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**THREE-DIMENSIONAL DEFORMATION OF A STATISTICALLY
HOMOGENEOUS ANISOTROPIC MATERIAL AT HIGH STRAINS,
BY FORMATION OF EXTENSIONAL DUCTILE SHEARS**

by

Athanassios Ganas, Ptychion

A thesis submitted to
the Faculty of Graduate Studies and Research
in partial fulfilment of
the requirements for the degree of
Master of Science

Ottawa-Carleton Geoscience Centre

and

Department of Earth Sciences

Carleton University

Ottawa, Ontario

February 6th, 1990

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Thesis Supervisor
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March 5th, 1990

ABSTRACT

Statistically homogeneous multilayers possessing an intrinsic rheological anisotropy (Biot, 1965) were experimentally deformed at high strains, in flattening and constrictional strain fields. Incremental deformation was irrotational, and isochoric. The multilayers were composed of plasticine layers (of 1mm thickness) alternating with thin films of petroleum jelly. In both experiments, extension was allowed to occur along the anisotropy plane and a significant part of bulk finite strain accommodated by slip along extensional ductile shears (EDS) of "octahedral" geometry, that do not appear to rotate with progressive deformation. EDS form at selected sites (heterogeneities) of the multilayers, where slip is canalised because of the anisotropy, and grow into finite structures because of strain-softening.

In constriction, EDS pattern is dominated by four, high-angle, oblique-slip, orthorhombic sets; in flattening, by a combination of four, high-angle, dip-slip, orthorhombic sets and four, low-angle, oblique-slip, orthorhombic sets (because finite strain deviated from axially symmetric shortening, as intended).

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"To make an experiment work the experimenter must deliberately create a setup of forces and motions and produce a fault, joint, fold or a dome. If his first arrangement does not work he must try another one. During this process he will inevitably come to grips with cause and effect... Besides that, experimenting is a good deal of fun."

Ernst Cloos (1955)

Chapter I. INTRODUCTION

I.1 Purpose of study.

Extensional fault systems have been extensively studied by use of model experiments (e.g Cloos, 1955; Oertel, 1965; Horsfield, 1980; McClay and Ellis, 1987; Vendeville, 1988; Serra and Nelson, 1988) with emphasis on the nucleation, propagation, and sequences of faulting and on the geometric evolution of individual fault planes. Normal faults of planar geometry usually occur as conjugate sets, and are typically oriented at a high angle to the direction of stretching. A common basis of most experiments, however, is that, they were undertaken in plane strain conditions, thus ignoring extension along the intermediate stress/strain axis which may be important during natural straining of rocks (Bott, 1959; Reches, 1978; Krantz, 1989).

Theoretical models for faulting of materials in a three-dimensional strain field have been proposed by Reches (1978, 1983), and by Krantz (1987, 1988, 1989). These authors suggested that multiple faults, composed of three, four or more sets of faults, and rhomboid patterns of faults may form when a body is strained three-dimensionally. However, there are certain limitations associated with these analyses. First, they are incomplete because they say nothing about how the faults developed, i.e, they are *post-failure/yielding* model. Secondly, they have been derived for infinitesimal strains, thus, ignoring subsequent fault kinematics during progressive deformation. Finally, they are concerned with three-dimensional deformation of

practically isotropic materials, since they assume that the body to be deformed contains pre-existing, *randomly oriented* planes of discontinuity.

On the other hand, the development of brittle and ductile structures (including faults) within a statistically homogeneous, anisotropic (layered) material has been examined under plane strain conditions only (for example, Donath, 1961, 1968; Cobbold et al., 1971; Watkinson, 1975, 1976; Platt and Vissers, 1980; Harris and Cobbold, 1985; Latham, 1985a, b; Hanmer, 1986; Arch et al., 1988; Peltzer and Tapponier, 1988; Shea and Kronenberg, 1989).

In the present experimental study the author presents a qualitative model for a three-dimensional, constant volume deformation of a statistically homogeneous anisotropic material, such as for instance rocks that acquire pervasive cleavage, foliation and/or lineation, accommodated by *extensional ductile shears* (EDS for short). For the purposes of this study, a ductile shear is a planar discontinuity regardless of whether it is marked by extreme ductile deformation (i.e. mylonitic production) or not, across which there has been no loss of cohesion (Wise et al., 1984), and which exhibits a tangential displacement parallel to itself. Shear nucleation, propagation, and finite geometry will be examined as well.

In this introductory chapter, a synopsis on faulting theories is presented first, followed by a brief discussion on the role of anisotropy in rock deformation, and in particular, the concept of rheological anisotropy as put forward by Maurice Biot (1965) is examined in detail. This preliminary information may be useful to the reader because this study, to the best of my knowledge, is the first attempt to incorporate planar anisotropy effects in a three-dimensional, fault-accommodated

straining of elastic-plastic materials.

1.2 Orthorhombic faulting and 3-D straining of rocks.

The widely accepted faulting theory of Anderson (1951) and associated theories (e.g., Sibson, 1974) when applied to isotropic materials that follow a Coulomb frictional behaviour, predict initiation of two sets of faults occurring as conjugate planes, inclined at acute angles to the direction of maximum compression and which intersect in the intermediate stress and strain directions (Figure 1a). The plane perpendicular to the intermediate axis contains both the maximum and minimum stress and strain directions and the fault slip vectors (Hobbs et al., 1976; p. 329). There is no slip component (i.e., no strain) in the direction of the intermediate axis and therefore the strain accommodated by faulting is plane strain.

Conjugate faulting is also predicted for frictionless isotropic materials ($\phi=0^\circ$; ϕ is the angle of internal friction), according to the same plane strain approach of fault mechanics. But, in this case, the conjugate fault sets are inclined along the maximum shear stress directions, that is, at 45 degrees to the direction of the maximum compressive stress (for example, Ranalli, 1987, p. 34; Harris and Cobbold, 1985, Figure 1). However, recent work suggests that conjugate faults are only a special case of a general, fault-accommodated deformation. Experiments with isotropic materials (Oertel, 1965; Reches and Dieterich, 1983) have produced fault systems with four sets of synchronous faults, arranged in orthorhombic symmetry. Oertel (1965) deformed clay cakes (7 and 9cm thick), by extending or shortening the

Figure 1. a) Conjugate fault planes (shaded) and principal stress directions in isotropic rock, with one principal stress vertical. Lower hemisphere projections, with the primitive circle representing the horizontal plane (after Hobbs et al., 1976). Note that angular relationships depicted here, are those of fault initiation, and that, the faults intersect along the intermediate stress axis. If the principal axes of the infinitesimal strain ellipsoid coincide with the axes of stress, then this is the axis of no strain.

b) Stereographic projection of orthorhombic fault sets in the clay experiments of Oertel, (1965) (lower hemisphere). In both elongation (left) and compression (right), four high-angle fault sets develop in the clay. Great circles represent the traces of fault planes, and solid half circles show the slightly oblique slip direction, on side with downward component of dip. Rest of the symbols represent poles to fault planes in other experiment series.

model in one direction, while the top and sides of the model were free surfaces. Four or more sets of faults with orthorhombic symmetry formed. To explain the fault pattern developed (Figure 1b), Oertel (1965) proposed that a mechanism of interference between the various fault sets was the controlling factor. Reches and Dieterich (1983) performed *polyaxial* tests on cubic samples (of about 2.2 cm each edge) of sandstone, granite and limestone, at room temperature. The fault pattern obtained, tended to be orthorhombic, with three or four high-angle fault sets. The development of this pattern was attributed to the three-dimensional character of the deformation.

Several field studies have also demonstrated that more than two sets of faults develop during a single episode of deformation (Reches, 1978; Mitra, 1979; Aydin and Reches, 1982; Krantz, 1988; Tibaldi, 1989). Such faults form a network that usually has a rhombohedral pattern, both in map and cross-sectional views, and they are of extensional character. Similar rhomboid patterns of normal faults have been also described in other fault-concerned field studies (see Reches, 1978; and Tibaldi, 1989, for literature reviews; Bruhn and Pavlis, 1980).

Reches (1978, 1983) analysed the infinitesimal and isochoric deformation of an idealised material due to slip along sets of faults, and suggested that four sets of faults are necessary to accomodate three-dimensional strain, if the material is confined by rigid boundaries that cannot rotate. In addition, if the axes of principal stress and strain coincide, then, for three-dimensional deformation in which there are four sets of faults, these activated faults must have orthorombic symmetry. Further, he showed that fault geometry and slip direction is a function of the ratios of the principal strains (Figure 2), especially the relative magnitude of the intermediate

Figure 2. a) Poles to preferred faults in the three-dimensional strain for various values of k (ratio of the principal strains, E_2 to E_1), after Reches (1978). X_1, X_2, X_3 , are the principal strain axes, solid lines refer to solutions in eqs. 11 of Reches (1978; p. 121), broken lines to solution for the complete range of k . Note that, this is a Wulff net projection.

b) Preferred faults and slip orientations for two specific values of strain ratio k (-0.5 and 1). The faults are shown as triangles intersecting the principal strain axes at coordinates corresponding to k . Heavy arrows indicate slip direction (after Reches, 1978).

In ideal flattening strain ($E_2 = E_3$, both positive), $k = -0.5$, and the direction cosines of the normal to an orthorhombic fault set yield : $\theta_1 = 45^\circ$, $\theta_2 = \theta_3 = 60^\circ$, where $\theta_1, \theta_2, \theta_3$ are the orientations of the normal with respect to the principal strain axes. The orthorhombic faults dip at 45° with respect to the compression direction E_1 (shown here in the equatorial plane; the projection of 30° shown in figure a is with respect to the extension direction E_3), and strike $\pm 45^\circ$ away from each of principal extensions, as seen on the principal plane E_2E_3 (again the projection shown in figure a is on the E_1E_2 principal plane). In figure b, this strain state implies reverse oblique-slip faulting, however, if we consider the compression direction vertical, and the direction cosines of the slip vector (Reches, 1978, p. 121), then dip-slip orthorhombic normal faults are obtained (an identical result has been also derived by Krantz, 1988).

In ideal constrictional strain ($E_1 = E_2$, both negative), $k = 1$, and the direction cosines of the normal to an orthorhombic fault set yield : $\theta_1 = \theta_2 = 60^\circ$, $\theta_3 = 45^\circ$. In figure a, the orthorhombic faults dip at 45° with respect to the extension direction E_3 , and strike $\pm 45^\circ$ away from each of the shortening directions, as seen on the E_1E_2 principal plane. In figure b, this strain state implies reverse dip-slip faulting. If one interchange the E_1, E_3 principal directions, however, an orthorhombic normal fault set is obtained, inclined at 30° to E_1 , and carrying an oblique slip vector to the down-dip direction.

b

strain, if the resistance to slip along the faults is cohesive, independent of the normal stress (Reches, 1978), but in part they are also a function of the friction angle, if slip occurs along individual surfaces that follow Coulomb frictional behaviour (Reches, 1983).

Four orthorombic fault sets or eight octahedral slip surfaces in space define an octahedron (in Figure 2b only the upper half is shown), which for infinitesimal deformations may describe the state of strain in both elastic and linear viscous materials.

1.3 Faulting in the plasticity field

A second alternative approach to structural analysis of faulted terranes, is to postulate that the material within which faults contained, rheologically behaves as a rigid-plastic substance (e.g., Ooé, 1960; Cummings, 1976; Tapponier and Molnar, 1976). These two-dimensional analyses involved a comparison of the mapped faults to a theoretical pattern of maximum shear stress trajectories (slip lines). In plasticity theory, the most widely used method of defining failure in isotropic, homogeneous materials, is by the maximum distortion-energy theory, also known as von Mises theory (for example, Chung, 1988, p. 315).

The von Mises yield criterion can be related to such useful quantities in continuum mechanics as the second invariant of the deviatoric stress tensor (Ranalli, 1987, p. 100) or the square of the octahedral shear stress (Chung, 1988, p. 317). The plastic mass under compression yields along two sets of isogonal (and orthogonal,

because of the assumption of frictionless behaviour) trajectories of maximum shear stress (slip lines), which are also parallel to the directions of maximum rate of shear strain, i.e to the characteristic directions of the flow field (Odé, 1960). Yielding is independent of the hydrostatic stress state but, is affected by the magnitude of the intermediate principal stress which is expected to play an important role during three-dimensional straining (Bott, 1959).

In continuum mechanics (Chung, 1988, p. 90), the octahedral shear stress is defined as the resultant shear stress on a plane that makes the same angle with the three principal stress directions. Such a plane is called an octahedral plane (Figure 3); eight such synchronously-formed planes occupy an octahedron in space. If bulk deformation is irrotational, the author suggests that fault geometry in a 3-D plasticity field may be represented by such an octahedron, because of the need to form four fault sets to accommodate strain (Reches, 1978; see also Oertel, 1965, p. 376). Then, it is reasonable to expect that in 3-D straining of an isotropic, incompressible, ideal plastic material, the ductile faults (similar to ABC in figure 3), *immediately after yielding*, will be arranged with orthorhombic symmetry with respect to the principal stress/strain axes. Moreover, the orientation and configuration of the octahedral faults do not change by subjecting the plastic material to different straining conditions because yield is independent of the mean stress (see above), and therefore any change in mean stress level displaces the co-ordinates of the octahedral planes by equal amounts in all principal directions (an important difference with predictions cited above). What changes however, is the pitch of the maximum shear stress resolved on the plane (Figure 3).

Figure 3. Configuration and geometric relationships of an octahedral plane in the engineering sense (after Chung, 1988). The direction cosines of a normal (n_1) to the octahedral plane relative to the principal axes are $1/\sqrt{3}$, or the octahedral plane is inclined 54.7° apart from the origin. This equality of the direction cosines of the plane ABC, implies that $\overline{OA} = \overline{OB} = \overline{OC}$ and consequently, $\Delta OAB = \Delta OBC = \Delta OAC$, and so the angles ω are all equal to 45° . Thus, the strike of the octahedral plane will be at ± 45 degrees to the horizontal axis X, and also dips with respect to the horizontal at an angle of $90^\circ - \phi = \theta = 54.7^\circ$. Note that, by definition, the orientation of the octahedral plane does not change by subjecting the plastic material in different straining regimes (i.e. constriction, flattening). What changes is the pitch of the maximum shear stress resolved on the octahedral plane (see also Bott, 1959). In flattening strain (Z is the principal shortening axis), the slip vector trends 135° (as projected on the X, Y principal plane; negative X points to the North) and plunges 54.7° (i.e. pure dip-slip movement); in constrictional strain (X is the principal extension axis) the trend and plunge of the slip vector are $206/25^\circ$.

Theoretical considerations presented so far, did not take into account the role of anisotropy, which is a significant mechanical property of materials. The mechanics of faulting, however, are in part a function of the material properties of the medium being deformed, and in particular, of their directional dependence, if the medium possesses a layering.

1.4 Anisotropy and rock deformation by faulting.

Layering in materials can be either compositional, a series of parallel discontinuities (e.g., a sequence of sedimentary rocks with infinitesimal bedding contact strength) or an inherited texture of tectonometamorphic or magmatic origin (for example, see Cobbold, 1976, figure 2). Due to such layering, the material acquires an anisotropy, which is likely to alter its response to a fault-accommodated, isochoric deformation.

In plane strain ductile deformations, the implications of slip-line theory for anisotropic materials are unclear because the principal directions of stress and strain rate are in general not parallel (Platt, 1984).

In plane strain brittle deformations, an intrinsic anisotropy (of planar character) tends to localise strain along a single set of fracture surfaces (e.g Jaeger, 1960). In particular, two sources of intrinsic anisotropy and their effects have been investigated in detail. First, consider a homogeneous material with a single plane (or a set of parallel planes) of weakness which has a different cohesive shear strength and coefficient of internal friction from the rest of the material. A single

set of parallel faults/fractures formed within a plutonic rock mass may be a corresponding geological example. The role of intrinsic anisotropy here, has been demonstrated from experimental plane strain deformation of test specimens that contain pre-existing fractures. Handin (1969) showed that fractures oriented at angles as high as 65° to σ_1 can be activated as faults, as well as that the critical stress level required to cause faulting along pre-existing fracture surfaces is less than that required to break an intact specimen of the same lithology.

Secondly, consider a homogeneous, layered material which possess a structural anisotropy, such as rocks with tectonically induced planar and/or linear fabrics. As a geological example, consider a mica schist which, possessing a schistosity, exhibits a variation of cohesive shear strength with direction. Donath (1961), in plane strain experiments, showed that the orientation of the planar anisotropy influences breaking strength (differential stress at failure) and fault orientation within test specimens. The least breaking strength is observed when the anisotropy is inclined at 30° to the loading axis (σ_1). The angle of shear fracture to σ_1 is dependent on the inclination of the anisotropy (see also Donath, 1968, plate 2). When foliation is at a very high angle ($> 75^\circ$) to σ_1 , faulting follows the Coulomb-Mohr failure criterion, while shear fractures develop along the foliation for 15° , 30° , and 45° orientations.

As another example, Arch et al., (1988) produced low-angle shear zones in experimentally deformed clays, and concluded that their "non-Coulombian" orientation is influenced by the anisotropy of the primary fabric.

Finally, a new approach to a general, fault-accomodated deformation of

a layered material can be adopted by using the theory of incremental deformations of Biot (1965). According to this theory, layering can be represented (to a first order of approximation), by a statistically homogeneous (Patterson and Weiss, 1961) material of anisotropic rheology (Biot, 1965; Cobbold et al., 1971).

Rheological anisotropy is defined as a difference in the stress/strain moduli for shear or compression in a given direction (Biot, 1965). It is a fundamental mechanical property of a layering and therefore it is likely to be an important factor contributing to faulting of rocks. Biot's approach at the development of structures is based on the following principles :

- (a) the material is linear elastic or Newtonian viscous;
- (b) it is anisotropic and statistically homogeneous;
- (c) the material deforms by plane strain;
- (d) the deformation is isochoric;
- (e) the material possesses orthotropic symmetry (i.e., the principal stress axes are symmetrically oriented with respect to the symmetry axes of the material properties);
- (f) the rectangular boundaries of the body remain undeflected.

The central theme of Biot's (1965) analysis, the rheological anisotropy, is expressed as a ratio M/L , where M and L are the shear and compressive moduli respectively, that were introduced to express the material constants N and Q (resistance to shear and compression) and their stress dependence. Therefore, materials for which M and L are very different have a high degree of anisotropy. It can be shown that there are at least two types of structures which are of geological

interest (Type 1 and 2 instabilities, Cobbold et al., 1971; First and Second Kinds of instability, Biot, 1965). Both follow *characteristic lines* which in the theory of plasticity (e.g., Odé, 1960) have important physical significance (they are the characteristic directions of heterogeneous simple shear along which local disturbances within a material tend to propagate).

