A SCANNING ELECTRON MICROSCOPY
STUDY OF
NATURAL ENGINEERING SOIL

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DEDICATED TO

MY DAUGHTER

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TEXT

ABSTRACT

This thesis forms part of an overall investigation of natural soil fabric being undertaken at Strathclyde University, and is directed towards those fabric features which can only be observed with the aid of a microscope, the soil microfabric. The investigation is split into two main parts.

The first is directed towards reviewing previous concepts of the nature of soil microfabric, appraising the available techniques for microfabric study and cataloguing the microfabric observations made on a wide variety of naturally occurring engineering soils. The mode of viewing used is the Scanning Electron Microscope, chosen because of its versatility in terms of its magnification range and ability to accept a wide range of soil textures. The sample preparation method used is the air-drying, fracture, peel and vacuum coat technique but a small comparitive study of the critical point drying technique is also undertaken to investigate the validity of the methods used. The soils investigated represent particular examples of geological groupings and engineering behaviours. In fact, thirty four naturally occurring engineering soils with a wide geographical distribution are studied and a scheme of microfabric characterisation is developed which it is suggested, can suitably describe all the aspects of fabric observed, both solid and pore space, and allow some semi-quantitative assessment to be made.

The second part deals with the geological and geotechnical significance of the microfabric observations. By relating these to the known geological histories the genesis of microfabric is investigated and compared to the findings of previous studies. Similarly, by relating the microscopic observations to the known geotechnical properties of the soils, the mechanisms of structural instability in sensitive, collapsing and expansive soils are considered.

The investigations, (1) show that many of the previous concepts of the nature of soil microfabric are unrealistic, (2) identify certain factors which play a significant role in microfabric genesis, and (3) place the role played by microfabric in the mechanisms of structural instability into a clearer perspective.

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CHAPTER 1.

INTRODUCTION.

Soil is a multiphase material, however, two main phases of its structure can be identified, namely, the skeleton and the pore phases. The skeleton phase comprises particles with a variety of sizes, shapes, densities, mineralogies and physical arrangements, and amorphous carbonates and iron oxides may also exist as coatings to the particles or at particle contact points. A variety of organic forms may also be present. The pore phase comprises pores with a variety of sizes and shapes which may contain air and water (with dissolved ions) in varying proportions.

Yong and Sheeran (1973) have defined the property of soil structure to include the various skeleton and pore phase characteristics described above, as well as the inter-particle forces, resulting from interaction between the skeleton and fluid phases. The important structural component, the 'Soil Fabric', may be defined as the physical arrangement of soil particles along with the pore shape and size distribution characteristics. Two main levels of fabric are identified, namely, macrofabric and microfabric. Macrofabric is that level of fabric which can be observed with the naked eye or hand lens, whereas microfabric requires the aid of at least the light microscope for study.

The need to study the fabric of natural engineering soils is well established. In terms of macrofabric, the influence of structural discontinuities such as joints and fissures on the undrained shear strength of soils has been well demonstrated by the studies of Marsland and Butler (1967), Skempton and Petley (1968), Marsland (1971), McGown and Radwan (1975) and many others. Rowe (1968, 1972), and Gabr (1975) and others, have demonstrated the influence which macrofabric features such as silt layers, dustings on laminations and open or silt filled fissures can have on the mass drainage properties of soil deposits. The nature and engineering significance of natural soil microfabric has also been extensively investigated, e.g. Mitchell (1956, 1976), Lambe (1958), Pusch (1966), Barden (1972a, 1973), Smart (1975a) and many others. These studies have indicated that microfabric study is essential to the understanding of the general fundamental principles of soil behaviour.

The short term objective of any microfabric investigation should be to characterise and if possible quantify the nature of natural soil microfabric. While several microfabric classification or characterisation schemes are available for use in the field of soil pedology, e.g. Kubiena (1938) and Brewer (1964), no suitable microfabric characterisation scheme is available for use in the discipline of geotechnical engineering. Furthermore, no comprehensive account is available of the microfabric character of a wide range of natural engineering soils. The long term objectives of microfabric study are first to relate microfabric to the geological processes of soil formation and, second to relate microfabric to the mechanisms of engineering behaviour. This ultimately, would allow the process of soil formation to be linked with the mechanical behaviour of soils, Barden (1973).

