6, pp. 4-6.


Commonwealth Scientific and Industrial Research Organization
Division of Industrial Chemistry
Melbourne, Australia