Type 1 structures develop in materials where $M/L > \frac{1}{2}$ and Type 2 structures in materials where $M/L < \frac{1}{2}$. Type 2 structures (Cobbold et al., 1971) include both normal and reverse kink bands, and differ from Type 1 structures (sinusoidal buckles and internal boudins) in that their axial planes are in general not normal to the maximum principal compression. *The angle that the axial plane of a Type 2 structure makes with the maximum principal compression direction depends on the anisotropy of the material.* It ranges from 45° to 90° (Cosgrove, 1976, figure 5). In a material with a high degree of anisotropy (i.e., $M/L \rightarrow 0$) the Type 2 structures make an angle approaching 45° to the principal compression direction. Paradoxically, such angular relationships are also predicted for isotropic frictionless materials (see above). However, in materials with a lower degree of anisotropy the angle increases until in materials with $M/L = \frac{1}{2}$ the axial planes of the structures that develop are at 90° to the compression direction. It can be seen (Figure 4) that the expression of buckling instabilities in anisotropic materials depends on both the degree of anisotropy and the orientation of the layering with respect to the maximum compression direction.

A first weakness of Biot's theory is that the predicted buckling displacement pattern is only valid for the first increments of plastic deformation. However, by using physical models constructed from plasticine (Cobbold et al., 1971)

to investigate the growth of buckling instabilities into finite structures, it is possible to demonstrate that the geometric amplification of the initial buckling displacement pattern gives a reasonable approximation to the geometry of the finite structures (Cobbold et al., 1971; Cosgrove, 1976). In addition, experimental work has shown that the development of buckling instabilities in anisotropic materials is not restricted to conditions of orthotropic symmetry (Cobbold et al., 1971, figures 14, 17, 18 ; Cosgrove, 1976, plate 2a, b, and c).

Another weakness of Biot's theory is the assumption that the material deforms permanently according to a linear viscous flow law. However, many laboratory experiments on rocks made to determine the stress-strain rate relationships, show that the empirical flow laws are generally not those of Newtonian rheology (for example, see extensive reviews in Kirby, 1985; Carter and Tsenn, 1987).

A reexamination of Biot's theory, including the effects of bending resistance and non-linear material properties by Latham (1985a, b) showed that oblique localized shearing into bands is an end-member process associated with "internal" instability. Latham (1985a), using a power-law elastic model, showed that a homogeneous isotropic material will have an *incrementally induced* anisotropic response when the stress/strain behaviour is nonlinear. In addition, he showed that incremental anisotropy is also induced in the average properties of a multilayer with a power-law flow law. For example, if each layer within a multilayer has an identical stress exponent $n=3$, and there is no competence contrast, then TYPE 2 instabilities develop, even if individual layer thicknesses are different (Latham, 1985a, figures 4, 5). Latham's characteristic directions (non-uniform displacement

fields) that offer the least resistance to layer-parallel compression follow angles of 30° - 45° to the bulk extension direction.

Figure 4. Summary of the combined effects of degree of anisotropy and orientation of layering on the form of internal fold structures which might develop in a statistically homogeneous rock (after Cobbold et al., 1971). The angle β is that between the compression direction and the layering or foliation. Note that when σ_1 is normal to the layering, as the degree of anisotropy is increased, a transition occurs between internal boudinage and conjugate extensional kink bands.

The above considerations have important implications when compared with fault pattern predictions presented above. In layer-normal shortening, the presence of a rheological anisotropy (in plane strain conditions) triggers initiation of two conjugate sets of low-angle normal faults of planar geometry, which is directly applicable to the case of low-angle normal faulting, at various scales, commonly observed in extensional terranes (for example, Wernicke and Burchfiel, 1982; Reynolds and Spencer, 1985). Shear instabilities (conjugate or single sets of reverse and normal ductile shears) may be the yielding (and high strain-rate ?) equivalents of reverse and normal kink bands and as a consequence we would expect extensional ductile shears to be inclined at an angle 0° - 45° to the layering, 45° - 90° to the maximum compression direction. In the field, when conjugate shear zones are observed, the angle of initiation between the shear zones and the compression direction is commonly greater than 90° (generally 90° - 130° , Ramsay, 1980, 1982).

1.5 Method of study.

Physical modelling of a three-dimensional, fault-accommodated straining of anisotropic materials was achieved by experimental work at the Department of Earth Sciences at Carleton University, Ottawa, during the June 1988-May 1989 period. The experimental stages consisted of: preparation of anisotropic multilayers using plasticine as modeling material and deformation of the multilayers at high strains using a deformation machine (Figure 7) provided by the Department of Geology of the University of Toronto.

Previous studies involving fault modeling have primarily used clay (e.g., Cloos, 1955; Oertel, 1965; Arch et al., 1988; Serra and Nelson, 1988) and sand (e.g., Horsfield, 1980; McClay and Ellis, 1987; Vendeville, 1988) as a modeling material, because they were mainly concerned with extension of the brittle upper crust and its sedimentary cover. These materials, however, are associated with many limitations, in particular in not having high degrees of anisotropy or competency contrasts.

In our experiments, plasticine was chosen, because it is a well known modeling material for geological research (see below), in which narrow shear zones develop with increasing strain, both in ideal simple shear (Harris and Cobbold, 1985), and in pure shear (Dubey, 1980a; Peltzer and Tapponier, 1988). It is regarded as one of the most rheologically adequate materials, for modeling strain localization in continental lithospheric rocks (see Peltzer and Tapponier, 1988, for a review). The experiments are not intended as typical scale models (e.g., McClay and Ellis, 1987), because only the strain field, not the stress field, was of any concern.

Pilot experiments in the constrictional strain field were conducted first, to test the homogeneity of the deformation and boundary effects, followed by the main experiments in both constrictional and flattening strain. Each experiment ran at a constant temperature of $25 \pm 1^\circ\text{C}$ and at atmospheric pressure conditions, needed approximately twenty-four working hours to complete (including model cutting and photographing), and was conducted by Dr. S.K. Hanmer and the author.

Chapter II. DESCRIPTION OF THE EXPERIMENTAL WORK

II.1 Plasticine as a modeling material.

Plasticine is a modeling material that has been widely used to simulate ductile deformations in geological research (Cobbold et al., 1971; Freund, 1974; Dubey and Cobbold, 1977; Dubey, 1980; Behzadi and Dubey, 1980; Tapponier et al., 1982; Harris and Cobbold, 1985; Hanmer, 1986; van den Driessche and Brun, 1987; Peltzer and Tapponier, 1988). The exact composition of plasticine is still unknown because of patent restrictions. It is probable that it is (McClay, 1976) a mixture of oils, wax, dyes and a mineral filler. S.E.M examination of this mineral filler (McClay, 1976) showed small platy cleavage fragments of calcite and dolomite, coccoliths and other microfossils. The grain size varies from 0.5 μm to 10 μm .

Plasticine rheology has been investigated by McClay (1976) and Peltzer and Tapponier (1988) in plane strain compression and stress relaxation tests (Figures 5, 6), at constant temperature. In brief, all constant strain rate compression tests indicate that plasticine deforms by non-linear viscous flow, governed by a constitutive law of the type $\dot{\epsilon} = K \sigma^N$, where $\dot{\epsilon}$ is the strain rate, σ the applied stress, K a constant depending exponentially on the temperature, and N is the power-law exponent ranging between 6 and 9. McClay also reported the appearance of microshears at the strain hardening stage of the deformation (seen in all tests at strains greater than 30%). I suggest that greater finite strains cannot be accommodated by homogeneous penetrative flow of plasticine; therefore microshears

(probably EDS) form and become the dominant mechanism of the deformation.

Stress relaxation tests indicate complex behaviour with probable microstructural changes during deformation, possibly due to the development of a grain fabric. Indeed, such a grain fabric seems to be responsible for the drastic difference observed between layer-parallel and layer-normal shortening of plasticine models, under plane strain conditions (Figure 6). Therefore, the influence of an anisotropy of textural origin in plasticine deformation is to change the mode of the deformation itself, i.e., plasticine deforms by slip along planar deformation zones (e.g., EDS), when the direction of shortening is at a high-angle to the shape fabric. The author suggests that this mechanism of plasticine deformation can be called a *non-penetrative shear thinning*, and that it is directly comparable to the operation of conjugate ductile shear zones (e.g., Ramsay and Huber, 1987, p. 617) that leads to the formation of "internal boudinage" structure (see Figure 6a).

However, there can be another source of intrinsic anisotropy in plasticine multilayers before deformation. This is the lubrication of layer interfaces facilitating slip along the layering, thus, rendering the material weaker in shear than in compression along this direction and across the layering as well (e.g., Cobbold et al., 1971). Plasticine deforms again by inhomogeneous flow, along characteristic directions where strain localisation occurs. In layer-normal shortening, conjugate extensional kink bands form at approximately 40° to plasticine layering. Similar angular relationships ($40^\circ \pm 4^\circ$) were observed in simple shear experiments using plasticine models (Harris and Cobbold, 1985), where layering was inclined to the shear plane of the deformation.

Figure 5. Stress-strain curves for plane strain compression tests on isotropic plasticine blocks (after McClay, 1976). (a) Standard hard plasticine 25°C. (b) Standard white plasticine 25°C. (c) Special soft plasticine 25°C. (d) Special soft plasticine 45°C.

At 25°C all curves show poorly defined yield transitions from elastic to plastic behaviour at strains from 2 to 5%. Notice that the yield or flow stresses decrease with strain rate for all types of plasticine. Notice also the difference in flow stress levels between (d) and (c); plasticine fluidity is not an intrinsic property of the material but depends on external conditions such as temperature.

Figure 6. Uniaxial plane strain compression tests on plasticine cubes (5cm)³ by Peltzer and Tapponier, 1988. Numbers on curves refer to photographs. (a) Plasticine layers perpendicular to shortening direction, $\dot{\epsilon} = 3.3 \times 10^{-4} \text{ s}^{-1}$, $T = 21^\circ\text{C}$. (b) and (c) Plasticine layers parallel to shortening direction, $\dot{\epsilon} = 3.3 \times 10^{-4} \text{ s}^{-1}$, $T = 21^\circ\text{C}$, and $\dot{\epsilon} = 6.6 \times 10^{-4} \text{ s}^{-1}$, $T = 27^\circ\text{C}$, respectively.

When bonded plasticine layers (of 5mm thickness) are set up perpendicular to the direction of shortening (a), a conjugate EDS pair forms at approximately 6-12% bulk strain. Each EDS is inclined at about 40 degrees to the extension direction (that is parallel to layering). In layer-parallel shortening, either buckling instabilities develop or the model deforms homogeneously by ductile flow. EDS absence in (b), (c) is explained by alignment of the small mineral particles in the plasticine, parallel to layering, brought about by rolling of the layers during model preparation. Notice the drastic difference in flow stress levels for anisotropic and isotropic (Figure 5) plasticine.

These experiments concerned the development of secondary extensional shears that accommodate part of the bulk strain, because of strain partitioning due to condition that slip between the layers was allowed.

II.2 Deformation machine.

The deformation machine used in the experiment series, shown in Figure 7, serves to deform a plasticine multilayer, in three mutually perpendicular directions simultaneously. The way the machine is built, however, provides only two potential directions of shortening. The third direction, being perpendicular to the free boundaries of the machine, can only serve as an extension direction, or as a direction of no strain if plain strain conditions are desired. In our experiments, model expansion towards the free boundary can be controlled by emplacing appropriate end-walls (2 transparent plexi-glass plates of 2cm thickness, that fit exactly to the machine), which provide a confining pressure during each increment of deformation.

Deformation is driven by two mutually perpendicular pairs of hand-operated pistons, which transmit (by a counterclockwise revolution) applied compression/s to the model, through the movement of a system of four interlocking rectangular, rigid frames. The system consists of four long (30cm) metal bars (two per a pistons pair), each of one confining 355 overlapping metal plates of approximately 1mm equal thickness, and of 3.4cm equal width. Half of the plates are ruler-shaped, the other half are square; both are solidly mounted, alternating, on the bars, by positioning pins (of the same length as the bars) that pass through

Figure 7. Deformation machine used for the experimental work (Bottom view; numbers on plates start at 1 and end at 355 for each frame). Principal strain axes are assumed to coincide with the experimental reference frame, that is defined as follows : the long horizontal axis of the deformation machine is taken as Y, the other horizontal axis directed normal to the plane of the figure as X, and the vertical one as Z. Incremental compression/s is applied to multilayered models along the vertical (Z) and one of the horizontal directions (Y), through the two pairs of hand-operated pistons (see text for detailed description). The 12 slots seen on the stable steel frame are reception sites of the bolts that serve to hold the end-walls, which when mounted to the machine, controll incremental extension towards the free boundaries. The dimensions of the machine are 30.5×42×32cm (corresponding to X, Y, Z, co-ordinate axes, respectively). The maximum separation of the four rigid boundaries, defines a "useful space" of dimensions 30.5cm(X) × 27cm(Y) × 17cm(Z). The boundary conditions for the first pilot experiment (PE1) are also shown (see page 33 for description).

slots in each plate.

The deformation proceeded in increments (see figure 14 for details). The normal forces, applied by hand along Z and Y axes, are maintained roughly constant throughout each increment. Therefore, in both experiments, slight changes of the strain rates between successive strain increments are assumed to be negligible.

Although the greatest advantage of this machine is that the deformation produced is three-dimensional coaxial strain, a major disadvantage of it is that fault initiation and development cannot be observed in the interior of the models, because of its construction.

II.3 Model preparation.

Each model was built of planar, rectangular, layers of Standard White plasticine (we picked yellow and violet or red colours) that were produced by rolling to the required uniform thickness ($1\text{mm} \pm 0.1\text{mm}$) (Figure 8). To prepare plasticine for rolling, plasticine bars (inside their covers) were left in a sink filled with hot water, for about 20 minutes, such that they become more easy to handle and rework, in order to eliminate any existing fabric due to fabrication. Practically isotropic plasticine cylinders were prepared in this way, ready for rolling.

Rolling was facilitated by using glycerine ($\text{C}_3\text{H}_8(\text{OH})_3$; distributed by Baxter Healthcare Co., IL, USA; cat.n. 5092-500), which provided the necessary lubricant for spreading of the plasticine sheets and prevented them from "breaking". The author experimented also with talc as an alternative lubricant during rolling, but,

Figure 8. Final stage of the rolling process. Plasticine layer has been cut using a template of dimensions 15cmx36cm (excess lengths were allowed for final cutting), and is 1mm thick (± 0.1 mm). Rolling proceeded in six successive stages, using pairs of guide metal plates of progressively smaller thicknesses (here of 1mm) resting on a rigid square glass base, along which a heavy metal roller moved back and forth until the plasticine sheet acquired a rectangular form and a uniform thickness. During each stage, rolling started always from the central part of the sheet and proceeded slowly towards both ends, to permit uniform plasticine "spreading" along the glass base, without any "folding" or "sticking" effects.

he found that plasticine sheets were sliding along and sticking on the glass base very easily, thus, making them difficult to handle even at a 2mm thickness. In addition, glycerine had no effects on plasticine rheology, plus has been used as a modeling material itself (e.g., Griffiths and Richards, 1989). Upper layer surfaces were lubricated with white petroleum jelly B.P. to reduce interlayer friction, so that interlayer boundaries were relatively weak, thus enhancing slip along the layering. The layers were then stacked together upon a planar marble base, in alternating colour, to form a multilayered model with nearly planar layers. A lightglass roller was used in regular intervals during stacking, to ensure an almost perfect planar upper surface for the next layer to sit. Then, the model was cut to acquire a square profile (on the YZ plane; figure 9) using a thin metal wire of high tensile strength (guitar string of 0.203mm diameter).

This multilayer allows us to consider its behaviour in terms of its average properties, instead of the properties of the individual layers (Figure 10). Therefore, the approach adopted here by the author, uses Biot's theory of deformation of a homogeneous, anisotropic material. Biot (1965) and a number of other workers since then (for example Cobbold et al., 1971; Behzadi and Dubey, 1980), showed that this anisotropic multilayer can become unstable when compressed, since no matter how perfectly it is made, it will always contain heterogeneities of various kinds, including small deflections in the layering. This will occur when a critical stress difference and/or degree of anisotropy (required to initiate plastic instabilities, both in elastic and viscous materials) is built up. Geological multilayers, and rocks with linear fabrics, which are statistically homogeneous (Paterson and Weiss, 1961), are expected to deform in a similar way to the homogeneous theoretical material.

Figure 9. YZ profile of a multilayered model after cutting, ready for deformation. In order to achieve a planar, clean cut, guide-lines were scratched on the top plasticine layer, the wire was aligned to them, and then, a vertical force applied to the wire. To achieve better analysis of experimental results, two markers of five red (violet) plasticine layers each, plus a main central marker consisting of ten red (violet) layers separated by two yellow ones, were incorporated in the models.

Figure 10 [following page]. A XZ profile of the multilayered models before deformation. Carefully performed cuts ensure that 3-D model geometry is represented by an orthogonal parallelepiped with dimensions $30 \times 12 \times 12$ cm (corresponding to X, Y, Z axes respectively, of the experimental reference frame). Such a model is large enough to keep boundary effects away from the region of interest (i.e., its interior).

Multilayers built like the one shown here, are not strictly homogeneous, because they contain discontinuities which are planes of potential slip, but because the block of the material is large compared with the thickness of the individual layers, the material is statistically homogeneous.

But each multilayer is also anisotropic, because the resistance of the whole stack to compression parallel to the layers (i.e., along X or Y principal axis) is dependent only on the resistance to compression of the material in the individual layers, whereas the resistance to layer-parallel shear is mainly dependent on the ease of slip between the layers (i.e, it has average stress/strain properties which are different for compression or shear in a given direction).

II.4 Pilot experiments.

A pilot experiment (PE1) was conducted first to test the homogeneity of the deformation plus the boundary effects. The model was emplaced inside a rubber sleeve (of 2mm thickness) which was held to the machine using 12 steel plates (three on each corner) of various thicknesses (see Figure 7). Original rubber sleeve and steel plates provided together with the machine, were replaced as the strength of the rubber induced a significant bending of the steel plates during preliminary machine testing. Petroleum jelly was used to lubricate rubber sleeve surfaces and the contacts between steel plates and deformation machine.