The process of microfabric study will tend to be a dynamic one in the sense that characterisation schemes will be added to, as more aspects of microfabric are identified and relationships between microfabric and geology or mechanical behaviour will also be developed continually as studies proceed. This study attempts to tackle the short term objectives, and also to some extent the long term objectives.

The scanning electron microscope has been selected as the observation tool for a number of reasons. This type of microscope can operate over a wide range of magnifications from x 20 - x 50,000, and can be used to examine a wide range of soil textures. Moreover, a scanning electron microscope was readily available, and expertise was also at hand, since microfabric studies using the scanning electron microscope had already been initiated at the University of Strathclyde, e.g. Barden (1972b), Barden and McGown (1973) and McGown (1973).

Therefore, this project involves the study of the microfabric of natural engineering soils using a scanning electron microscope. The thesis is divided into two main parts. Part I, Chapters 2, 3, 4 and 5, deal with the nature of natural soil microfabric and Part II, Chapters 6 and 7, discuss as far as possible, the geological and geotechnical significance of the microfabric observations made in this study.

Thus in Part I, Chapter 2 gives a brief review of the principal techniques available for the observation and study of microfabric as well as their associated sample preparation procedures. The main microfabric models which have been presented as a result of these studies, are also reviewed. Chapter 3 gives details of a semi-quantitative scheme for the characterisation of natural soil microfabric which it is suggested, is suitable for use in the discipline of geotechnical engineering. Details of the various scanning electron microscopy techniques employed, including those of sample preparation, are presented in Chapter 4. Chapter 5 sets out to initiate the compilation of a 'catalogue of natural soil microfabric'. An attempt is also made to give an idea of the likely global character of natural soil, in microfabric terms. The validity of previous concepts is examined where possible.

In Part II, Chapter 6 first reviews the existing concepts of microfabric genesis. It then goes on to identify rough trends and thus examine where possible, the validity or otherwise of these concepts and to introduce some new ones, in the light of the observations made in this study and detailed in Chapter 5. Lack of sufficient data does not allow consideration to be given to the role played by microfabric in the general mechanisms of engineering behaviour, e.g. consolidation, shear and water conductivity. The data which is available, however, has afforded the opportunity to examine, primarily from the microfabric viewpoint, certain characteristic mechanisms of soil behaviour, namely, sensitivity, collapse and expansion. This is given in Chapter 7.

Chapter 8 synthesizes the findings of and the conclusions drawn from this study.

Finally, recommendations for future research are given.

PART I

THE NATURE OF NATURAL SOIL MICROFABRIC

CHAPTER 2

THE STUDY AND NATURE OF NATURAL SOIL MICROFABRIC: A GENERAL REVIEW

This very brief literature review will be presented in two parts. The first deals with the principal techniques for the study of natural soil microfabric and the second with the microfabric models, both descriptive and schematic, which have been developed from such studies.

2.1. TECHNIQUES FOR STUDYING NATURAL SOIL MICROFABRIC.

A large number and wide variety of techniques are available for the study of soil microfabric. In general these techniques can be placed into one of two main groups:

(a) Those involving the examination of small (usually disturbed) samples. Such techniques are either, visual involving optical and electron microscopy, or non-visual involving x-ray diffraction and porosimetry. Useful reviews of these techniques have been presented by Tovey (1973a), Stoops (1973) and Mitchell (1976).

(b) Those involving the measurement of certain bulk (undisturbed) sample properties, including acoustical, electrical, thermal and mechanical techniques. Reviews have been presented by Tovey (1973a) and Mitchell (1976).

A brief discussion of the merits and demerits of the various techniques is given below under two broad headings, namely sample preparation and microfabric assessment.

(i) Sample Preparation.