This experiment was undertaken in the constrictional strain field (see analytic description of the experimental technique in figure 14), and it ended when finite strain had reached an amount of roughly 50% bulk extension along the X axis, because deformation was evidently heterogeneous (Figure 11). After taking the model out of the machine, it was cut lengthwise (XZ section) into slices using the metal wire (Figure 12). These cuts revealed a competence contrast between plasticine layers. I suggest that the competence contrast rendered the multilayer heterogeneous. This intrinsic heterogeneity caused the observed bimodality of the deformation style : brittle in the competent layers (yellow) and ductile (viscous flow) in the incompetent ones (violet). The extent to which yellow layers "boudinaged" is rather impressive; this may be called a "penetrative" type of boudinage. A significant part of finite strain, however, accommodated by slip along EDS of planar geometry (probably of an "octahedral" type of geometry in 3-D), that maintain moderate inclinations to the bulk extension direction (Figure 12).

Figure 11. YZ profile in PE1 immediately after the end of the experiment. Finite strain is 50% bulk extension perpendicular to the plane of the page. Notice the two folds that dominate the central part of the section, and the trace of a large extensional shear below the central marker. However, the folds are boundary effects, that initiated at about 10% bulk extension and quickly propagated towards the center of the model. Nevertheless, fold axial direction is aligned parallel to the axis of extension of the bulk finite strain ellipsoid, indicating that they form as a result of shortening along the Y-direction. The author suggests that, boundary effects are due to the presence of the eight steel plates (two on each corner) plus the strength of the rubber, which may induce unequal distribution of compressive stresses on the surfaces of the model.

Figure 12. XZ cross-section of the pilot experiment in constrictional straining conditions. Initial dimensions as in figure 10. Finite strain is 50% bulk extension along X, resulting from approximately 20% shortening along Y and 29% shortening along Z. Heterogeneity of the deformation can be easily observed. The yellow layers of plasticine deformed brittlely forming boudins, whereas ductile flow was the rheological behaviour of the violet layers. Boudins formed as a material response to vertical compression along the Z-axis and the tension cracks formed in planes perpendicular to the direction of bulk extension (X).

In addition, notice that incremental extrusion of plasticine on both ends of the model resulted in "end-effects", observed along the last four centimeters in the extension direction. Their formation is associated with the sticking of plasticine on the end-walls during progressive deformation, as a result of viscous drag, thus, creating a space problem for the material which continues to extrude. Continuous extrusion forces the outgoing volume of plasticine to escape upwards and downwards respectively, but with the central part remaining stationary as it is stuck on the walls. "End-effects" are more visible on the upper violet marker since the lower one has experienced more attenuation and shearing as a result of heterogeneous strain.

A second pilot experiment (PE2) was conducted in order to test new boundary conditions, including the strength of new sleeves. Instead of the boundary conditions used in PE1, only waxed paper lubricated (both sides) with petroleum jelly was used this time. Three dimensional straining was applied again in the constrictional field, as in PE1. However, individual layer thickness was $5\text{mm} \pm 0.1\text{mm}$, and no interlayer lubricant was used. It was found that new boundary conditions could keep boundary effects away from the interior of models and that intrinsic anisotropy was reduced significantly in favor of an isotropic, "massive" response to straining that rendered impossible any attempt to continue the experiment after 11 % bulk extension, because the forces required for further deformation exceeded the capacity of the hand-operated machine. No induced anisotropy due to non-linear properties of plasticine developed during deformation. Also, tension cracks developed again only in the yellow layers, perpendicular to the direction of bulk extension.

These important results reveal that during rolling, plasticine layers develop a planar(-linear?) shape fabric normal to the vertical direction of the roller-applied force, which itself may be the primary contributor to the intrinsic anisotropy, accompanied by the secondary contribution of the planes of potential slip (i.e., layer interfaces). However, it appears that the thicknesses of the individual plasticine layers, and consequently the degree of the rolling-induced textural anisotropy, plays an important role in plasticine deformation. The thinner the layers, the higher the degree of intrinsic anisotropy due to the presence of a shape fabric before deformation.

II. 5 Main experiments.

The main experiments were conducted in the constrictional (ME1) (Figures 14, 15) and flattening strain field (ME2)(Figure 16), respectively. No competence contrast existed since the red plasticine used, exhibited identical material properties with the yellow plasticine. A major improvement in experimental conditions was the use of waxed paper (tested successfully in the PE2) that replaced the rubber sleeve and steel plates. Each model was carefully wrapped up twice with waxed paper, that accomodated its shortening along Z and Y during the ME1 mostly by intense microfolding (Figure 13) along the model corners, whereas it was allowed to unfold away from the compression direction (with the help of plenty of petroleum jelly) during ME2. Also, before each strain increment, both end-walls and model free boundaries were sprinkled with talc powder (see also Harris and Cobbold, 1985), for greatest possible lubrication, in order to limit "end-effects".

ME1 ran up to 30% shortening along Y and Z axes that implies a 60% bulk extension along X (Figure 15). This amount of bulk strain accumulated in eight hours, that was the duration of ME1. Under steady-state straining conditions, this would imply a constant strain rate of $2.08 \times 10^{-5} \text{ s}^{-1}$. However, in our experiments strain accumulation was not continuous but incremental. Therefore, I suggest empirically that true strain rates are of the order of 10^{-3} or 10^{-2} s^{-1} . In ME2 (Figure 16), bulk shortening along Z reached 40% and was accumulated in seven hours (duration of ME2). Again, I suggest that ME2 was undertaken under a true incremental strain rate of 10^{-3} s^{-1} .

Deformation was homogeneous throughout each experiment, as revealed by careful examination of individual layer thicknesses and geometry after deformation (Figures 15, 16). Three-dimensional strain was accommodated mostly by slip along discrete shear planes, and by a significant "internal" ductile strain that was uniformly distributed over the deformed models. The homogeneity of deformation validates an earlier assumption that, during incremental straining of the models, principal strain trajectories remain in an orthorhombic symmetry arrangement, and also remain parallel to the co-ordinate axes of the reference frame, as defined in Figure 7. The above important implications break down only when one approaches both free-boundaries of each model, where end-wall friction produced "end-effects", which (see Figure 12 for explanation) inhibit the development of EDS in both ends of the models; however, their extent has been substantially reduced as a result of the new experimental conditions.

EDS lengths, orientations and displacements along them, were measured using a magnifying lens allowing an accuracy of 0.1mm for the lengths and 0.5° for the angles, respectively. The slip along individual EDS was determined by measuring the amount of relative displacement of marker horizons (i.e., individual plasticine layers) across it. Bulk strain was recorded by measuring changes in both horizontal and vertical separation (length) of the rigid boundaries, after each increment. The alternative traditional way of recording strain in model experiments (e.g., Cloos, 1955; Oertel, 1965; Wilcox et al., 1973), i.e., by inscribing circles on the top and sides of the model, was not used on purpose, because it would disrupt the homogeneity of the multilayers, plus it might localise deformation "artificially".

Figure 13. Picture showing the intense microfolding of the waxed paper in the corners, which accommodated its shortening along Y and Z axes of the finite strain ellipsoid, during ME1. Sufficient lubrication of its external face with petroleum jelly ensured continuous contact with the Al plates of the machine throughout the experiment, and prevented any tearing. Thus, the waxed paper was able to slide on top of its substratum, away from the shortening directions, and towards the corners of the machine where the interlocking Al plates inhibited crossing. Progressive accumulation of this kind, lead to the establishment of rigid, rectangular, frictionless, boundary conditions.

Figure 14. General picture of experimental set-up, before ME1 begins. The model was shortened at equal amounts (half a counterclockwise turn) along Z and Y axes, by rotating simultaneously the two pairs of the hand-operated pistons of the deformation machine and was allowed to extend along the X axis. Thus, the type of strain experienced by the multilayered model is an irrotational axially symmetric extension (e.g Hobbs et al., 1976, p. 27).

After initial strain increments, a certain amount of extruded plasticine started sticking on the central part of the end-walls, as a result of viscous drag (see also figure 12). To prevent the development of end-effects as well as to allow incremental extension along X, we let the end-walls withdraw in a uniform manner. However, progressive deformation results in additional amounts of extruded plasticine to continue accumulating, such that after three strain increments (one and a half full turn of the pistons) the end-walls could no longer be loosened, the resistance of the material increased, and further deformation was inhibited. Then, the end-walls were unbolted from the machine, the excess material was removed using the guitar string and the experiment proceeded in the next stage of deformation. Thus, during each stage the model was subjected to a constant volume deformation.

Figure 15 [following page]. General picture of plasticine multilayer after deformation in ME1. Finite strain is equal to 60% extension along X (perpendicular to the plane of the page). In particular, all 106 layers experienced the same amounts (30%) of shortening along Z, because they were found to occupy a uniform final thickness of approximately 0.8mm. Notice that boundary effects did not propagate towards the central region of the model but remained confined to the corners.

Figure 16. General picture of the deformed multilayer in ME2. In this experiment, all 114 layers have been uniformly stretched to their final thickness of 0.7mm each. The incremental deformation of the multilayer in the ME2 proceeded as follows : Each increment of shortening along the Z axis was followed by nearly equal half-increments of model expansion along X and Y axes. The half increment of extension along Y, was simply achieved by a clockwise revolution of the pistons. The increment step corresponded to a quarter of a full turn; half turn was the counterclockwise increment step along Z. Then, we let the end-walls withdraw outwards, by loosening the bolts keeping them attached to the machine, such as the resultant half increment of extension could be accommodated along X. This type of three-dimensional strain closely approximates an irrotational axially symmetric shortening.

Chapter III. RESULTS OF THE EXPERIMENTAL WORK

III. 1 Results of ME1 (constriction experiment)

Three vertical cuts (cross sections) of the deformed multilayer were analyzed in detail, to unravel EDS geometry and kinematics, as well as to study EDS evolution with progressive deformation. Two of the sections (ME1-SSb; Plate 1 and ME1-SSe; Plate 2) represent serial cuts parallel to the YZ principal plane of the finite strain ellipsoid. The third section, ME1-CLS (Plate 3), is a part of a longitudinal section of the multilayer, located at its center, and it is parallel to the XZ principal plane of the finite strain ellipsoid (which has a prolate shape), that contains the bulk extension direction (X). This direction, as we have seen earlier (Figure 11), is fixed parallel to the long dimension of plasticine layering before deformation and as a consequence to the plane of rheological (intrinsic) anisotropy. The preservation of horizontality of the orientation in space of the bulk extension direction (X), with progressive strain, is a result of axially symmetric extension straining conditions that prevailed throughout ME1. Rigid, irrotational boundary conditions (Figure 7) also prevent the extension direction of the infinitesimal strain ellipsoid from changing orientation in space and in time.

Strain has been accommodated in part by the operation of multiple, discrete EDS, along which plasticine layers are dislocated. EDS, in general, can be distinguished as follows : EDS dipping to the right, as seen on either YZ or XZ principal planes shall be referred to as right-handed (R.H.) EDS; EDS dipping to

the left, left-handed (L.H.) EDS. Thus, for each shear, in addition to its length, inclination and amount of displacement, its orientation of dip is also presented.

Plates 1, 2, 3 show a rather rhomboid pattern of EDS in all these sections. Ductile shears maintain a variety of angular relationships with respect to the plane of anisotropy (plasticine layering). Layering itself remained parallel to the XY principal plane. Minor layer rotations can be seen at the boundaries of the model, but these do not affect bulk deformation. Let us cite a few observations at this point, concerning EDS geometry and development. First, similar rhomboid patterns of linear traces of EDS were seen in cuts parallel to layering, suggesting an "octahedral" type of geometry in 3-D. In addition, the way shears terminate is a key to understanding their kinematic evolution. EDS are seen to terminate against each other without any preference to their orientation with respect to the extension direction. For example, in ME1-CLS, in the domain below the lower violet marker (Plate 3) a L.H. shear (#136) terminates at a R.H. one (#135), whereas 3 centimetres to the right, a R.H. shear (#139) terminates at a L.H. one (#140). This observation is also valid for high-angle and low-angle shears. For example, shear 37 terminates against shear 39 and inversely, shear 43 terminates at shear 42.

Moreover, in ME1-CLS, cross-cutting relationships among EDS are few and non-systematic. This agrees with identical observations in the serial sections, that, most of EDS develop synchronously and form a 3-D network, instead of operating sequentially where systematic offsets would have been produced. Where EDS cross-cut each other, either no mutual offset is observed, suggesting indeed a local sequential development (for example, #16 has been offset along #15), or, on

Plate 1. General picture of serial section ME1-SSb. The vertical plane of the section is parallel to the YZ principal plane of the finite strain ellipsoid. 164 ductile shears that carry substantial ($>0.1\text{mm}$) displacements were identified (for complete data sets see Appendix A). Note that, any diagrams constructed to investigate the kinematic behaviour of EDS in this section, as well as in other sections analyzed from ME2, do not depict relationships among real magnitudes of shear length, inclination and associated slip along it. This is because EDS shown as linear traces in such planes as ME1-SSb are the projections of three-dimensional slip surfaces on these vertical cross-sections which cut through them. However, any observations made on these sections, as well as any conclusions drawn after analysis of data sets recorded, are valid, because EDS geometry and kinematic evolution in space is certainly reflected on finite fault patterns, found on such mutually perpendicular planes of apparent dip.

Plate 2 [following page]. General picture of serial section ME1-SSc. EDS pattern is nearly identical to that of ME1-SSb. In this section 153 shears that carry substantial displacements were identified (complete data for each EDS are given in Appendix B). Note that this section is 7cm apart from ME1-SSb (as measured along the X-direction) and towards the interior of the model.

PLATE 1

PLATE 2

Plate 3. General picture of the central longitudinal section ME1-CLS. Ductile shears that accommodate extensional strains form a very similar pattern to those of ME1-SSb and ME1-SSe. This similar geometric arrangement, as viewed in a plane parallel to the bulk extension direction, indicates that the three-dimensional geometry of EDS is, first, of planar character and, secondly, it obeys symmetrical rules in its development, with respect to the three principal strain axes.

Other important observations include domains shown as circles in the hanging wall of various faults where the "reverse drag" effect has formed, as well as numerous vaseline bubbles along layer interfaces are shown, indicating that lubricant is still in effect, so that rheological anisotropy due to sufficient lubrication between layers has not been reduced with finite strain. Squares indicate a number of domains in the multilayer where EDS are seen to intersect each other without any apparent offset. Indeed, nearly 90% of the faults in this section terminate at other faults or simply die out. Finally, stars mark a few regions in the multilayer where at least two EDS are seen to initiate. In most cases, EDS appear to form symmetrically about the vertical axis of shortening, forming a variety of dihedral angles.

the other hand, no offset at all is observed (for example, shears 120, 121; 66, 68; 78, 79) at the millimetre scale (Plate 3). This is perhaps explained by a mechanism of interference (Oertel, 1965) where sequential extensional movements occur alternatively along opposing shears.

The EDS population is almost equally split in two groups according to their sense of dip with respect to plasticine layering (Figure 17). This balance between R.H. and L.H. EDS is maintained also in the distribution of cumulative lengths (Figures 17b, e) as well as in the distribution of the total displacement produced as a result of ductile shearing (Figures 17c, f). These first results establish an internal consistency, that is, the equalization of strain partitioning between R.H. and L.H. shears, that is important for a number of reasons. First, it is an additional evidence for the homogeneity of the deformation in ME1. Secondly, it is a strong argument towards the documentation of a similar geometric evolution for both groups. Fault patterns in these principal sections of the finite strain ellipsoid, are projections of EDS three-dimensional pattern. A symmetric arrangement of these 3-D planar surfaces with respect to the principal strain axes is more likely to produce this equalization in strain partitioning, reflected in Figure 17, than a random one. Moreover, it is a direct indicator that both groups had nearly identical kinematic evolutions with progressive strain. While not ruled out, it is difficult to understand a different kinematic evolution with progressive strain for each group and still exhibiting the same cumulative amounts of length and slip. Similar kinematics and geometry of both groups indicate, to my opinion, an "octahedral" type of fault geometry (Figure 3) with orthorhombic symmetry to the principal strain axes.

Figure 17. The distribution of EDS in ME1-SSe (a, b, c), and ME1-CLS (d, e, f) according to their orientation with respect to the plane of rheological anisotropy. (a) Right-handed EDS comprise 54% of the total number (153), while L.H EDS comprise the rest 46%. (b) the distribution of length between the two groups follows a ratio 50-50%, which is nearly identical to that (c) yielding the distribution of displacements between the two groups. (d) in ME1-CLS, a similar frequency ratio is present (53-47%; total shear population: 144) (e) the distribution of lengths follows a ratio 46-54%, which also holds for the distribution of displacements (f). Ratios from (a) to (f) provide a definite support for the statistically homogeneous character of the deformation. Notice the arithmetic values of cumulative length and slip for each section.

Right-handed EDS
83.54%

a

Left-handed EDS
70.46%

b

Total length of EDS = 1322.1 mm

Right-handed EDS
62.86%

c

Left-handed EDS
61.40%

Total displacements of EDS = 124 mm

Right-handed EDS
77.63%

d

Left-handed EDS
67.47%

e

Total length of EDS = 1421.9 mm

f

Total displacements of EDS = 178.6 mm

To further investigate the kinematic evolution of EDS in ME1, a series of diagrams involving different kinematic elements, were constructed. Diagrams of EDS lengths against corresponding displacements (Figure 18a, c) give a rather random distribution of points, indicating that there is not a systematic relationship between EDS length and slip with progressive strain. Similar diagrams for both R.H. and L.H. EDS (Figure 19a, c) do not indicate any significant contrasts.

A second important kinematic relationship, is that between EDS inclinations with respect to layering and associated slip (Figure 18b, d). Again, this diagram does not show any systematic arrangement of EDS population. In serial sections, however, displacements over 1mm, occur along EDS which are inclined at less than 45 degrees to the layering (Figure 18b); more specifically, the majority of the greatest displacements recorded, correspond to EDS inclinations lower than 35 degrees to layering. In the longitudinal section, points are more scattered and a weak trend can be seen in high inclinations (Figure 18d). Large displacements imply large amounts of extension. This, in turn, implies that large extensional strains can be accommodated more effectively by low-angle EDS than by moderate or high-angle ones. The above argument holds for both R.H. and L.H. EDS as further analysis showed (Figures 19b, d). Furthermore these diagrams showed that, for both groups, the low-angle shears which carry the greatest displacements do not correspond to the greatest lengths, but nearly all fall into the main spectrum of lengths, i.e., 5 to 10 mm. *Above results demonstrate that, although kinematic evolution of both orientation groups is similar with progressive strain, it is not dictated by any specific relationships between shear length and slip, or by shear dip and slip.*

Figure 18. (a) Diagram of EDS lengths versus corresponding displacements in ME1-SSb. EDS are commonly found within the range of 4-14mm of lengths, while corresponding slip rarely exceeds the value of 1mm. Almost 90% of the population concentrates within these boundaries. Therefore, it can be inferred that fault propagation with progressive deformation was independent of the intensity of accompanied strain localization. As a representative example, notice the spectrum of EDS population that carry identical slip of 0.5mm. This spectrum appears at 4.5mm of finite length, and terminates at approximately 12mm.

(b) Diagram of EDS inclinations to the anisotropy plane versus corresponding displacements, ME1-SSb. Notice that about two-thirds of the faults are enclosed within a rectangle defined by the ranges 38 to 80 degrees (inclinations), and 0.2 to 1mm (displacements), respectively. However, a very weak trend can be seen when displacements above 1 mm are considered.

(c) In ME1-CLS, the diagram of EDS lengths against corresponding displacements shows a weak trend. Greater displacements, in general, tend to occur along shears that become progressively longer. For example, all EDS that measure more than 16 mm in length carry slip equal to or greater than 1 mm. On the other hand, shears measuring 5 - 10 mm in length are seen to carry a wide spectrum of slip, that starts at 0.4 mm and stops at 2.5 mm. It is this random distribution of most points, that inhibits any systematic relationship to be drawn in this diagram.

(d) The diagram of EDS inclinations against corresponding displacements in ME1-CLS also shows a weak trend. In general, it appears that the lower the EDS is inclined to layering, the greater is the slip that accumulates along it. However, this can only be safely stated for inclinations greater than 50 degrees. Below this value, slip seems to accumulate along shears irrespective of their angular relationship with the plane of anisotropy.

Figure 19 [following page]. Kinematic behaviour of R.H EDS (a, b) and L.H EDS (c, d) groups in ME1-SSb. (a) and (c) Diagrams of fault lengths versus corresponding displacements. (b) and (d) Diagrams of fault inclinations versus corresponding displacements. In this section, the plotted points show a greater dispersion in the L.H. EDS diagram partly because of the greater number of L.H EDS, and partly because L.H. EDS accommodated slightly more extensional strains than R.H. EDS did.

a

c

b

d

EDS length distribution histograms (Figure 20) show that approximately two-thirds of the total shear number fall within the length range of 6.1 - 10mm, as well as that an internal consistency exists between R.H. and L.H. shears for the same length range. These results point again towards a similar kinematic evolution of both groups. Note that, by similar kinematic evolution is not implied that each individual EDS followed the same evolutionary path with progressive strain, irrespective of its orientation. Rather, it is meant that both groups did not show any significant deviations at the length range of 6.1 - 10mm, in terms of EDS efficiency to propagate, with progressive strain.

The EDS displacement distribution histogram for serial sections (Figures 21a) shows a cluster at the 0.41 - 0.6mm range of finite slip. As far as the main population is concerned, both group histograms (Figures 21b, c) show similar arrangement of clusters for slip ranges below 0.6mm. Slip distribution in the longitudinal section follows closely these magnitudes (Figures 21d, e, f; a cluster appears at 0.7-1mm of finite slip; formed by almost equivalent contributions of both orientation groups), but histograms are uniformly shifted to the right along the horizontal axis. This happens because of the greater amounts of displacement recorded in this longitudinal section, in comparison with the serial ones (Figure 17), which is due to the greater proximity in space of the ME1-CLS strike, with the pitch of the slip vector, resolved along the octahedral faults. This, in turn, is due to the fact that ME1-CLS strikes parallel to the bulk extension direction, close to which fault slip vectors are expected to trend in space.

Figure 20. EDS length distribution histograms.

(a) General histogram for ME1-SSb. Maximum EDS concentration is almost equally split between the length ranges of 6.1 - 8 mm and 8.1 - 10 mm. Only 5 faults are shorter than 4mm, whereas only 12 faults display lengths over 12mm.

(b) R.H EDS length distribution diagram, ME1-SSb.

(c) L.H EDS length distribution diagram, ME1-SSb. Notice that, L.H. EDS comprise more than the two-thirds of the shears displaying lengths over 10 mm.

(d) General histogram for ME1-CLS. The histogram reveals an integral consistency between serial sections and ME1-CLS. The predominant cluster appears at the range of 5 - 7 mm of length, while more than half of the total population occupies lengths shorter than 9.1 mm. 14 (about 10%) of the total EDS number have lengths greater than 17 mm.

(e) and (f) R.H and L.H EDS length distribution histograms for ME1-CLS, respectively. These analytic histograms do not show any contrasts for the main range of lengths (5-9 mm). In higher ranges, L.H. shears are more abundant than R.H. ones.

Figure 21. [following page] (a) EDS displacement distribution histogram in ME1-SSb. Approximately two-thirds of EDS carry finite slip less than or equal to 0.6mm. Only 18 EDS display slip greater than 1mm.

(b) and (c) R.H and L.H EDS displacement distribution histograms, respectively. Notice that, slip over 1mm has accumulated more along L.H than along R.H EDS.

(d) Histogram of the distribution of displacements in ME1-CLS. It shows a predominant cluster at the slip range of 0.71 - 1 mm. Almost half of the shears in this section carry slip greater than 1 mm, and, in particular, 16 shears were found to carry slip greater than 2 mm. The increase in the slip increment shown in the horizontal axis, was adopted by the author as necessary to depict better the wider range of slip recorded in ME1-CLS.

(e) and (f) R.H and L.H displacement distribution histograms for ME1-CLS, respectively. The breakdown of frequency magnitudes between R.H. and L.H. EDS is satisfactory (i.e no significant differences exist) for slip ranges up to 1.7 mm. Above this value, L.H. EDS outnumber R.H. ones, and this result may be directly correlated with the fact that L.H. EDS also outnumber R.H. ones in the greater length ranges (Figure 20e, f).

a

b

c

d

e

f

The main EDS population in ME1-CLS behave kinematically similar to the way EDS in the serial sections do, in terms of average amount of accumulated slip as well as of average amount of planar propagation, as we have seen earlier (Figure 20). *This result is of great significance, because for the majority of faults in ME1, the accumulation of slip and consequently, the localization of extensional strains, occur rather symmetrically, without any preference along R.H. or L.H. shears.* Anomalies in the kinematic behaviour of L.H. EDS, are only confined in the higher ranges of lengths and displacements, respectively, and are not regarded by the author as of primary importance.

Finally, a series of histograms was constructed to examine the distribution of EDS inclinations with respect to plasticine layering. The two resultant clusters (Figures 22, 23) comprise almost the half of the total EDS population in the serial sections, suggesting that within this range of 20 degrees, it is easier for EDS to initiate and propagate with progressive strain. The propagation may also involve rotation of the shears towards the bulk extension direction (X) of the finite strain ellipsoid (note that this rotation can be only documented in a XZ section of the finite strain ellipsoid, and not in YZ sections where fault traces remain stationary in space with progressive deformation, because finite strain is axially symmetric extension). Alternatively, shear rotation may occur after termination of extensional movements along them, in which case extensional strains would have to be accommodated by newly-formed shears or by others currently active. These possibilities will be discussed in detail in the next chapter, however, at this point, the range of 36 - 55 degrees is adopted as the "preferred" range of EDS initiation and

propagation, because smaller EDS concentrations occur above and below this range (Figure 22, 23), defining a wide spectrum of currently observed inclinations.

The breakdown of the "preferred" range between the two orientation groups is practically symmetric (Figures 22b, c; Figures 23b, c). Now, consider the distribution of inclinations as seen in an alternative histogram (Figure 22d; where different inclination classes have been used in the horizontal axis). This difference in the presentation of EDS inclination distribution in ME1-SSb might intuitively lead to identification of two other "preferred" ranges (however, no such difference is observed in ME1-SSe; Figures 23d, e, f). But, consider the breakdown of this general distribution between the two orientation groups (Figures 22e, f). An asymmetric development of EDS in the high-angle ranges is evident. It is, therefore, apparent that any identification of EDS sets operating in serial sections should be constrained within the range of 36-55 degrees, and in particular in the range of 46-55 degrees, which is the predominant one.

In the longitudinal section, more than half of the population is confined within the range of 36 - 55°, while the rest of EDS are symmetrically arranged above and below this range (Figure 24). Again, as for serial sections, R.H. and L.H. shears appear in nearly equal amounts within the range of 36 - 55 degrees (Figures 24b, c). The tendency for EDS greatest concentrations to be seen at the 36 - 55 degree range, implies that these particular directions in space favour EDS initiation over lower-angle or higher-angle ones. Also, the fact that both orientation groups display similar range peaks to those in YZ sections, imply that EDS in a 3-D space possess an "octahedral" geometric arrangement with respect to the principal strain axes.

Figure 22. (a) EDS inclination distribution histogram in ME1-SSb (a YZ section). A dominant cluster at the range of 46 - 55 degrees, is shown, followed by a second dominant cluster at the range of 36 - 45 degrees. Only 27 shears are inclined at more than 65 degrees to layering as well as only 16 shears are inclined at less than 26 degrees. In fact, high-angle and low-angle EDS are almost symmetrically arranged outside the 36-55 degrees range: 49 EDS between 56°- 85°, 44 EDS between 12°- 35°. (b) and (c) R.H and L.H EDS inclination distribution histograms, respectively. Note that, R.H EDS tend to concentrate at more high inclinations, whereas low-angle ranges are dominated by the presence of L.H shears.

(d) Presentation of the distribution of EDS inclinations in ME1-SSb, using different angle increments in the horizontal axis. Two clusters can be seen immediately, a low-angle one at the range of 31 - 40 degrees and a high-angle one at the range of 51 - 60 degrees. (e) and (f) R.H and L.H EDS inclination distribution histograms, respectively. The two clusters seen on the L.H. EDS histogram, coincide with clusters in identical ranges seen in (d), while the R.H. EDS inclination distribution shows a cluster at 31 - 40 degrees and a high-angle cluster at 71 - 80 degrees.

Figure 23 [following page]. The distribution of EDS inclinations with respect to the anisotropy plane, in ME1-SSe (a YZ section). Almost half of the total shear population is found within a range of 20 degrees, namely within 36 - 55 degrees. The maximum concentration occurs at the range of 46 - 55 degrees and has been formed by almost equal contributions of both orientation groups (b), (c). In fact, both orientation groups display nearly identical histograms except for the high-angle ranges, where R.H. EDS outnumber L.H. ones.

A series of different EDS inclinations histograms was constructed (d). The difference is found in a change that has been made in the horizontal axis, i.e., increments of 10-20, 21-30, etc., are now used as ranges of inclinations. These histograms while verifying the above patterns of EDS inclinations, they also clarify better the distribution of the total population in low-angle, high-angle ranges. It can be seen immediately, that, (typically called) low-angle ($< 40^\circ$) EDS are as abundant as high-angle ($> 50^\circ$) EDS.

a

b

c

d

e

f

Figure 24. In ME1-CLS (a XZ section), the histogram of the EDS inclination distribution (a) strongly resembles similar histograms constructed in the serial sections. More than a third of EDS population are inclined at the range of 46 - 55 degrees to plasticine layering.

(b) and (c) In higher ranges of inclinations R.H. EDS outnumber L.H. ones. In fact, only seven L.H. shears are inclined at more than 55 degrees to layering, in contrast to R.H. ones that reach a number of 25. This distribution of EDS inclinations strongly indicates a synchronous operation of EDS sets at the range of 36 - 55 degrees, and, in particular at the range of 46 - 55 degrees.

(d), (e), (f) Further investigation of the inclination distribution using different angle increments verifies above results. Predominant clusters appear at the ranges 41 - 50 and 51 - 60 degrees, respectively, as well as these clusters, and especially the former, are nearly equally split between both orientation groups (e), (f).

In order to document the operation of an EDS set in our experiments, the following requirements have to be met:

- i) a cluster in the distribution of EDS inclinations has to exist, indicating that within this range of inclinations, more EDS are able to initiate and propagate, as opposed to other unfavourable directions in space;
- ii) this cluster has to be almost equally split between R.H. and L.H. shear groups because of symmetry arguments of bulk deformation. These symmetry arguments arise from the mechanical conditions of straining (axially symmetric extension) and the statistically homogeneous character of the deformation;
- iii) the EDS set has also to display a significant amount of slip along its members, thus, proving that, in addition to its arithmetic dominance, its role in strain accommodation was equally important.

The last condition is fully investigated next. The distribution of EDS lengths according to their inclinations with respect to the plane of anisotropy (Figures 25a, c, e), shows that, almost one-fourth of the total cumulative length recorded occurs along EDS ranging between 46 - 55 degrees, while for the same range of inclinations, corresponding cumulative slip (Figures 25b, d, f) is less than 20% of total slip recorded in serial sections, and approximately 28% of the total slip recorded in ME1-CLS. These magnitudes are slightly more influenced by the contribution of L.H. shears as analytic diagrams show (Figures 26a, b, c, d).

All these results point out that any attempt to define EDS sets in any other than the 46°- 55° range fails. This is because R.H. shears have been, in general, developed more efficiently in the high-angle ranges whereas L.H. shears did

not. This difference in kinematic evolution, however, almost disappears in moderate inclinations, namely 46 - 55°, where both EDS groups contribute approximately the same to the deformation of the multilayer. Therefore, the facts that:

- i) EDS occurring within the range of 46 - 55 degrees outnumber their counterparts both in lower and higher ranges of inclinations (Figures 22, 23, 24);
- ii) they are equally distributed between R.H. and L.H. EDS (Figures 22, 23, 24);
- iii) they accommodate a significant part of extensional strains (Figures 25, 26)

are sufficient to document the operation of two distinct sets of planar normal faults in each of serial sections as well as in the longitudinal section of the multilayer analysed (Figure 27), namely

Sets I, III : R.H. EDS at 46 - 55 degrees to layering.

Sets II, IV : L.H. EDS at 46 - 55 degrees to layering.

The 3-D nature of these faults permits the author to document the operation of four distinct sets of octahedral faults in ME1 (Figure 27), that possess a symmetry of orthorhombic character with respect to the principal strain axes. These octahedral faults define a high-angle octahedron in space, when the bulk extension direction coincides with the orientation of the plane of rheological anisotropy. Thus, final fault dips around 60° are expected to appear along a dip-slip cross-section, a numerical value often characterizing initial fault dips found on most upper crustal rocks (Figure 38). In addition, slip vectors resolved along all octahedral faults in ME1, have an oblique-slip sense of movement towards the extension direction.

Figure 25. (a) EDS length distribution histogram, according to their inclinations with respect to plasticine layering, in ME1-SSb. It is shown that high-angle shears measure a greater amount of cumulative length (42% of total length recorded in ME1-SSb) than their low-angle counterparts do. This relationship, however, is inverted, in the distribution of EDS displacements according to their inclinations (b).

Now consider the distribution of lengths (c) as well as the distribution of displacements (d) among low-angle EDS, EDS within the range of 40 - 50 degrees and high-angle EDS, in ME1-SSe. The difference in the kinematic evolution is evident. While the distribution of lengths is more or less balanced between low-angle and high-angle EDS, the distribution of slip is unequal, slip being more effectively accumulated along low-angle EDS. EDS ranging between 40 - 50 degrees measure the one-fourth of the total EDS length and carry the one-fifth of total slip recorded in ME1-SSe. Nearly equal magnitudes of cumulative length and slip are obtained for EDS ranging between 46 and 55 degrees to plasticine layering.

In ME1-CLS, shears propagate more efficiently within this moderate range of inclinations (e), but also slip accumulation and consequently strain accommodation proceeded more efficiently (f). Strain has been more or less equally partitioned between high- and low-angle shears, while almost half of it has been accommodated by EDS moderately inclined to the horizontal. EDS inclined between 46 and 55 degrees to the layering accommodate a little less than a third of the total extensional strain.

a

Total length of FDS = 1330.6 mm
values in parentheses are degrees

b

Total displacement of EDS = 117.4 mm
values in parentheses are degrees

c

Total length of FDS = 1327.1 mm
values in parentheses are degrees

d

Total displacement of EDS = 174 mm
values in parentheses are degrees

e

Total length of FDS = 1421.9 mm
values in parentheses are degrees

f

Total displacement of EDS = 174.9 mm
values in parentheses are degrees

Figure 26. Breakdown of cumulative magnitudes of EDS length and slip in ME1-SSe, according to their inclinations with respect to plasticine layering.

- (a) L.H EDS length distribution histogram,
- (b) R.H EDS length distribution histogram,
- (c) L.H EDS displacement distribution histogram and
- (d) R.H EDS displacement distribution histogram.

Different magnitudes of cumulative length and slip are obtained for high-angle shears and for shears ranging between 40 - 50 degrees. In the former, strain localization was more effective along R.H. EDS, whereas in the latter, strain localization occurred more effectively along L.H. EDS. However, both group contributions are nearly balanced as far as EDS length and displacement distribution in the range 46-55° (and in the low-angle range), respectively, is concerned. It appears, therefore, that the operation of two EDS sets at the range of 46-55 degrees is feasible.

Total length of LH EDS = 661.5 mm
values in parentheses are degrees

a

Total length of RH EDS = 660.6 mm
values in parentheses are degrees

b

Total displacements of LH EDS = 61.1 mm
values in parentheses are degrees

c

Total displacements of RH EDS = 62.9 mm
values in parentheses are degrees

d

Figure 27. Fault geometry in ME1. Faults are shown as octahedral planes intersecting the two horizontal principal strain axes at equal magnitudes. X, Y, and Z are the principal axes of the finite strain ellipsoid (X is the axis of bulk extension). Roman numbers refer to EDS sets identified in the cross-sections analysed (see text for explanation). R and L denote right-hand and left-hand orientation, respectively, of EDS sets as seen on either XZ or YZ plane. Since $46^{\circ}55'$ is the apparent dip of these faults in planes of section one can estimate their true dips that are found at higher inclinations than those predicted for isotropic materials (see Figures 2 and 3). Notice that the equatorial plane of the geometric solid coincides with the XY principal plane of the finite strain ellipsoid. Note that this is an average statistical representation of octahedral fault sets identified (octahedral faults occur at both higher and lower inclinations to the plane of anisotropy than those shown here, however they do not occur in sets). This finite geometry implies no significant rotation of fault planes towards the bulk extension direction (X) of the finite strain ellipsoid, with progressive strain.

III.2 Results of ME2 (flattening experiment)

In ME2 (Figure 16), the mechanical conditions of straining approximated well those of axially symmetric shortening (a small, unintentional deviation from ideal flattening strain occurred with progressive deformation, that rendered the need to interchange the spatial directions of maximum (X) and intermediate (Y) extension axes; i.e, the intermediate axis of strain is now directed normal to the page of figure 7). Bulk shortening along the Z-axis of the finite strain ellipsoid reached the amount of 40%. The amount of extension along the X-axis was 22.5% (final length of the multilayer along X-axis 14.7 mm; initial length 12 mm), while 17.5% of extension occurred along the Y-axis. Two mutually perpendicular cuts (cross-sections) of the deformed multilayer were analyzed in detail.