No matter how much care is exercised sample preparation will induce microfabric disturbance. The collective disadvantage therefore of the 'small sample' techniques, which usually require either the removal or replacement of the pore fluid, is that they are not being applied to the 'natural' fabric. In contrast, however, the 'bulk sample' techniques offer the great advantage that they do not require samples to be pretreated and therefore the natural fabric is essentially being measured.

Procedures for the removal and replacement of pore fluid are varied and numerous and it is not the intention of this investigation to consider the details of such procedures. Many excellent reviews have recently been presented which deal specifically with the various aspects and stages of these sample preparation procedures as well as their respective advantages and disadvantages. Notable among these are Barden and Sides (1971) Greene-kelly (1973), Tovey and Wong (1973a), Smart (1973a), Gillot (1973) and Mitchell (1976).

The appropriate impregnation procedures for optical and electron microscopy and x-ray diffraction, while reducing shrinkage considerably are lengthy and laborious and those involving a substitution stage cannot be applied successfully to moisture deficient soils containing swelling clay minerals. The dehydration techniques required for scanning electron microscopy and pore size distribution studies offer the advantage of being relatively quick on the one hand while being either rather complex (freeze and critical point drying) or rather crude, (e.g. air-drying for very wet clays) on the other.

In fact the relatively rapid and simple air and oven drying techniques usually induce the greatest shrinkage, and it is recommended that for soils wetter than their shrinkage limit, only qualitative assessment should be made on specimens prepared by these techniques. Air-drying then is most suitable for stiff soils, partly saturated soils and other soils which do not undergo significant shrinkage on drying. Tovey and Wong (1973a) have reported that in the case of a soft sample with high water content, air-drying may in fact cause greater shrinkage than oven-drying because of the greater time (24 hours or more) available for particle rearrangement in the case of the former. However, undesirable stresses are induced during oven-drying which may result in particle breakage.

Substitution-drying, involving the replacement of the pore fluid by one of less surface tension (methanol, dioxan), and subsequent air-drying in many cases reduces the shrinkage somewhat Greene-kelly (1973). Substitution itself, however, may cause particle rearrangement, Tovey and Wong (1973a) or sample swelling and disintegration, particularly where desiccated expansive soils are involved. Recommendations for prevention of specimen disintegration have been given by, e.g. Tovey and Wong (1973a). A new promising technique has recently been developed by Jalili (1976) for preparation of samples for pore size distribution analysis. This involves impregnation with carbowax 6000 which is subsequently dissolved and replaced by chloroform which is then dried off in the air. Although both freeze-drying and critical point drying induce much less shrinkage than do the other less elaborate drying techniques, their procedures are far more involved and time consuming. They also have their inherent limitations and these have been discussed by Tovey et al (1973), Greene-kelly (1973) and Gillot (1973).

(ii) Microfabric Assessment.

A limitation common to all the small sample techniques is that they only examine a relatively small portion of a fabric in any one region and therefore a large number of regions require to be considered before a meaningful assessment, either qualitative or quantitative can be made. This problem is most severe in electron microscopy and with the aim of safeguarding against misinterpretation McConnachie (1971), Smart (1973b) and Foster (1973) have discussed statistical data trends.

The optical and electron microscopy techniques however, offer a great advantage over the other techniques in that they allow a direct visual appreciation of fabric to be obtained.

Of these methods optical microscopy is limited to low magnification fabric study facilitating visual assessment of only sand and silt particles and large solid (shear zones; layers, etc.) and pore features. On the other hand electron microscopy allows fabric and particles to be investigated over a range of magnifications from x 20 to x 50,000 (scanning) and x 1000 to x 1,000,000 (transmission). A further advantage of scanning electron microscopy is that the image produced is analagous to normal vision and stereomicrographs are easily obtained allowing for a three-dimensional appreciation of fabric features. The microscopy techniques other than the stereomicroscopy, only provide two-dimensional images within which it is often very difficult to discern clearly interaction between the granular and clay particle phases. On the other hand, quantitative evaluation of microfabric in two dimensions is readily facilitated by transmission electron micrographs taken of ultra-thin sections, e.g. Pusch (1970), Foster and Evans (1971), Foster (1973), Smart (1973b), Tovey (1973a) and McConnachie (1974).