The first section, ME2-SSB (an abbreviation for ME2-Serial Section B) shown in Plate 4, represents the second serial cut towards the interior of the multilayer, and is also parallel to the XZ principal plane of the finite strain ellipsoid. The data sets used to analyze EDS geometry and kinematics are given in Appendix D. The second cross-section, ME2-LS2 (standing for ME2 - Longitudinal Section 2) shown in Plate 5, represents a vertical cut parallel to the YZ principal plane of the finite strain ellipsoid. Data sets for this section are presented in Appendix E.

Three-dimensional deformation was accommodated in part, by multiple, discrete EDS, of planar geometry. Their pattern is nearly identical in both sections analysed. The equivalent development of EDS in these mutually perpendicular cross-sections of the deformed multilayer, results from the symmetry of the 3-D

strain and from the homogeneous character of the deformation. In particular, deformation was statistically homogeneous, as revealed by the nearly identical amount of stretching, experienced by each individual layer and the preservation of the parallel relationship between plasticine layering and the XY principal plane (this does not apply to model boundaries, where individual layers display different thicknesses and consequently different amounts of stretching).

Furthermore, the need to characterize deformation as statistically homogeneous arises from the easily visible EDS pattern, in the central domain of the model. In this domain (Plates 4, 5), and in contrast with lower and upper domains, finite strain has been accommodated by two opposing EDS networks, both of planar geometry and of equivalent development. The shears comprising these networks, shall be referred to as "master" EDS, because of their greater length and amount of displacement recorded, as opposed to the majority of EDS that follow a different kinematic history. Cross-cutting relationships between the two "master" EDS sets clearly refutes the idea of a typical conjugate pattern, where faults operate in sequence (Freund, 1974). At first, it appears that the L.H network has been offset due to the initiation of movement along the R.H one (Plate 4), but at the area of intersection, instead of the typical development of a conjugate system (for example, Ramsay and Huber, 1987, p. 515), a complex system of EDS formed, accommodating a major part of the local strain. In addition, a smaller offset of the R.H "master" set can be also seen. This mutual offset and the small-scale deformation in the crossover region, suggest synchronous movement along these opposing EDS networks. Analogous patterns have been observed on sand-box experiments by Horsfield (1980), under irrotational plane strain conditions.

Plate 4. General picture of ME2-SSB (a XZ section) and EDS pattern. The central part of the section deforms by two networks of opposing "master" EDS. The R.H network of "master" EDS consists of the shears with numbers, 4, 10, 37, 71, 75, and 79. The L.H network consists of the EDS 19, 49, 48, 47, and 61. Notice that the graben structure formed by the contemporaneous operation of both networks occupies the central region of the section as required by symmetry of bulk strain.

Both networks are inclined to the layering at approximately equal angles, within the range of 35-45 degrees, measure approximately the same cumulative length (93.6 mm for the R.H versus 83.4 mm for the L.H), and carry approximately the same cumulative displacement (20.2 mm for the R.H versus 16.8 mm for the L.H). Also note that cumulative offset along both networks is approximately identical to those of the following figure.

Plate 5 [following page]. General picture of ME2-LS2 (a YZ section) and EDS pattern. Similarly, the central part of the section deforms by two networks of opposing "master" EDS. The first set comprises a R.H EDS network, formed by the synchronous operation of EDS 4 and 17. The opposing set consists of the L.H EDS 27, 24 and 23.

The inclinations of "master" shears lay within the range of 37 to 54 degrees, with three of them falling around 45 degrees. Both networks measure approximately the same cumulative length (69.8 mm for the R.H EDS versus 76.3 mm for the L.H EDS) as well as carry approximately the same cumulative displacement (16.1 mm for the R.H versus 17.8 mm for the L.H).

The cross-cutting relationship indicates that both "master" networks formed approximately at the same time. As in ME2-SSB, extensional strains were canalized simultaneously along the opposing "master" EDS, resulting in the mutual offset of both sets. In the cross-over area, deformation becomes complex, mostly taken up by L.H EDS and by late splay shears (for example, EDS 69, 22). The offset of the R.H network along the L.H one, is greater than the offset of the L.H. This is in accord with the greater amount of cumulative slip recorded along the L.H set, and indicates a slightly uneven localization of finite strain, although the opposing networks were synchronously active.

PLATE 4

PLATE 5

2 CM

2 OF/DE 2

MICROCOPY RESOLUTION TEST CHART
NATIONAL BUREAU OF STANDARDS-
1963-A
STANDARD REFERENCE MATERIAL 1010a
(ANSI and ISO TEST CHART No. 2)

Proceeding with the statistics part of data analysis, a first investigation concerned the distribution of EDS according to their orientation with respect to the plane of anisotropy. This yielded a 48 - 52 ratio between R.H and L.H EDS, respectively (Figure 28a). This ratio also holds for the distribution of finite length between the two groups (Figure 28b), and is very close to the ratio 45-55, of the distribution of displacements among them (Figure 28c). This systematic analogy between L.H and R.H groups, strongly suggests that they had almos. equivalent contributions to the deformation of the multilayer. Furthermore, this analogy, after 40% bulk shortening, implies nearly similar kinematic histories for R.H and L.H groups. Indeed, further evidence presented below verify this important implication.

Figure 28. EDS distribution according to their orientation with respect to the anisotropy plane, in ME2-LS2 (a). (b) and (c) EDS length and displacement distribution histograms, respectively, according to their orientations, in the same section.

However, diagrams of EDS lengths versus displacements for both sections analysed, do not show any systematic relationship between these two kinematic elements; only weak trends (Figures 29a, c). The lack of strong trends is an adequate proof that *the kinematic behaviour of EDS in flattening strain does not follow specific evolutionary paths as these usually are identified by progressive increase in fault length and slip, with progressive strain* (as also seen in Figure 18). As a consequence, the preferred mode of fault-accommodated deformation is by the operation of EDS displaying lengths ranging from 5 to 15 mm, and displacements from 0.5 to 2.5 mm, respectively. Only few EDS broke this rule and propagated in an extremely efficient way (for example, EDS 17; Plate 5) accompanied by a corresponding increase in slip. Nearly identical diagrams were obtained by analyzing separately R.H and L.H EDS data (Figures 30a; c).

A similar non-systematic relationship is indicated by plotting EDS displacements against corresponding inclinations, with respect to the plane of rheological anisotropy (Figures 29b, d; see also Figure 18). The preferred mode of EDS-accommodated deformation results in a wide spectrum of inclinations, corresponding to a slip range of 0.5 mm to 2.5 mm. The lower limit of this spectrum occurs around 20 degrees to layering, whereas the upper limit approaches 80 degrees. However, by analogy to Figures 29a and c, a weak trend can be identified. In general, low-angle EDS tend to carry greater displacements than the high-angle ones, with the amount of displacement increasing as inclinations decrease. This is also valid for both groups (Figures 30b; d). and thus permits the author to conclude that low-angle EDS accumulate slip more effectively, than high-angle ones do.

Figure 29. Diagrams of EDS lengths versus displacements (a), (c) and EDS inclinations versus displacements (b), (d) in ME2-LS2, and ME2-SSB, respectively. In (a) a weak trend can be seen. However, in general, slip accumulated along an EDS, does not appear to be a function of length. For example, EDS measuring 10 mm can be efficient enough to carry slip of 2.2 mm, yet highly inefficient to display slip of only 0.5 mm; or, for shear lengths of about 20 mm, finite slip ranges from 1 mm to 9 mm, almost one order of magnitude larger. In (b), a weak trend can be seen between the ranges 80° and 55° , and 25° to 6° , respectively, separated by a domain, where any attempt to define a trend fails. Notice that the greatest displacements (> 4 mm), correspond to inclinations ranging from 6° to 54° to layering, and the main population is concentrated within the range 20° to 50° .

Similarly, in ME2-SSB (c), it can be seen for example that a slip of 3 mm can be found along EDS ranging in length from 4.7 to 25 mm. However, a progressive increase in EDS length tends to correspond to greater slip. Large displacements (over 5 mm) require lengths over 12 mm, to accumulate. In (d), most of small displacements (< 1 mm) correspond to inclinations between 60° and 40° to layering. Indeed, no displacement greater than 2 mm, was found on EDS inclined more than 52° to layering. On the other hand, notice that for EDS inclinations less than 20° , corresponding slip ranges from 0.8 mm to 11 mm.

Figure 30. (a) and (c) R.H EDS and L.H EDS diagrams, respectively, of lengths against corresponding displacements. ME2-LS2 data.

(b) and (d) R.H EDS and L.H EDS diagrams, respectively, of inclinations against corresponding displacements. ME2-LS2 data.

The striking similarity in kinematic behaviour of each orientation EDS group, strongly suggests almost identical kinematic histories, during progressive deformation. Notice that the distribution of the main shear population between the two groups, shows that the higher displacements occur below or at 45 degrees for both R.H (b) and L.H group (d). These results reveal that the weak trends observed in Figure 29b, are equally influenced by the contribution of both EDS groups.

a

c

b

d

The length distribution histogram (Figure 31; longitudinal section) shows a cluster at the 5 - 7 mm range. More than half of the shears in this section have lengths less than or equal to 9 mm. This characteristic value is only 1 mm greater than the corresponding one in ME2-SSB (not shown here), suggesting that in the flattening experiment EDS propagation commonly terminates somewhere at this point. Although this is true for the majority of EDS, a significant number of them develop lengths greater than 17 mm; these shears usually carry the greatest displacements recorded.

The displacement distribution histogram (Figure 32) shows a cluster at the range of 1 - 2 mm of slip. Only one-third (approximately) of total EDS carry displacements greater than 2 mm. Again, similar displacement histograms are obtained by analyzing both R.H and L.H EDS. So far, accumulating evidence (Figures 28, 31, 32) point out that strain was equally partitioned among R.H- and L.H- dipping EDS, indicating common evolution of both orientation groups, during progressive deformation. Cross-cutting relationships also indicate common initiation of both groups. The preferred angular relationships between EDS and the plane of anisotropy remain to be identified, so that the author can demonstrate, an "octahedral" type of fault geometry in ME2 as well.

The final histogram series (Figures 33, 34) show that the greater concentration (over two-thirds of the total EDS number) occurs between 30° - 60° , with a maximum at 41° - 50° . A low-angle cluster is shown at the range of 10° - 20° to layering (Figure 33a). The breakdown of EDS inclinations, according to their orientation, reveals again an internal consistency (Figures 33b, c; Figures 34b, c).

However, the histogram of ME2-LS2, when compared to that of ME2-SSB, certainly poses a problem, i.e., the absence of well-defined low-angle clusters. Previous diagrams have already shown that the contribution of low-angle EDS to the deformation is not major (compare Figures 29b and 29d; plus, this contribution is not balanced among R.H and L.H EDS (L.H EDS occur more frequently than R.H at low-angles to layering).

One way to investigate this problem, is by constructing the same histogram using different inclination classes (Figure 34d). The distribution of moderate and high-angle EDS inclinations according to their sense of dip (Figures 34e, f), follows the systematic breakdown observed in earlier results. However, the same histograms still fail to document the existence of a low-angle R.H EDS set at the range of 15 - 25 degrees. I suggest that, results concerning EDS inclination distribution in ME2, document sufficiently the synchronous operation of four EDS sets at the range 40° -55°. The four fault sets seem to be represented better within the range 41°-50° (Figures 38a; 39a). In addition, there are geometric constraints favouring the above range of inclinations.

If we accept that the range of 46° -55° is a most accurate representation of EDS sets inclinations in ME2-LS2, then we have also to accept that the high-angle octahedron bounded by the high-angle octahedral planes (EDS) is not axially symmetric with respect to the shortening axis (Z), as axially symmetric shortening conditions demand. The only way to overcome this mechanical condition is by assuming that the high-angle octahedron is slightly tilted with respect to the vertical shortening axis (Z). In this case, a uniform tilt either to left or to the right, as seen on the YZ principal plane, requires a steepening of EDS inclinations with respect

Figure 31. EDS length distribution histogram (a) in ME2-LS2. (b) and (c) R.H. EDS and L.H. EDS length distribution histograms, respectively, in the same section. The breakdown of length distribution (a) into the R.H. and L.H. group, does not show any significant difference in EDS behaviour with respect to this kinematic element. The cluster of EDS with lengths greater than 17mm forms due to the existence of "master" faults in this experiment (see Plates 4, 5).

Figure 32 [following page]. The EDS displacement distribution histogram (a; it refers to ME2-SSB) shows a cluster at the range of 1 - 2 mm. More than two-thirds of the total EDS number, carry slip less than or equal to 2 mm. A small number of shears display slip greater than 5 mm. The analysis of each group (Figure 32b refers to R.H EDS; Figure 32c to L.H. EDS) for the distribution of displacements, produced the same patterns as the overall picture.

b

c

a

b

c

a

Figure 33. EDS inclination distribution histogram (a) in ME2-SSB (an XZ section). It is noteworthy to emphasize that only seven out of 130 shears are inclined at more than 60 degrees with respect to the plane of anisotropy. Notice the appearance of a low-angle cluster at the range of 10° - 20° .

(b) R.H. EDS inclination distribution histogram.

(c) L.H. EDS inclination distribution histogram.

Figure 34 [following page]. Analysis of EDS inclinations in ME2-LS2 (an YZ section), shows that the main population concentrates at the range of 31° - 60° with a cluster at 41 - 50° . High-angle shears occupy the immediately smaller cluster, whereas the low-angle shears are almost equally distributed among the ranges 21 - 30 and 31 - 40 degrees, respectively (Figure a). Identical breakdown of the cluster at 41 - 50 degrees between R.H. and L.H. EDS is shown in (b), (c), respectively. However, low-angle shears tend to show more a left-sense of dip than a right sense.

(d) the same histogram as in (a) using different inclination classes, i.e., in the X-scale of the histogram, instead of the class 10 - 20 , etc., the class 15 - 25 , etc., is used. A low-angle cluster can be immediately seen at the range of 15 - 25 degrees, while the high-angle cluster has been vanished, in favour of the dominant cluster, now transferred to the range of 46 - 55 degrees and representing approximately a third of the total EDS population.

(e) and (f) R.H. and L.H. EDS histograms, respectively. Notice that, a low angle L.H. EDS set can be easily recognized, at the range of 15 - 25° , whereas a corresponding R.H. EDS set not.

b

c

a

a

b

c

d

e

f

to layering towards the tilt direction accompanied by a shallowing of EDS inclinations towards the opposite direction. However, this alternative is in direct confrontation with the results presented in Figures 33a, 34a, where almost identical patterns is shown.

Therefore, in each of both sections, we can document the synchronous activity of two EDS sets at the range of 41- 50 degrees as follows:

Set I : R.H EDS at 41 - 50 degrees to the layering

Set II : L.H EDS at 41 - 50 degrees to the layering

Moreover, the author investigated in detail the kinematic behaviour of each set (Figures 35, 36) and verified their importance in strain accommodation. In general, quantitative analysis of EDS length distribution according to their inclinations with respect to the plane of anisotropy, showed that low-angle shears measure 55% of the total EDS length in ME2-SSB (Figure 35) and the 40% in ME2-LS2 (Figure 36). Similar analysis of the EDS displacement distribution, showed that low-angle shears carry 67% of the total slip recorded in ME2-SSB (Figure 35) and 47% in ME2-LS2 (Figure 36). Both results categorically prove the extreme efficiency of low-angle ductile shearing in ME2, despite the fact that, arithmetically, low-angle EDS comprise only one-third of the total EDS number (Figures 33, 34). In addition, length and displacement distribution histograms that were constructed for low-angle ranges (Figure 35) do not display any significant contrasts, plus, they show that EDS between 10-20° measure together 20% of total EDS length and carry 30% of total slip.

On the basis of these results, the author suggests that, in section ME2-

SSB (Plate 4) two low-angle sets of EDS can be also identified, in terms of their inclinations and sense of dip, with respect to plasticine layering:

Set III : R.H. EDS at 10°- 20° to the layering

Set IV : L.H. EDS at 10°- 20° to the layering

The operation of two additional fault sets in one of the two sections analysed, bears the question of asymmetric accommodation of strain seen on these mutually perpendicular principal planes of the oblate strain ellipsoid. The author suggests that the deviation in the amount of extension allowed during the experiment between Y, X principal directions (17.5% along the former; 22.5% along the latter) is responsible for this asymmetric development of fault patterns. Low-angle faults also are of "octahedral" geometry, therefore I suggest that four, low-angle, EDS sets with orthorhombic symmetry operate in ME2, in addition to the high-angle ones (Figure 37). However, because linear traces of low-angle "octahedral" faults have not been equally developed in the longitudinal section, I suggest that the linear traces of the low-angle sets on the latter section, are included within the spectrum of EDS inclinations at the range of 41° -50° (Figure 37). Resultant low-angle fault geometry does not display a symmetry with respect to the X and Y principal strain axes, and it also implies that slip vectors resolved along the low-angle fault sets have an oblique-slip sense of movement towards the maximum principal extension axis.

Figure 35. Quantitative analysis of EDS length and displacement distribution according to their inclinations with respect to the plane of anisotropy, in ME2-SSB (an XZ section).

- (a) R.H EDS length distribution,
- (b) L.H EDS length distribution,
- (c) R.H EDS displacement distribution,
- (d) L.H EDS displacement distribution.

Notice that, sets I and II (see text) share almost equal contributions, (a), (b) to the portion of length found along EDS at this range as well as carry identical portions of slip, (c), (d). In addition, Set IV (i.e., the low-angle L.H. EDS set), has reached an advanced stage of development, in contrast to Set III (i.e., the low-angle R.H. EDS set) that accounts for a little more than one-third of cumulative magnitudes at this range. This internal inconsistency, however, is not regarded by the author as of major importance, such as the number of EDS sets operating in ME2-SSB, be reduced.

Figure 36 [following page]. Quantitative analysis of EDS length and displacement distribution according to their inclinations with respect to the plane of anisotropy, in ME2-LS2 (a YZ section).

- (a) R.H EDS length distribution,
- (b) L.H EDS length distribution,
- (c) R.H EDS displacement distribution,
- (d) L.H EDS displacement distribution.

Notice that, sets I and II (see text) show nearly identical kinematic histories as well as they accommodate more than a third of total strain due to slip along EDS, as revealed by the breakdown of length and displacement distribution among them.

a

Total length of ~4 EDS = 508.2 mm
values in parentheses are degrees

b

Total length of L H EDS = 775.2 mm
values in parentheses are degrees

c

Total displacements of RH EDS = 96.2 mm
values in parentheses are degrees

d

Total displacements of L H EDS = 157.1 mm
values in parentheses are degrees

a

Total length of RH EDS = 778 mm
values in parentheses are degrees

b

Total length of LH EDS = 856.9 mm
values in parentheses are degrees

c

Total displacements of RH EDS = 129 mm
values in parentheses are degrees

d

Total displacements of LH EDS = 154.7 mm
values in parentheses are degrees

Figure 37. Fault geometry in ME2 (flattening experiment). Note that this is an average representation of octahedral fault sets identified in this experiment (other octahedral faults operate during the experiment, however, they do not occur at sets). X, Y, and Z are the principal axes of the finite strain ellipsoid (Z is the axis of shortening). Roman numbers refer to EDS sets identified in the two mutually perpendicular cross-sections analysed (see text for explanation). R and L denote right-hand and left-hand orientation, respectively, of EDS sets as seen on either XZ or YZ plane. Note that "master" EDS are not depicted here because of their "plane-strain" geometry. The formation of a second octahedron enclosing the high-angle one is due to strain asymmetry prevailed throughout ME2, with more extensional strains being accommodated along the maximum principal extension axis (X). Both octahedra share the same equatorial plane which coincides with the orientation of the anisotropy. Both octahedra formed at approximately the same time, however, with finite strain, the role of the low-angle one becomes increasingly important (see below).

Chapter IV. DISCUSSION

Finite extension accommodated in part by non-rotating faults

Plane strain theory predicts modifications in the angular relationships between faults, as strain intensity increases. In coaxial deformations, the dihedral angle between conjugate fault zones increases, because faults become rotated towards the XY principal plane of the finite strain ellipsoid, while slip vectors rotate towards the greatest finite extension X within this XY plane. In our experiments, observation of all cuts indicates that plasticine layering was uniformly stretched as a result of slip along discrete, multiple EDS, and of "internal" ductile strain, without any finite rotation. In 2-D deformations, such type of extension does not preclude the possibility of fault plane rotation away from the compression direction, provided that the deformation is not constrained to be isochoric (for example, Ramsay and Huber, 1987, p. 615). Although incremental deformation in our experiments is isochoric, the possibility of fault plane rotation has to be discussed at this point. As a first example, consider the angle formed by EDS 63 and 67 in ME2-SSB (Plate 4). This angle is obtuse to the compression direction in ME2 (Z) and has a value of 92° (Appendix D). Is this angle the original angle formed when EDS initiated, or is it the final product of EDS rotation on either side, as a result of progressive strain?

We recall that, EDS observed in this XZ section of the finite strain ellipsoid are the projections of octahedral planes on this vertical plane. If octahedral planes rotate with progressive strain towards the XY principal plane, so do their projections (as lines). One, therefore, can compare the angles formed by EDS

intersecting each other, with those predicted by rotational models (for example, Jackson and McKenzie, 1983). These authors determine fault rotation towards the extension direction in plastic 2-D deformations, according to the equation : $\tan \theta_f = (1/\lambda^2) \tan \theta$ where θ is the initial fault dip, θ_f is the final fault dip after fault plane rotation has occurred, and λ is finite stretch along the extension direction.

In ductile shearing, initial dihedral angles between conjugate shear zones range from 90 - 120° (Ramsay, 1980; 1982), constraining initial extensional shear zone dips in the range of 30 - 45°. Assuming for a moment that this is also true in our experiments, then, an octahedral plane would respond to a 40% bulk horizontal extension by rotating to a final dip of 16-27° (Figure 38), and the predicted final angle between two conjugate faults/shear zones is within the range of 126-148°. This range is expected to be much greater on a section of apparent dip, as in ME2-SSB, which is not the case for the currently observed apparent angle between EDS 63 and 67. In addition, nearly identical angular relationships between "master" EDS and the rest of the population are observed in both sections analysed. For example, consider the angle formed by EDS 37 and 48 in ME2-SSB (Plate 4), which is obtuse to the compression direction (Z) and has a value of 101° (Appendix D); the angle formed by the shears 17 and 23 (Plate 5) has a value of 81° (Appendix E), even lower than the one predicted for conjugate extensional shear zones at the time of initiation. One however, might question that the assumption concerning initial fault dips (i.e 30-45°) is a feasible one, especially when high-angle shears are present in both experiments. That EDS can form at high angles to the anisotropy plane is unequivocal, and the author has in fact suggested (see below) a

Figure 38. Ductile extension accommodated by rotating faults (shear zones) and predictions for final angle of fault dip, after Jackson and McKenzie (1983). Curves drawn here correspond to an amount of extension (beta) of 1.4, to compare predicted fault inclinations to those found on our flattening experiment. The curve showing brittle faulting predicted inclinations is also given for comparison (for derivation of this curve, see also Jackson and McKenzie, 1983). Bars with labels B and D refer to angular ranges of fault initiation in the brittle and ductile field, respectively.

mechanism for their nucleation. However, these faults comprise a minority of total EDS population in ME2 (Figures 33, 34), and previous experiments in plane strain (Peltzer and Tapponier, 1988; see also Figure 6) have not produced high-angle shears at all. Further, if one assumes that all faults initiate at such high-angles to plasticine layering such as 60 to 70 degrees (in order to obtain final fault dips between 40-50°; Figure 38), then, since there is no systematic cross-cutting relationship among EDS, why do fault finite inclinations appear at such wide a spectrum ? The only answer, I might give to this question, would be that the rotation rates of individual fault planes vary with progressive deformation; this answer, however, cannot be tested in our experiments, since any fault plane rotation cannot be observed directly because of deformation machine construction (Figure 7). These considerations favour the initial assumption adopted by the author, to test experimental results with those predicted by rotational models.

The above discussion can be equally applied to the constriction experiment, where high-angle shearing (and consequently currently observed dihedral angles between EDS display values lower than 90°) contributed more to the fault-accommodated part of total strain (compare Figure 25 to Figures 35 and 36). *Therefore, I suggest that, in both experiments, the currently observed apparent angular relationships among the high-angle octahedral fault sets are those of EDS initiation.*

Although the low-angle EDS sets in both experiments intersect each other within the range of angles predicted by rotational models (Figure 38; see for example the angle formed by EDS 108 and 110 in ME2-SSB of 134°), they also have not rotated as a result of progressive strain. If they had rotated, then, if most of

EDS would form at 30 - 45 degrees to layering, one has to explain why some selected EDS rotate away from the compression direction while the majority does not. Such selective rotation is difficult to understand. If EDS found within the moderate range of inclinations are indeed final products of fault plane rotation, then the problem is transformed to proving that all octahedral faults, irrespective of their initial inclinations have experienced the same rate of rotation towards the plane of the anisotropy, that itself did not become rotated with progressive deformation. This problem certainly deserves further investigation.

In addition, cross-cutting relationships between high-angle and low-angle sets, do not indicate any systematic offset of either sets. Therefore, I suggest that low-angle sets formed approximately the same time, together with the high-angle sets. Field evidence (e.g. Reynolds and Spencer, 1985; Miller and John, 1988) has shown that extensional fault systems have been initiated at angles of less than 30° and accumulated a significant amount of slip with progressive deformation.

Low-angle ductile shearing and finite strain

A second major implication of EDS kinematics in the flattening experiment, is the drastic difference in strain intensity between low-angle and high-angle shears. Since low-angle ductile shearing is not a product of rotation of shears towards the anisotropy plane, then, strain accumulated much more effectively along low-angle EDS sets because of energy requirements of the deformation. The principle of minimum energy (for example, Casey, 1980) states that in general, when a body is subjected to stresses, the deformation suffered by the body is that which

gives the least stored elastic strain energy, or the least rate of energy dissipation (for viscous materials). Then, we are faced with a paradox : Since strain accumulates more efficiently along low-angle faults why do observations of EDS geometry in both experiments reveal that low-angle EDS account for approximately one-third of the total EDS population ? Let us assume for a moment that the sole mechanism of deformation in our experiments is by slip along octahedral faults, in order to briefly investigate what would be the preferred mode of deformation, in terms of EDS inclinations to layering, at the yield point.

Then, the stretching experienced by each layer should equal the sum of horizontal separations between offset (along EDS) segments of each particular layer. In general, the total amount of stretching let us say along the Y-direction in ME2, again should equal the sum of horizontal separations between offset (along EDS) plasticine layers (Figure 39; assuming for simplicity plane strain). The horizontal separation (S) is equal to the product of displacement (d) along each shear, times the cosine of the angle Θ of dip. Therefore : $S = d \cos \Theta$. Assuming a uniform finite dip-slip of 2mm (an average value; Figure 32), we can distinguish the following cases :

case i) $\Theta = 15^\circ$ then $S = 1.93 \text{ mm}$

case ii) $\Theta = 45^\circ$ then $S = 1.41 \text{ mm}$

case iii) $\Theta = 60^\circ$ then $S = 1 \text{ mm}$

i.e., as the angle of dip increases so the horizontal separation between offset layers decreases. This implies that for the same amount of extension along Y, smaller horizontal separations along EDS result in the need for more EDS to initiate. This

Figure 39. Fault profiles in plane strain (pure shear) with the axis of no strain parallel to X (i.e. normal to the plane of the page). Vertical strain along Z is negative (shortening). Only faults accommodate resultant extension along Y, which for a single strain increment equals the amount of horizontal separation (S) between disrupted segments of a horizontal marker (m) (for example, a single plasticine layer in ME2, if we ignore for a moment the component of "internal" ductile strain). Uniform dip-slip of 2mm is assumed along each fault, irrespective of its dip (θ ; dips of 15°, 45°, and 60° are illustrated here). Notice that, as fault dip increases, so the amount of horizontal extension accommodated by slip decreases; the amount of throw (t), however, increases proportionally with fault dip. See text for explanation.

conclusion is not altered if a component of "internal" ductile strain has contributed to the deformation, provided that this component has been uniformly distributed along the strained material (as is the case in ME2; see Figure 16). Above analysis proves that low-angle ductile shearing requires the formation of fewer octahedral faults necessary to accommodate a given amount of extensional strain, which is in direct confrontation with the preferred mode of deformation in both experiments. This is because, since all EDS form approximately at the same time, the principle of minimum energy requires that at the yield point less stored elastic strain energy is released, when a ratio 2:1 holds between EDS at the range $40 - 55^\circ$ and EDS ranging from 30 to 10° (Figures 22; 23; 24; 33; 34). Therefore, the answer for the greater efficiency of low-angle EDS has to be found in the different kinematic history of the low-angle shears with progressive strain, and can be adequately explained on the basis of Figure 39, i.e., low-angle shears are difficult to initiate; however, as soon as they do initiate they become favorable directions in space for strain to localise.

Fault nucleation

In both experiments, anisotropic multilayers deform by a combination of "internal" ductile strain and by slip along shear instabilities that are attributed to the yield of the material. They initiate at about 5% bulk extension in ME1 and between 5-7% bulk shortening in ME2. These yielding instabilities displace the planar anisotropy along multiple, spaced, inclined, planar, faults. Their rhomboid pattern, observed, on all sections analysed, suggests that they are not inclined

perpendicular to any of the principal strain axes. Thus, they comprise TYPE 2 instabilities (Cobbold et al., 1971; see also Figure 4). This happens despite the fact, of the large number of layers (106 in ME1; 114 in ME2) in the confined multilayers, that imply a low bending resistance coefficient (Latham, 1985a), which should promote TYPE 1 structures.

I suggest that the reason for the instability is the stored strain energy associated with the compaction (initial) stage of the experiments. During this stage, energy has been stored in the model, and equals the external work done on the multilayer. This stored energy is available as work at the yield point. In addition, one important effect of this stage may be the further development of the planar fabric in plasticine, thus, enhancing the degree of the intrinsic anisotropy. Inhomogeneous flow, by the operation of localised plastic instabilities (as opposed to a diffused, homogeneous flow) is the result of the pre-existing (intrinsic) anisotropies, i.e., rheological anisotropy and plasticine shape fabric.

Fault nucleation in our experiments does not follow predictions listed at the introductory chapter of the thesis. Indeed, if one assumes that EDS form along planes of maximum shear stress (since plasticine is practically frictionless), one has to accept that only four sets of EDS will form at any stage during deformation, since the octahedral shear stress is maximum in only four directions in space in isotropic (Figure 3) and probably in anisotropic materials as well (when bulk deformation is irrotational). On the basis of wide spectrum of fault inclinations produced in both experiments, the author suggests that nucleation of EDS involve *failure* of the layering at selected sites, where there are discrete heterogeneities in

the deformation (see also Cobbold et al., 1971; Cobbold, 1976, 1977a,b; Watkinson, 1976; Hanmer, 1979).

These heterogeneities can be invisible (at the scale of observation) undulations along the boundaries of individual layers, associated with local thickness variations, or can be caused by compositional variations within individual plasticine layers, brought about by rolling. The spacing of these heterogeneities is in general rather irregular. Their significance can be appreciated by considering as a particular example, the statistically homogeneous anisotropic material of Figure 40, in which there is a small local deflection (without any loss of cohesion along it; most of EDS in both experiments nucleate at layer interfaces, see Plates 3, 5). This sketch could represent an XZ section of the ME2, during the early stages of deformation. As the material has a high degree of intrinsic anisotropy (113 potential slip surfaces of small finite contact strength), we would expect the ratio $M/L \gg 1$ (see section 1.4). It is interesting also, to consider the effects of the preferred orientation of plasticine grains (see PE2), that may enhance drastically the degree of intrinsic anisotropy. The rheological moduli in the Z-direction are M_z, L_z , whereas along AB (Figure 40) are M_a, L_a (M, L are the compressive and shear moduli, respectively). Biot (1965, p. 187) shows that along AB (assuming an angle of 45° with the layering, where one of orthotropic symmetry conditions is satisfied) the local volume of the material acquires a new low shear resistance direction, the ratio M/L inverts, and consequently a strong local reduction to compression along Z is created.

For type II instabilities, as M tends to 0 (assuming that L maintains a finite value), the ratio M/L tends to 0, the characteristic directions of the flow field

will tend to develop symmetrically at $\pm 45^\circ$ to the normal to the direction of layering (Cobbold et al., 1971, p. 33). This means that in Figure 40, characteristic directions will develop parallel and normal to the deflection, along which the resistance to inter-layer slip is easy to overcome (note that one of the characteristic directions is parallel to the anisotropy plane that has been locally diverted, along the deflection). Three-dimensional straining conditions require the activation of an octahedral plane intersecting the principal plane XZ along AB. Since compression direction is vertical, slip will have a normal sense of movement and an EDS starts operating.

The author suggests that low-angle or high-angle faults in plasticine initiate in a similar way to the particular case of 45° that satisfies orthotropic symmetry conditions. In other experiments, it was shown that the development of internal instabilities in anisotropic materials is not restricted to conditions of orthotropic symmetry (Cobbold et al, 1971; Cosgrove, 1976). The author further suggests that, fault initiation is closely related to an inversion of the compressive/shear moduli ratio along random deflections (heterogeneities). The inversion in strain moduli canalises one of the characteristic directions of local deformation along the anisotropy plane, where slip is easy to initiate. This is purely a qualitative suggestion which has no mathematical support so far. In addition, this model fails to explain the variety of dihedral angles formed by conjugate octahedral faults (for example see Plate 3), that certainly deserves further investigation.

When the onset of plastic deformation gives rise to the first EDS, our results indicate that they form more frequently in a certain preferred range of inclinations, where obviously, shearing would be easier. It is interesting to note that,

Figure 40. EDS nucleation in plasticine possessing a strong intrinsic rheological anisotropy, such as for example in ME2 (flattening experiment), XZ section. Thick and short arrows indicate shortening (Z) and maximum extension direction (X), respectively, of the finite strain ellipsoid. Thin and long arrows on the boundaries of the sketch indicate the variation of the shear moduli with direction. Faults initiate along selected sites of the layering where heterogeneities (mostly of the form of local deflections located at layer interfaces) exist before deformation. The particular case of a deflection AB at 45 degrees to the shortening direction is illustrated here. Thin arrows within the local volume of the material where faults are about to initiate indicate sense of movement. Not to scale. See text for discussion.

according to the theoretical analysis presented above, they should form in random directions without any variations of their frequency, being dependent on the geometry of each deflection. Therefore, *the role of initial (intrinsic) heterogeneities in deformation, appears to be restricted at the very onset of plastic deformation, i.e., they provide only the physical basis for an instability to locally originate, but, in general, they do not direct its development in space and time.*

Fault propagation

The suggestions developed so far, are concerned with EDS nucleation or with the onset of the plastic deformation process. Biot's (1965) theory for anisotropic materials, while being the most efficient in explaining the initiation of perturbations in a flow field, deals only with infinitesimal deformations. Other experimental evidence (Cobbold et al., 1971, Figure 19) indicate that similar extensional structures (for example, "normal" kink-bands) grow with finite strain without any significant deviations from the initial buckling geometry. The nature of this experimental work, however, did not permit the author to actually observe EDS initiation and subsequent growth in the interior of the models. Therefore, it is necessary at this point to address the growth of yielding instabilities into finite structures (EDS).

Finite EDS geometry is the result of an amplification process that takes over immediately after nucleation. Amplification refers to the propagation of slip surfaces into previously undeformed domains of the multilayer.

It is obvious that no progressive growth of a yielding instability into a

well-developed slip surface (EDS) will occur, unless successive increments of strain continue to localise in the already deformed zone. Therefore, EDS amplification occurs because it becomes easier to further deform an already deformed zone than to initiate deformation elsewhere (strain-softening). This, in turn, stems from the requirement for minimum work that leads to shear zone development at various scales (Poirier, 1980), and bears the following question : what is the reason for continuous strain localization along a shear instability in our experiments? (i.e., what is the predominant strain softening mechanism?)

Strain softening mechanisms have been reviewed by White et al., (1980), Poirier (1980), and Ranalli (1987). External physical factors (P-T) under which the experiments took place preclude related softening mechanisms. There is no evidence that principal directions of anisotropy become rotated with progressive deformation, so rotation softening (Cobbold, 1977b) is ruled out. Gross chemical composition of plasticine did not change either, but differences in microstructure may have occurred. However, microstructural changes (McClay, 1976) lead to strain hardening when plasticine deforms homogeneously by viscous flow. I suggest that strain hardening (probably of geometric origin) of plasticine multilayers in our experiments, is inhibited by the operation of multiple EDS. The ability of multilayers to deform by EDS at such high strains as 60% bulk extension for ME1 and 40% bulk shortening for ME2, suggests that intrinsic anisotropy is the rheological property of the materials that provides a strain-softening mechanism, that is difficult to identify (for example, plasticine is an extremely delicate material to examine in a thin section).