The use of birefringence measurements in polarising microscopy also yields quantitative data, e.g. Mitchell (1956), Smart (1966a) Morgernstern and Tchalenko (1967 a, b) and Krishnamurthy (1974). However, as emphasised by Lafeber (1968) such approaches are only really applicable to monomineralic soils with the simplest of orientation patterns. In contrast, the scanning electron microscope image is not readily quantified and this perhaps is the principal disadvantage of the technique. Quantification of particle orientation in scanning electron micrographs has been investigated by e.g. Tovey (1973b),Tovey and Wong (1973b), Koff & et al (1973) and Matsuo and Kamon (1973). None of the methods however, have as yet been thoroughly evaluated with natural soil fabrics.

The x-ray diffraction, pore size distribution, and bulk property techniques all offer the advantage of providing a quantitative measure of soil microfabric. Collectively, however, their main limitation is the fact that they rely heavily on simplifying assumptions and on the interpretation of test data. The danger of ambiguity is therefore ever present. Also in the case of the bulk sample methods, while the very size of sample is a meritous aspect in terms of representation, it also means that macrofabric features, if present, may mask the microfabric.

From the foregoing discussion of the merits and demerits of the principal techniques available for soil microfabric evaluation, several general points emerge:

a) No single observation technique can provide qualitative and quantitative information relating to all the characteristics of microfabric at all levels of microfabric.

b) Several complimentary observation techniques therefore may be required before a complete appraisal of soil microfabric is achieved.

c) The observation and specimen preparation techniques selected for a particular investigation will depend on the nature and state of the material(s) being studied; on the characteristics and levels of microfabric which are to be examined, and on the type of assessment required, i.e. qualitative or quantitative or both.

d) To serve as a safeguard against misinterpretation where possible a particular characteristic should be assessed using more than one observation technique, i.e. several techniques should be employed in parallel, Tovey (1973a) and others.

2.2. THE NATURE OF SOIL MICROFABRIC: REVIEW OF PREVIOUS FINDINGS.

It requires to be made clear from the outset that the following review concerns itself, essentially with the nature of 'microfabric forms' and not with the genesis, occurrence in nature, or engineering significance of microfabric forms. Furthermore, consideration is given mainly to the findings of studies with a strong engineering bias. The reasons for this are two fold (1) many of the morphological investigations in the fields of pedology and soil science are almost by definition much involved in the examination of essentially non-engineering soils and therefore their findings are not strictly relevant here, and (2) the fabric terminology used in such studies, e.g. Kubiena (1938), and Brewer (1964), is highly complex and detailed and is of little value, and it may be argued actually serves to only confuse in engineering discussions. Reference to such works therefore, will be limited and as broad as possible.

2.2.1. The Skeleton Phase.

2.2.1.1. The Constituent Particles.

The basic elements of the skeleton phase are the soil particles. These may be classified as either inorganic (i.e. crystalline clay and non-clay minerals, non crystalline clay materials and precipitated solids) or organic. The inorganic particles comprise by far the greatest proportion of the skeleton phase in most engineering soils and are classified on the basis of 'equivalent diameter' as being either 'clay size ($\sim < 2\mu$) or non clay size/granular'. It requires to be made clear from the outset, that the clay size fraction of natural soils does not usually consist wholly of the so called clay mineral particles but also of non clay minerals such as quartz and feldspar in different proportions.

(a) The Clay Mineral Particles.

These are primarily hydrous aluminium - silicates and belong to the larger phyllosilicate mineral family. They occur mainly in the 'clay size fraction' and are generally formed from the weathering of pre-existing minerals, e.g. quartz, feldspars and are the source of soil cohesion,plasticity and shrinkage and swell. For detailed information on the structural and other characteristics of the clay minerals reference should be made to one of the detailed works, e.g. the treatise of Grim (1968) and the general review of Mitchell (1976).