Since three-dimensional deformation is irrotational in our experiments,

the coaxiality of stress/strain axes throughout the models (except for model boundaries) implies that finite directions of resolved octahedral shear stress on any slip surfaces remain stationary in space and in time. Propagation is fastest in the direction of the resolved octahedral shear stress, because this is usually believed to be the direction of slip (e.g., Bott, 1959), thus, causing a slip surface to increase in length and adopt a lens-like form (e.g., Cobbold, 1977b). Progressive in-plane propagation of this kind (terminal propagation after Cobbold, 1977b), causes a lens to acquire a long planar form, visible as linear traces in vertical cross-sections of apparent dip, as in those cut parallel to principal strain planes.

Termination of slip along EDS

The rate of fault propagation may be steady with increasing strain, or even accelerating. This is caused by further strain softening along a shear, whereas a decelerating propagation rate, due to strain hardening eventually "locks-up" an EDS. When EDS propagation comes to an end, it "locks-up". For example, shears that terminate against their counterparts, are probably "locked-up". If they were active, either a mutual offset ought to be observed (like the EDS pattern in the central domain of ME2), or a cross-cutting relationship caused by a mechanism of interference (Oertel, 1965).

The mechanical reason for slip termination, is that the energy needed to cause further shearing is greater than that needed to form new shear planes and/or to maintain slip along shears in a more favourable orientation to the principal strain axes. The latter case needs to be examined more analytically,

because of the difference in kinematic evolution of low-angle shears. We recall that, a fundamental mechanical condition of faulting is that the shear stress on the plane of the fault must exceed the shear resistance to slip along the fault. In our experiments, the shear stress required for sliding on an EDS is controlled only by viscous drag which is practically zero. This implies also, that, sliding is independent of the octahedral normal stress acting on the slip plane (see also Reches, 1978). Therefore, whatever is the inclination of the newly-formed slip plane, it continues to propagate with progressive strain, since its propagation (and consequently the capacity to maintain sliding) is only dependent on the intensity of the resolved shear stress along it. In turn, this intensity is controlled only by a single variable, the ratio of principal stress differences (Bott, 1959; provided that EDS and layering do not rotate). It is for these reasons that, low-angle shears, also kinematically favoured (Figure 39), accommodate extensional displacements more effectively than shears at any other inclinations to layering.

Let us now examine in some detail processes that may lead to termination of slip along EDS. First, if the resolved shear stress acting on the slip plane decreases dramatically, then, propagation rate decelerates and slip diminishes gradually, such that eventually, it is reasonable to expect that further movement is inhibited. Such reduction in shear stress level is commonly explained by fault plane rotation away from the optimal direction of shear failure (for example, Nur et al., 1986). However, fault plane rotation does not occur in our experiments (see above). A second alternative for increasing resistance and/or cessation of slip along a shear, is that an EDS zone (referring to the grain scale) strengthens with progressive

deformation, probably due to microstructural changes, such that it becomes stronger than surrounding material, therefore, redirecting deformation in space. Other alternatives arise from the interaction among faults within a local volume of material. A rapidly growing low-angle shear for example, may render adjacent high-angle ones progressively inactive.

ME1 and ME2 : a difference in EDS patterns

The development of opposing networks (synchronously active) in the central domain of the model in ME2 (Plates 4, 5), marks a drastic difference in the way the anisotropic multilayer responded to plastic deformation, as compared with ME1. In ME2 there are two types of faults: "master" EDS and faults of dimensions similar to those of ME1 (the latter faults are of "octahedral" geometry). However, *"master" EDS are not of octahedral geometry because on sections parallel to the XY principal plane (where fault traces appear at "map" view), they are seen to strike parallel to subparallel to one of principal strain axes, i.e either they strike parallel to X or parallel to Y.* Fault planes containing the X axis appear as 4 (four) conjugate sets, they carry a small amount of oblique slip and they systematically offset fault planes containing the Y axis. It is not clear to the author why these "master" faults formed, and why they have developed more efficiently with progressive deformation.

I suggest, however, that the change in mechanical conditions of straining that occurred during ME2 may be responsible for the formation of "plane-strain" type faults. In addition, they are inclined within a range of 40-55° to plasticine layering. As shown above (pp. 104-108), such angular relationships are those existing at the

yield point and are not the result of fault plane rotation. Conjugate EDS formed within this range of inclinations may possess a proximity in space with the trajectories of maximum shear stress, which do not rotate with progressive deformation because of irrotational boundary conditions. The progressive growth of "master" shears may result from further strain softening along these first-formed shears at the central domain of the model.

A feasible hypothesis for further strain softening along "master" shears is their increase in width (lateral growth) with progressive strain. However, this width increase is not significant enough at the scale of resolution, such that the author would draw an extensional shear zone instead of an EDS (Plates 4, 5). Yet, it is visible that "master" EDS are slightly wider than the rest. The author suggests that this small width increase is due to the fact that crushed (?) material has started to accumulate as shear displacement increases. This crushed (?) material may be of lower (reduced) strength relative to hanging wall and footwall material. The accumulation of weaker material within the boundaries of an EDS, provides a continuous feedback of strain softening, and further strain localization is possible.

Chapter V. CONCLUSIONS

- 1) In both experiments, a significant part of bulk finite strain was accommodated by slip along EDS of "octahedral" geometry. Cross-cutting relationships, suggest that, EDS sets develop synchronously and form a three-dimensional network, instead of operating sequentially where systematic offsets would have been produced.
- 2) Diagrams of EDS lengths and inclinations plotted against corresponding displacements, show very weak trends; greatest displacements tend to occur along longer and low-angle shears, yet, the main EDS population exhibits a non-systematic relationship to displacement (Figures 18, 29). These results demonstrate that, EDS kinematics with progressive strain is not dictated by any specific relationships between shear length and slip, nor by shear dip and slip. With the exception of "master" EDS that developed in the flattening experiment, this result supports the idea that the rheology of the material exercises more influence on fault kinematics than states of finite strain do.
- 3) EDS form because extension is allowed to occur parallel to plasticine layering and nucleate at selected sites (heterogeneities) of the multilayers (Figure 40), where slip is canalised because of the anisotropy, from where they grow into finite structures because of strain softening. I propose that this mechanism of EDS formation and subsequent growth is directly comparable to the formation of shear bands in natural anisotropic materials, that always involves a softening process (e.g., Cobbold 1977a, b; Poirier, 1980; Peltzer and Tapponier, 1988).
- 4) In the constrictional strain field, our results indicate that, a significant part of

the fault-accommodated strain is taken up by the synchronous operation of four, high-angle, oblique-slip fault sets, with orthorhombic symmetry to the principal strain axes. In flattening strain, four, high-angle, dip-slip fault sets arranged in orthorhombic symmetry form, unless the mechanical conditions of straining deviate from axially symmetric shortening, in which case four, low-angle, orthorhombic fault sets also form, carrying oblique-slip vectors towards the maximum principal extension direction. In addition, this deviation from ideal flattening strain may be responsible for the formation of "master" EDS, of "plane-strain" type.

5) The finite geometry of the faults, the lack of any systematic offset among them, together with the preservation of horizontal layering are evidence that no significant rotation of fault planes occurred towards the XY principal plane of the finite strain ellipsoid, with progressive strain.

6) The author suggests that, above results may describe the finite strain state due to slip along octahedral faults, of isothermal, non-linear, elastic-plastic or rigid-plastic, anisotropic materials subjected to a general 3-D deformation. In addition, they may be directly applicable to active extensional terranes. In continents, extension usually takes the form of rift systems. These are zones of divergent plate motion characterised by crustal thinning and subsidence along the rift axis. Roughly rhomboid map patterns of normal faults are characteristic in these regions (see Reches, 1978; Aydin and Reches, 1982, for literature reviews). Such faulting patterns cannot be interpreted in terms of plane-strain rift models like those of LePichon and Sibuet (1981), Wernicke (1985), and Lister et al., (1986), which only explain the formation of conjugate or asymmetric normal faults, perpendicular to the

direction of regional principal extension.

7) Further related work should focus on the effects of strain rate and temperature on the number, orientation and geometric evolution of fault sets. Fault kinematics and angular relationships among them can be further investigated by conducting a series of experiments up to different amounts of bulk finite strain. Finally, a series of experiments could examine the effect of the shape of the finite strain ellipsoid (other than that of end-members; i.e., constriction, flattening), on faulting processes in plasticine.

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APPENDIX A

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Data of ME1-Serial Section b

Shear number	Length (in mm;acc. 0.1mm)	Angle (with layering; acc. 1degree)	Displacement (in mm;acc. 0.1mm)	Orientation L.H.-R.H.
1	9.0	39	1.0	L
2	10.0	26	1.0	L
3	7.0	58	0.5	L
4	10.5	39	1.0	L
5	11.0	51	0.4	L
6	6.7	47	1.2	L
7	7.0	26	2.0	L
8	18.0	28	4.0	L
9	6.7	22	1.0	L
10	10.0	31	0.5	R
11	8.3	77	0.5	L
12	5.0	58	0.5	L
13	8.8	28	1.0	L
14	6.9	54	0.6	L
15	6.2	37	0.3	R
16	9.5	13	4.0	L
17	3.3	82	0.2	L
18	5.1	61	0.4	R
19	5.2	48	0.5	L
20	6.8	28	1.0	L
21	5.8	78	0.3	R
22	10.7	21	2.5	L
23	4.5	74	0.6	R
24	7.1	62	0.5	L
25	10.8	40	1.0	L
26	4.0	41	0.2	R
27	6.2	68	0.6	L
28	7.0	45	0.5	R
29	6.0	50	0.5	R
30	4.8	52	0.5	R
31	8.8	43	0.8	L
32	9.7	51	1.0	L
33	10.0	38	0.6	L
34	9.6	42	0.5	R
35	4.5	38	0.4	L
36	5.0	79	1.0	R
37	6.2	20	1.0	L

Data of ME1-Serial Section b

38	5.0	67	0.6	L
39	10.0	24	2.0	L
40	8.5	12	2.0	R
41	7.9	19	0.5	L
42	4.0	72	0.8	R
43	4.9	26	1.5	L
44	7.7	38	1.0	L
45	7.9	32	1.0	L
46	9.4	62	0.5	R
47	5.5	77	0.2	R
48	11.6	40	0.5	L
49	9.3	51	0.5	L
50	7.5	31	0.5	L
51	11.8	52	0.6	L
52	10.0	36	0.6	L
53	7.2	49	1.0	R
54	5.0	39	1.2	L
55	7.8	52	0.8	L
56	9.2	68	0.4	L
57	8.3	32	0.5	L
58	8.0	38	0.2	R
59	9.5	42	0.8	L
60	4.3	76	0.5	R
61	7.0	71	0.4	R
62	5.0	32	1.0	L
63	5.5	79	0.4	R
64	10.0	36	0.3	R
65	6.0	64	0.8	R
66	6.9	31	0.5	L
67	6.1	47	0.5	R
68	5.9	26	0.5	L
69	7.0	56	0.5	R
70	5.0	51	0.7	L
71	4.8	26	0.2	R
72	8.0	78	0.8	R
73	10.0	77	0.3	R
74	7.3	48	0.4	L
75	8.5	40	0.5	R
76	8.0	53	0.3	L
77	10.8	53	0.5	L
78	9.0	35	0.4	R

Data of ME1-Serial Section b

79	10.9	33	0.6	L
80	12.7	42	0.3	R
81	9.9	51	0.4	R
82	5.8	37	1.0	R
83	8.0	34	0.2	L
84	12.0	50	0.5	L
85	13.0	35	0.8	R
86	5.5	25	0.5	L
87	6.3	65	0.6	R
88	9.0	40	0.5	R
89	5.9	23	0.5	L
90	11.8	81	0.5	L
91	8.5	62	0.7	L
92	7.4	53	0.4	L
93	5.3	68	0.5	L
94	11.9	62	0.2	R
95	9.5	63	1.0	R
96	6.0	67	1.0	R
97	12.1	51	1.0	R
98	7.8	22	1.5	L
99	6.9	53	0.3	L
100	9.8	47	0.5	L
101	12.8	51	1.0	L
102	8.5	44	0.2	L
103	6.2	47	0.2	R
104	13.5	50	0.2	L
105	9.8	57	0.5	R
106	9.0	74	0.4	R
107	12.1	50	0.3	L
108	6.0	32	1.0	R
109	6.5	12	1.5	R
110	12.7	55	1.0	L
111	5.5	52	0.8	R
112	6.2	61	0.8	R
113	8.5	25	2.0	L
114	5.0	27	1.8	R
115	7.3	53	0.5	L
116	12.0	68	0.4	L
117	16.5	56	0.5	L
118	6.2	50	0.3	R
119	9.0	38	0.6	L

Data of ME1-Serial Section b

120	10.5	75	0.2	L
121	6.8	55	0.5	R
122	8.8	33	0.4	R
123	7.3	42	0.4	R
124	10.8	39	0.5	L
125	8.9	56	0.3	R
126	10.0	37	0.3	L
127	6.2	63	0.7	R
128	21.9	49	1.0	L
129	5.8	59	1.0	L
130	5.0	15	1.1	R
131	12.6	62	1.1	L
132	5.9	34	0.3	R
133	7.0	36	0.2	L
134	13.3	68	0.9	L
135	9.9	34	0.5	R
136	6.3	55	0.4	L
137	7.0	51	0.3	R
138	7.4	52	0.5	R
139	5.1	78	0.4	R
140	5.2	21	1.8	R
141	10.0	30	0.3	L
142	8.1	46	0.6	L
143	5.2	71	0.5	R
144	10.5	23	1.0	R
145	8.5	38	0.4	L
146	6.6	63	0.5	R
147	5.9	34	0.4	R
148	7.0	58	0.2	R
149	6.8	41	0.4	L
150	5.2	45	0.5	L
151	9.0	40	0.5	L
152	9.0	48	0.5	R
153	7.9	24	1.8	R
154	9.8	39	0.7	R
155	8.0	44	0.6	L
156	10.8	46	0.7	L
157	4.0	70	0.6	R
158	5.7	70	0.5	L
159	7.4	56	0.5	L
160	2.9	27	0.6	R

Data of ME1-Serial Section b

161	11.5	74	0.4	L
162	9.5	65	0.9	L
163	8.5	33	2.1	L
164	8.9	32	0.6	R

Total length (mm) of EDS = 1330.5

Total displacement (mm) of EDS = 117.4

Total length (mm) of R.H EDS = 514.6

Total length (mm) of L.H EDS = 815.9

Total displacement (mm) of R.H EDS = 44.3

Total displacement (mm) of L.H EDS = 73.1

APPENDIX B

135

Data of ME1-Serial Section e

Shear number	Length (in mm acc. 0.1mm)	Angle (with layering acc. 1 degree)	Displacement (in mm;acc. 0.1mm)	Orientation L.H-R.H
1	12.0	31	1.0	L
2	4.1	42	0.8	R
3	4.9	53	0.6	R
4	5.7	52	0.3	R
5	6.4	35	0.5	R
6	14.0	47	1.0	L
7	8.9	21	2.0	R
8	10.8	41	0.8	L
9	17.6	35	1.0	L
10	4.5	75	0.5	R
11	14.1	35	1.0	L
12	5.8	75	0.7	R
13	5.0	51	0.7	R
14	6.3	46	0.4	R
15	9.4	23	0.6	R
16	6.6	58	0.8	L
17	9.0	52	1.0	L
18	9.8	67	0.5	L
19	13.7	66	0.6	R
20	10.9	27	0.3	R
21	7.4	57	0.5	R
22	9.2	35	0.5	L
23	4.0	77	0.3	R
24	7.0	36	2.2	L
25	6.1	64	0.8	R
26	6.0	63	0.3	R
27	10.8	28	0.4	L
28	7.5	47	0.5	L
29	7.0	36	0.5	R
30	10.6	42	1.0	L
31	14.2	50	0.5	R
32	4.4	47	0.6	R
33	12.2	55	0.5	L
34	7.8	48	0.3	L
35	7.8	17	3.0	R
36	7.6	51	0.4	R
37	9.0	26	1.6	R

Data of ME1-Serial Section e

38	8.0	18	1.7	R
39	17.0	45	1.0	L
40	6.0	30	0.5	L
41	8.6	46	0.4	R
42	5.5	60	0.3	R
43	10.0	33	0.6	R
44	3.1	76	0.9	R
45	6.7	31	2.8	R
46	14.3	31	0.5	L
47	9.6	66	0.4	R
48	11.0	15	4.5	L
49	7.0	53	1.3	L
50	4.8	48	1.0	L
51	5.8	33	1.8	R
52	3.2	63	1.0	R
53	6.4	47	0.6	L
54	5.0	75	0.4	R
55	8.5	49	0.4	L
56	14.8	55	0.8	L
57	11.7	45	1.0	L
58	10.0	17	2.6	L
59	11.0	60	0.5	L
60	6.3	62	0.9	L
61	7.0	65	1.0	L
62	5.2	57	0.6	R
63	9.4	68	0.8	R
64	5.0	70	1.0	L
65	8.0	44	1.1	R
66	5.6	39	1.3	R
67	7.0	51	0.5	R
68	9.3	45	0.3	R
69	10.0	61	0.3	L
70	9.0	53	0.5	R
71	8.0	33	1.0	L
72	7.8	32	2.5	L
73	10.0	23	3.2	R
74	12.0	35	0.4	R
75	6.0	39	0.4	R
76	10.3	25	0.7	L
77	15.6	17	1.4	R
78	11.5	17	1.0	R

Data of ME1-Serial Section e

79	7.0	23	2.0	L
80	5.0	46	0.6	R
81	12.9	40	0.6	L
82	12.5	32	1.0	L
83	4.2	65	0.5	R
84	13.3	39	1.0	R
85	7.5	60	0.7	R
86	12.0	37	2.1	L
87	5.0	55	0.3	R
88	15.0	42	0.5	L
89	5.6	44	0.7	R
90	3.6	66	0.7	R
91	7.0	42	0.5	L
92	12.0	26	1.0	R
93	17.0	18	2.0	L
94	8.5	53	0.8	L
95	7.0	51	0.5	R
96	14.0	38	2.6	R
97	11.9	57	0.5	R
98	11.0	51	0.7	L
99	7.0	73	0.5	L
100	12.0	48	0.4	L
101	5.9	57	1.1	R
102	7.9	58	0.4	R
103	5.3	72	0.3	R
104	8.0	25	1.6	L
105	6.6	55	0.4	L
106	13.2	38	0.4	R
107	15.2	45	0.4	R
108	15.3	60	0.3	R
109	8.4	69	0.5	L
110	9.3	22	1.5	R
111	12.5	37	1.0	L
112	3.4	71	0.3	R
113	7.9	39	0.4	R
114	7.9	40	0.4	L
115	9.1	77	0.4	R
116	6.4	44	0.4	L
117	5.0	34	0.3	R
118	7.4	79	0.5	L
119	11.0	31	0.7	L