Smart (1975)highlighted the rather diffuse situation concerning the meaning of the term 'particle' when applied to clay minerals. This point then requires some consideration here. In the case of the kaolinite and illite minerals the unit layers are bound strongly together to form crystals or plates. These crystals may form 'stacks'[*], 'packets'[+], 'discrete domains'[o] or 'micro-aggregates'[x]. Depending on the type of adsorbed cation, illite packets can exhibit limited inter-crystalline swelling-calcium or extensive inter-crystalline swelling - sodium, Quirk (1968). In the case of montmorillonite the unit layers are weakly bound together in a face-face association to form what may be termed a 'quasi-crystal'[**]. Quasi-crystals are relatively stable where the adsorbed cation is calcium (only limited intra-crystalline swelling occurs) whereas extensive intra-crystalline swelling leading to complete dissociation of unit layers can occur in sodium montmorillonite, Quirk (1968).

It would appear therefore, that a clay particle has generally a 'maximum diameter' of several microns or less and can take the form of: a single kaolinite or illite crystal; a stack, packet, etc. of kaolinite or illite crystals; a single unit layer of Na montmorillonite; or a quasi-crystal of montmorillonite. The opinion expressed by Smart (1975) that ...... "It seems preferable to avoid defining a particle", has undoubted foundation therefore, in the case of clay minerals.

(b) Non Clay Mineral Particles.

The gravel[-] (coarse fraction 76-19 mm); (fine fraction 19-5 mm) and sand (coarse fraction 5-2 mm); (medium fraction 2-0.4 mm);

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[*] 'stacks': are groups of plates tightly cemented together, often by a true mineral-to-mineral bond. (Smart 1975).

[+] 'packets': are small groups of plates arranged face-face with water between them. (Smart 1975).

[o] 'discrete domains': small volumes filled with approximately parallel clay plates, well defined domain boundaries, definite inter-domain voids. (Smart 1975).

[x] 'micro-aggregates': small fabric unit within which there is haphazard interaction between clay particles of various sizes (Pusch 1970).

[**] the term tactoid has also been applied here - Blackmore and Millar (1961) and others.

[-] according to the Unified Soil Classification System - 1953

(fine fraction 0.4 mm - 74 μ) as well as the bulk of the silt (74-2 μ) and some proportion of the clay ($< 2 \mu$) fractions are composed of non clay minerals. Generally these fractions are composed mainly of quartz with smaller amounts of feldspar and mica and also carbonate minerals, mainly calcite and dolomite. Also iron and aluminium oxides are abundant in residual soils of tropical regions. In geotechnical engineering particles have been classified according to either their degree of angularity or form, or both. For example BS.812 (1975) provides six classifications of particle shape, Table 2.1., namely rounded, irregular, angular, flaky, elongated and flaky-elongated. Other shape classification systems have been suggested as for example Müller (1967). The characteristics of surface texture and roughness have also been employed in particle description and terms such as dull, polished, smooth, rough, streated, frosted and pitted have been introduced.

2.2.1.2. Models of Individual Clay Arrangements.

Individual clay arrangements are those arrangements which comprise clay size particles. Early concepts were primarily concerned with the interaction of individual clay plates or groups of clay plates. Terzaghi's model (1925) assumes that the individual clay plates stick to each other at the points of contact with forces sufficiently strong to form the 'cell' of a honeycomb, Fig. 2.1. Goldschmidt (1926) presented the now well known and widely cited 'cardhouse' model and later casagrande (1932) postulated a 'honeycomb' arrangement very similar in concept to Terzaghi's model.

Much later Lambe (1953, 1958) presented three different clay platelet models; firstly, the 'non-salt flocculated' model involving an open arrangement of clay plates with essentially edge-face contacts, Fig. 2.2. which earlier was called 'cardhouse' by Goldschmidt; secondly, the model involving an open stepped arrangement of clay plates with edge-edge, face-face and edge-face contacts, Fig. 2.3. which earlier was called 'salt flocculated' by Schofield and Samson (1954); thirdly, the 'dispersion' model involving essentially face-face associations of clay plates, Fig. 2.4. Tan (1957) however presented a schematic picture which reflected a three-dimensional arrangement involving contacts between the corner of one plate and the face of another. Some years later further models were suggested, e.g., the 'cluster model' of Olsen (1962), Fig. 2.5. and the range of models of Van Olphen (1963), Fig. 2.6.

In more recent years electron microscopy techniques have been introduced to observe, directly, the microfabric of both laboratory prepared pure clay and natural soil samples. A variety of other models have been put forward on the basis of these observations.

O'Brien (1971) presented a 'stair-stepped cardhouse' model involving a three dimensional network of twisted chains of face-face orientated platelets, Fig. 2.7.(a). He likened this arrangement to the model of Van Olphen (1963), Fig. 2.6.(g). His description also compares favourably with Lambe's salt-flocculated model, Fig. 2.3. O'Brien (1971) also postulated a 'pinwheel' arrangement, Fig. 2.7.(b) involving curved and face-face orientated flakes.

Other workers arrived at the general conclusion that clay arrangements involve small regions of face-face orientated flakes.

The concept of 'stepped clusters' of face-face orientated flakes has been introduced by O'Brien (1971) and Smalley and Cabrera (1969). Aylmore and Quirk (1959, 1960) put forward a dense 'turbostratic domain system', Fig. 2.8. while Sloane and Kell (1966) suggested the use of the term 'bookhouse' to describe a random clay packet arrangement and 'parallel packet' to describe an arrangement of orientated clay packets.

Pusch (1966, 1970) reported the occurrence of arrangements consisting of extremely small aggregations ($< 2\mu$ diameter) comprised of individual clay plates in random associations, and linked by a small number of very fine clay plates, Figs. 2.10.(a) and (b). Bowles (1968) talked of small random closely arranged particle clusters.

Another, rather different concept was introduced by Emmerson (1962) who put forward a 'tactoidal' model involving stable quasi-crystals linked edge-edge into undulating sheets and joined at intervals to adjacent sheets by face-face attraction, i.e. crystal sharing Fig.2.11. Stocker (1969) expressed the opinion that an extremely perturbed version of this tactoidal model was more realistic. He inferred both an irregular and closer association of undulating sheets and made comparisons with the turbostratic model cited previously. Smart (1969) has suggested use of the term 'complete preferred orientation' or 'c.p.o.-structure' for the case where all particles are approximately parallel to the same direction.

The question of edge-edge particle interaction or intergrowing has also been considered by Smart (1969), who presented the model shown Fig. 2.12. It should perhaps be pointed out here, that although there is some evidence supporting the occurrence in nature of individual clay mineral platelet configurations, i.e. the card-house model, e.g. Rosenqvist (1959), Smart (1975) the bulk of observational evidence throws doubt on the validity of such arrangements. In fact some tendancy toward grouping, clustering or edge-edge intergrowth of clay mineral particles seems generally to exist, e.g. Smart (1971, 1975), Barden (1972b).

2.2.1.3. Models of Individual Granular Arrangements.

Granular arrangements in engineering soils usually involve silt and sand size particles. Likely modes of granular particle association have been considered on the basis of possible arrangements resulting from the packing of equal sized spheres. For example, Deresieivicz (1958) suggested five possible packings, these being (a) simple cubic, (b) cubic tetrahedral, (c) tetragonal spheroidal, (d) pyradidal, and (e) tetrahedral. These models of course are idealisations of the actual situation, since in natural soils granular particles display a variety of sizes and shapes. A wide variety of combinations of packing must therefore be possible. In most cases arrangements are shown comprising 'clean' grains. Granular arrangements however, consisting of particles, clothed in fine matter have been identified and termed 'chlamy domorphic' by Kubiena (1938) and 'aggregated grain' arrangements by Dudley (1970), Fig. 2.13.

2.2.1.4. Models of Overall Skeleton Organisation.

The overall skeleton organisation depends on the spatial distribution, interaction and orientation of the various constituent particles and individual particle arrangements, throughout the soil skeleton. It is perhaps a fair generalisation to state that, compared to the numerous individual particle arrangement models, examples of which were described previously, relatively few 'organisation' models, either descriptive or schematic have been put forward. In many cases it appears to have been simply assumed or implied that like individual particle arrangements extend in three dimensions to form a continuous uniform configuration. Nontheless, a number of 'organisation' models have been presented and these may be grouped as follows.