Data of ME1-Serial Section e

120	12.6	9	1.6	R
121	10.0	69	0.5	R
122	7.7	54	0.6	R
123	5.0	30	0.5	L
124	5.5	44	1.0	R
125	9.2	58	0.4	L
126	6.0	46	1.0	R
127	9.5	43	0.3	R
128	7.0	72	0.3	R
129	7.0	46	0.9	R
130	5.4	50	0.3	R
131	11.3	37	0.3	R
132	8.3	66	0.4	R
133	8.6	30	0.3	R
134	7.0	83	0.5	L
135	9.0	61	0.5	L
136	7.0	29	0.5	R
137	9.5	40	0.4	R
138	7.5	44	0.4	R
139	12.1	69	0.7	L
140	8.0	49	0.5	L
141	7.3	36	0.3	L
142	9.0	35	1.0	L
143	7.1	60	0.3	L
144	9.3	19	0.4	L
145	5.8	37	0.9	L
146	8.5	44	0.4	L
147	7.0	22	0.6	L
148	7.0	43	1.0	L
149	8.1	50	0.4	L
150	10.1	52	0.4	R
151	4.8	51	0.5	L
152	11.3	63	0.5	L
153	7.8	47	0.5	R

Total number of EDS = 153
 Total length (mm) of EDS = 1322.1
 Total displacement (mm) of EDS = 124

Data of ME1-Serial Section e

Total length (mm) of R.H EDS	=	660
Total length (mm) of L.H EDS	=	662.1
Total displacement (mm) of R.H EDS	=	47.7
Total displacement (mm) of L.H EDS	=	76.3

Data of ME1-Central Longitudinal Section

Shear number	Length (in mm; acc. 0.1mm)	Angle (with layering; acc. 1degree)	Displacement (in mm;acc. 0.1mm)	Orientation L.H-R.H
1	12.0	44	0.9	R
2	9.5	29	2.2	L
3	9.0	50	1.2	L
4	7.6	64	0.9	L
5	9.0	47	0.8	L
6	8.0	57	0.5	L
7	10.5	38	1.7	L
8	16.0	49	2.4	L
9	7.9	45	1.0	R
10	10.2	50	1.0	L
11	7.4	54	0.9	L
12	25.8	44	1.7	R
13	13.0	34	0.7	L
14	9.4	57	0.6	R
15	14.1	12	1.0	L
16	5.1	66	0.7	R
17	5.3	43	1.4	R
18	7.5	50	1.3	L
19	8.0	50	1.7	L
20	6.2	79	0.8	R
21	5.0	69	0.4	R
22	4.5	74	0.4	R
23	22.7	46	3.2	L
24	15.8	45	1.9	L
25	8.2	43	1.8	R
26	7.0	36	0.4	R
27	5.0	58	0.5	R
28	7.5	47	1.5	R
29	3.2	68	0.3	R
30	4.8	36	1.3	R
31	8.0	35	1.0	R
32	9.7	29	2.0	L
33	6.0	59	1.0	R
34	15.0	30	2.2	R
35	6.7	41	1.5	R
36	7.1	65	1.3	R
37	9.5	43	1.6	R

Data of ME1-Central Longitudinal Section

38	15.4	45	2.2	L
39	18.6	24	2.0	L
40	6.5	53	0.8	L
41	9.4	44	0.5	L
42	13.0	55	1.8	R
43	10.6	11	1.0	L
44	20.8	42	1.9	L
45	9.0	47	1.4	L
46	15.3	26	2.1	L
47	8.0	24	2.0	L
48	8.5	41	2.0	R
49	5.0	32	0.8	L
50	9.0	56	1.0	L
51	14.5	25	1.0	L
52	7.8	47	1.2	L
53	12.8	24	2.0	L
54	6.5	39	1.5	L
55	3.9	70	0.8	R
56	7.0	63	1.0	L
57	5.7	45	1.8	R
58	13.9	30	2.8	L
59	8.2	41	2.0	R
60	7.5	46	1.4	L
61	6.2	43	1.0	R
62	5.1	47	0.4	L
63	7.0	35	2.1	L
64	12.0	38	1.7	L
65	19.0	40	2.3	L
66	8.6	60	1.6	R
67	4.5	39	0.8	R
68	18.0	41	1.7	L
69	6.0	55	0.4	L
70	6.6	37	1.0	L
71	19.5	48	1.8	L
72	3.9	55	1.0	R
73	8.0	47	1.1	R
74	15.3	39	2.1	L
75	23.0	44	1.2	L
76	3.8	58	0.5	R
77	15.0	41	2.7	L
78	14.0	43	2.8	L

Data of ME1-Central Longitudinal Section

79	7.8	67	1.2	R
80	15.8	65	2.5	R
81	6.7	42	1.0	L
82	10.7	42	2.3	L
83	5.8	59	0.7	L
84	4.0	62	0.8	R
85	4.0	51	0.6	R
86	8.4	69	1.0	R
87	7.3	55	0.9	R
88	13.2	55	0.9	R
89	9.2	55	1.0	L
90	6.4	50	1.0	R
91	21.3	43	1.0	L
92	21.3	46	1.5	L
93	15.3	55	0.7	R
94	9.3	7	1.0	R
95	5.0	17	0.8	R
96	16.0	46	1.7	R
97	7.6	68	1.0	R
98	20.7	50	1.8	L
99	13.5	35	0.6	R
100	6.5	28	2.1	R
101	7.8	54	0.8	R
102	10.0	63	0.5	R
103	12.7	40	2.0	L
104	4.8	46	1.0	R
105	6.9	47	0.8	R
106	22.0	28	1.2	L
107	7.8	61	0.5	R
108	6.9	57	0.5	R
109	7.0	55	1.0	L
110	10.0	22	1.0	L
111	6.1	49	0.8	R
112	6.9	38	1.0	R
113	14.6	32	2.0	L
114	8.5	52	0.8	R
115	6.8	50	1.0	L
116	9.4	46	0.5	R
117	7.3	42	1.6	R
118	7.0	52	0.9	R
119	6.4	51	0.9	R

Data of ME1-Central Longitudinal Section

120	10.8	51	0.7	R
121	6.5	56	0.8	R
122	9.0	41	0.8	R
123	20.0	45	1.2	R
124	9.9	30	0.6	R
125	12.0	25	1.0	R
126	6.8	37	0.8	R
127	6.6	43	0.9	L
128	10.2	50	1.0	L
129	11.3	77	0.6	R
130	12.0	59	1.0	R
131	5.8	52	1.0	L
132	5.3	58	0.6	L
133	8.0	56	1.0	R
134	7.9	30	2.5	R
135	10.0	27	1.5	R
136	6.8	53	1.4	L
137	7.0	28	1.8	R
138	5.2	69	0.6	R
139	9.0	55	1.0	L
140	13.0	48	1.3	R
141	7.0	55	0.5	R
142	5.7	66	0.7	L
143	21.5	30	1.7	R
144	10.3	34	1.8	L

Total number of EDS = 144

Total length (mm) of EDS = 1421.9

Total displacement (mm) of EDS = 178.6

Total length (mm) of R.H EDS = 657.8

Total length (mm) of L.H EDS = 764.1

Total displacement (mm) of R.H EDS = 82.5

Total displacement (mm) of L.H EDS = 96.1

APPENDIX D

144

Data of ME2-Serial Section B

Shear numbe	Length (in mm; acc.0.1mm)	Angle (with layering; acc.1 degree)	Displacement (in mm; acc.0.1mm)	Orientation L.H-R.H
1	8.5	47	0.6	R
2	4.2	60	0.3	L
3	8.0	32	1.0	R
4	17.2	45	1.7	R
5	3.3	40	1.0	L
6	5.5	31	2.5	L
7	10.8	11	6.0	L
8	6.0	48	1.0	L
9	5.5	39	0.7	L
10	15.1	35	4.7	R
11	6.6	49	1.8	L
12	17.9	16	3.0	L
13	7.5	18	3.0	L
14	8.0	14	3.0	R
15	23.8	13	5.1	R
16	6.7	58	0.3	L
17	11.9	53	0.8	R
18	5.8	68	0.5	L
19	12.5	50	4.0	L
20	7.5	7	3.5	R
21	7.0	10	5.0	L
22	11.0	32	2.5	L
23	8.0	46	0.9	L
24	11.0	37	3.0	R
25	4.7	24	3.0	R
26	8.6	50	1.3	R
27	9.8	53	0.8	L
28	10.6	52	1.0	R
29	6.0	55	1.4	L
30	15.0	35	1.5	R
31	8.1	50	1.0	L
32	5.9	46	0.3	L
33	3.8	55	0.6	L
34	10.0	37	1.7	L
35	7.5	47	1.6	L
36	14.0	54	0.4	L
37	26.0	41	6.3	R

Data of ME2-Serial Section B

38	16.5	10	11.0	L
39	6.2	53	0.7	R
40	8.0	75	1.7	R
41	6.1	48	0.9	L
42	9.0	30	0.7	L
43	7.8	60	1.6	R
44	4.0	48	0.6	L
45	13.5	9	4.0	L
46	9.5	45	0.5	R
47	21.8	35	2.8	L
48	20.8	38	3.0	L
49	25.3	43	5.0	L
50	7.8	45	0.3	R
51	2.9	69	0.3	R
52	17.0	26	0.5	L
53	7.7	34	1.0	R
54	6.0	53	0.8	L
55	9.6	45	3.6	L
56	19.0	16	6.0	L
57	7.6	48	0.5	L
58	9.0	52	3.8	L
59	5.4	27	4.5	L
60	3.6	72	0.5	R
61	12.5	37	2.0	L
62	14.0	52	1.0	L
63	5.3	45	0.6	R
64	9.0	20	2.0	L
65	3.4	55	0.6	L
66	8.3	50	1.0	R
67	11.5	43	1.9	L
68	11.0	33	2.5	L
69	7.5	63	1.0	L
70	15.4	42	1.0	L
71	10.8	24	3.0	R
72	10.0	48	0.3	L
73	8.6	22	1.5	L
74	10.2	20	0.8	L
75	12.5	39	2.5	R
76	3.2	56	0.4	R
77	6.3	26	1.9	L
78	14.0	54	1.5	R

Data of ME2-Serial Section B

79	12.0	45	2.0	R
80	8.8	49	0.8	R
81	7.0	53	0.7	L
82	5.0	47	0.8	R
83	11.6	33	1.3	L
84	11.1	45	0.7	L
85	9.0	39	1.5	R
86	12.0	18	3.0	L
87	7.3	31	3.0	L
88	16.5	12	5.0	L
89	25.0	30	3.0	L
90	16.0	39	4.0	L
91	12.5	20	3.0	L
92	14.0	27	3.1	R
93	9.0	50	1.2	L
94	10.6	33	1.5	R
95	8.1	15	3.1	R
96	8.0	54	0.5	R
97	9.0	43	2.0	L
98	7.5	59	1.0	L
99	22.5	18	2.5	L
100	12.3	14	3.8	L
101	5.0	55	1.2	R
102	5.5	65	1.2	R
103	13.7	25	3.0	L
104	8.0	59	1.5	R
105	9.0	46	2.1	R
106	7.0	44	1.0	R
107	10.0	50	1.6	L
108	11.6	29	2.1	R
109	4.0	27	1.8	L
110	7.5	17	2.0	L
111	5.0	56	1.0	L
112	7.5	19	3.0	R
113	3.4	43	1.2	L
114	11.7	27	2.7	R
115	6.4	54	1.5	L
116	7.3	39	1.3	R
117	8.6	24	1.7	L
118	7.0	46	0.4	L
119	7.9	35	1.5	R

Data of ME2-Serial Section B

120	7.0	16	3.0	R
121	7.5	15	2.0	R
122	6.9	39	1.7	R
123	6.0	58	1.5	R
124	4.4	37	2.0	L
125	5.9	18	2.0	R
126	8.2	49	0.3	R
127	15.7	65	0.6	L
128	17.8	19	1.6	L
129	11.0	38	2.0	R
130	10.2	47	0.7	R

Total number of EDS = 130

Total length (mm) of EDS = 1278.4

Total displacement (mm) of EDS = 253.3

Total length (mm) of R.H EDS = 502.2

Total length (mm) of L.H EDS = 776.2

Total displacement (mm) of R.H EDS = 96.2

Total displacement (mm) of L.H EDS = 157.1

APPENDIX E

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Data of ME2-Longitudinal Section 2

Shear number	Length (in mm) (acc. 0.1mm)	Angle (with layering; acc. 1degree)	Displacement (in mm;acc. 0.1mm)	Orientation L.H-R.H
1	12.5	30	1.5	R
2	10.0	28	1.0	R
3	8.9	19	1.2	R
4	17.0	37	1.3	R
5	8.0	55	0.5	R
6	9.2	55	0.5	R
7	10.5	46	1.0	R
8	7.0	48	0.7	R
9	5.0	61	0.4	L
10	10.0	34	0.5	L
11	37.0	38	2.5	R
12	6.0	24	1.0	R
13	10.0	17	1.6	R
14	5.5	53	1.0	R
15	7.0	49	1.0	R
16	5.9	46	0.9	L
17	52.8	45	14.8	R
18	6.3	45	1.1	R
19	6.4	32	1.0	L
20	6.5	62	0.3	L
21	9.6	56	1.0	R
22	20.5	51	1.8	L
23	27.8	54	6.0	L
24	32.6	46	7.8	L
25	10.8	48	2.0	L
26	4.0	20	0.2	L
27	16.5	46	4.0	L
28	8.2	25	2.0	L
29	6.5	19	4.0	L
30	9.6	33	0.8	L
31	6.2	26	2.0	L
32	7.7	40	1.8	L
33	6.3	55	0.5	R
34	6.5	25	0.7	L
35	9.0	23	0.8	L
36	13.8	24	1.1	L
37	11.0	23	0.7	L

Data of ME2-Longitudinal Section 2

38	6.3	55	0.5	R
39	12.0	59	0.7	R
40	12.7	54	1.0	R
41	8.0	34	0.4	L
42	9.0	42	0.6	L
43	8.0	25	1.0	L
44	7.0	51	0.4	L
45	5.0	52	0.4	L
46	9.5	38	1.1	L
47	9.0	55	0.4	L
48	6.4	51	0.7	L
49	5.0	60	0.4	L
50	6.0	50	0.5	R
51	11.0	40	1.8	L
52	9.6	24	2.0	L
53	5.0	53	1.0	L
54	17.9	34	2.2	R
55	4.8	54	1.2	R
56	16.8	18	3.0	R
57	4.9	30	1.4	R
58	20.2	55	2.1	R
59	8.0	55	1.1	L
60	5.4	54	0.5	R
61	7.2	34	2.2	R
62	20.0	12	5.6	R
63	5.9	49	2.3	R
64	19.8	18	4.3	L
65	6.7	40	1.0	L
66	6.2	57	0.5	R
67	5.8	55	1.7	L
68	20.5	45	9.0	L
69	13.8	42	1.0	R
70	5.8	79	0.7	R
71	8.0	15	3.0	L
72	3.2	38	1.4	R
73	5.7	47	0.5	L
74	15.2	42	2.0	R
75	8.4	23	1.5	L
76	6.8	46	1.0	R
77	7.8	42	3.2	L
78	6.8	35	1.8	L

Data of ME2-Longitudinal Section 2

79	7.5	23	1.5	R
80	9.4	35	2.5	L
81	6.8	42	2.0	L
82	5.9	32	1.4	R
83	4.6	8	3.3	L
84	6.4	24	1.6	L
85	18.0	32	2.5	L
86	6.2	33	1.0	R
87	7.9	35	2.1	L
88	7.3	43	1.9	R
89	12.0	58	1.8	R
90	7.8	43	1.0	R
91	10.0	25	2.2	R
92	23.0	6	5.0	R
93	6.7	58	1.5	L
94	10.8	25	2.7	L
95	8.4	50	1.5	L
96	30.5	32	11.8	L
97	6.2	57	0.5	L
98	5.9	25	0.7	R
99	6.2	19	2.0	L
100	5.4	44	0.6	R
101	12.1	35	0.5	L
102	10.9	28	2.0	R
103	14.9	46	3.6	R
104	7.5	47	0.8	L
105	15.0	50	1.0	R
106	10.0	41	0.8	R
107	9.2	42	1.0	R
108	19.3	25	2.6	L
109	6.7	53	1.0	R
110	13.5	63	0.7	L
111	20.0	47	4.8	L
112	8.0	65	0.3	R
113	21.0	40	1.0	L
114	2.6	58	0.6	R
115	10.0	73	0.5	R
116	6.2	50	1.0	L
117	6.2	66	1.0	R
118	9.0	50	0.7	L
119	8.4	26	0.5	L

Data of ME2-Longitudinal Section 2

120	4.3	74	0.4	R
121	5.0	54	0.5	R
122	10.8	49	0.8	L
123	12.9	48	1.2	L
124	18.1	49	1.1	R
125	9.8	38	1.2	L
126	11.0	51	2.1	L
127	9.0	50	0.4	L
128	10.0	65	1.1	R
129	12.1	72	1.2	R
130	7.9	28	1.0	L
131	8.6	54	0.8	L
132	9.1	39	2.0	R
133	12.8	44	1.7	L
134	7.0	46	0.7	L
135	23.0	45	1.5	L
136	4.0	72	1.0	R
137	7.4	44	0.5	L
138	5.8	55	0.5	R
139	7.6	43	5.8	R
140	8.5	45	1.3	L
141	10.6	31	2.4	L
142	11.2	40	2.0	L
143	6.7	55	1.5	L
144	7.0	53	1.2	R
145	7.0	47	1.0	R
146	7.0	71	0.6	L
147	16.0	36	6.0	R
148	14.0	28	5.5	R
149	4.3	48	0.3	L
150	8.9	49	2.3	R
151	7.3	54	0.4	R
152	10.0	41	2.0	R
153	11.0	44	2.5	R
154	17.8	22	9.0	L
155	8.0	40	1.5	L
156	9.2	18	1.5	L
157	7.8	15	1.6	R
158	7.8	15	1.0	R
159	6.0	25	1.0	R

Data of ME2-Longitudinal Section 2

Total number of EDS	=	159
Total length (mm) of EDS	=	1634.9
Total displacement (mm) of EDS	=	283.7
Total length (mm) of R.H EDS	=	745.5
Total length (mm) of L.H EDS	=	889.4
Total displacement (mm) of R.H EDS	=	113.6
Total displacement (mm) of L.H EDS	=	170.1

END

27/02/91

FIN