(i) Models representing extensive and essentially uniform configurations of like individual clay arrangements but with interference from granular particles.

Casagrande (1932) put forward the model shown in Fig. 2.14. and suggested that although the clay arrangements are all of the honeycomb variety those located in the smallest gaps between adjacent silt particles are more highly compressed than those contained in the larger spaces. He called these arrangements 'bond clay' and 'matrix clay' respectively. Kubiena (1938) described a 'porphyropectic fabric' in which grains are isolated and embedded in a dense 'ground mass', being either non-coated and easily removed, or coated and cemented. This notion that silt particles do not touch but in some fashion float in a clay background has also been put forward by Mitchell (1956), Lafeber (1963) and Fookes and Best (1969). Moreover Smart (1969) put forward a 'brownian structure' involving the separation, by random clay configurations, of horizontally orientated grains, Fig. 2.15. Considerably more granular particle interference was represented in the 'quicksand clay model' of Terzaghi and Peck (1948), Fig. 2.16. Here grains are shown touching but uncemented, against a background of highly orientated clay arrangements.

(ii) Models in this group are those representing extensive but more complex individual particle arrangement configurations.

For example, Mitchell (1956) based on observations, put forward the concept of abrupt discontinuities, irregular silt distribution and local zones of orientated clay within a random clay mass. Ostrey and Deane (1963) described a 'cross-fabric' involving the orientation of elongated grains in a cross-wise pattern so that two directions of preferred orientation are exhibited, usually mutually perpendicular. Similar concepts have been introduced by other workers, for example Korina and Faustova (1964) described a clay microfabric wherein 'perpendicular fibrous', Fig. 2.17. and 'criss-cross fibrous' patterns are in evidence, Fig. 2.18. As shown, the former involves extensive well defined regions, consisting of highly orientated clay, which are located at right angles to each other. The latter involves a haphazard interaction of less well defined and generally more extensive regions of orientated clay and would appear to be similar in character to the 'turbostratic structure' as defined by Smart (1975).

Korina and Faustova (1964) also observed that, in moraines containing much sand and silt, the spaces between the sand grains are filled with haphazardly arranged 'elongated scales' of orientated clay and silt. They called this 'scaly texture'. The idea that degree of anisotropy varies with the level of fabric considered has been presented by Smart (1966a) and Mitchell (1956) and supported by the 'block structure' model put forward by Yoshinaka and Kazama (1973).

Korina and Faustova (1964), Burnham (1970) and others have reported a concentric orientation of clay particles around and in the immediate vicinity of sand grains. Such features are referred to as 'cutans', and these can also be found around pores. Lafeber (1964) described a 'partial stripping' of clay cutans in a black-earth soil, Fig. 2.19.

(iii) Models in this group are those representing the organisation of constituent particles and individual clay arrangements into higher order or multi-level fabric features.

Several models have been presented in which 'granular particles' are separated and bridged by clay arrangements, e.g. 'intertextic fabric', Kubiena (1938), 'intergranular braces', De Bruyn et al (1957), and 'ring buttresses', Dudley (1970), Fig. 2.20. A number of levels of fabric have been defined by Brewer (1964). The term 'ped' as used by Brewer is taken to mean an individual soil aggregate consisting of a cluster of primary particles and separated from adjoining peds by surface of weakness. Smart (1973c) reported an 'isotropic' multi-level 'crumb structure'. The tendancy for clay arrangements consisting of domains, to form into larger discrete fabric units (peds) has been reported by Yong and Warkentin (1975). They presented four basic models, Fig. 2.21. to illustrate the cases of 'total fabric isotropy', 'fabric unit isotropy', 'fabric unit anisotropy' and 'total fabric anisotropy'. Barden and McGown (1973) talked of 'higher order' features such as 'peds' and 'interweaving bunches of clay'.

Several workers have described the occurrence of narrow, fairly extensive microfabric features comprising parallel clay arrangements orientated in a different direction from that of the remainder of the material. For example, 'veins', Mitchell (1956); 'plasma separators', Brewer (1964); and the pattern described by Lafeber (1964).

2.2.2. The Pore Phase.

Characteristics of the pore phase component of soil microfabric such as size, shape and orientation, have been investigated by many workers and some have classified and described pores according to certain of these characteristics.

Larionov (1965) put forward the concept of three levels of porosity, ultra microscopic (0.0003 - 2 μ), inter particle (2.0 μ - 0.5 mm) and macroporosity. A more detailed pore size classification has recently been tentatively suggested by Smart (1975). In this system three main pore groups are identified, mini pores (6 mm - 0.2 mm), macropores (0.2 mm - 6 μ) and micropores (6 μ - 0.2 μ). Each of these groups, Smart suggests, can be subdivided into coarse, medium and fine sizes according to the 2 - 6 system used for the M.I.T. particle size classification.

Consideration has also been given to pore shape particularly by Brewer (1964) and Bochko (1973). These and many other workers have also characterised pores on the basis of the fabric features which form their boundaries or within which they occur. For example, Olsen (1962) discussed 'intra-cluster' and 'inter-cluster' pores whilst Brewer (1964) considered pore spaces associated with the presence of soil 'peds' and described three main groups, 'intrapedal', 'interpedal', and 'transpedal'*. Adopting a similar approach, Yong and Warkentin (1975) defined inter-fabric unit or interpedal pores as macropores (visual) and intra-fabric unit or intrapedal as micropores. Bochko (1973) discussed microporosity in terms of 'intra' and 'inter' - microblock and microaggregate pores.

2.2.3. General Points.

From the foregoing sections several general points emerge:

(a) The great majority of microfabric investigations have been directed towards study of the skeleton phase.

(b) It is perhaps fair to say that the bulk of the skeleton

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* 'transpedal' pores refer to those pores traversing the soil material without any specific relationships to the occurrence of peds; they usually extend beyond the limits of a single ped.

studies to date have been concerned with the nature of the individual clay and granular arrangements.

(c) In many cases uniformity of configuration has been either assumed or inferred.

(d) The many investigations, of all aspects of microfabric, have yielded a multiplicity of descriptive terminology which now presents an added difficulty to the understanding of an already complex subject.

(e) It becomes clear that a unified system to describe the various types of and levels of microfabric requires to be devised. Such a system should allow for variation within its overall structure since the various disciplines of e.g. soil science,engineering geology and soil mechanics impose varying demands on any fabric characterisation scheme.

(f) No comprehensive account of the microfabric of a wide range of engineering soils is available. There is, therefore a need to initiate compilation of such information, i.e., a 'catalogue of natural soil microfabric' is required.

CHAPTER 3

THE DEVELOPMENT OF A SCHEME FOR MICROFABRIC CHARACTERISATION

3.1. INTRODUCTION.

A semi-quantitative scheme for the characterisation of natural soil microfabric was developed specifically for use in the disciplines of engineering geology and soil mechanics. It is believed however, to be sufficiently flexible to be used in other disciplines providing certain appropriate additions and extensions were to be made. Development of the characterisation scheme was made mainly on the basis of observations of the microfabric of a large number and variety of natural as well as some laboratory prepared soils using a scanning electron microscope. Account was taken at all stages, however, of the previous fabric models and general points discussed in section 2.2. Most of the natural soils investigated are included in the 'Catalogue of Natural Soil Microfabric' presented in Chapter 5. A list of those soils not specifically included is given in Appendix (A).

It was recognised from the outset that the 'geotechnical system' to be devised must be at the very least:

(a) Comprehensive without being too specific.

(b) flexible enough to account for any previous models or any features as yet unobserved.

(c) rational and consistent throughout all fabric levels up to and including the macrolevel.

(d) memorable and simple to use.

To ensure that these requirements would be satisfied it was necessary to first, establish as far as possible the full range of microfabric features likely to be encountered in natural soils. For this purpose, therefore, a scanning electron microscope was used to study the microfabric of a large number of natural soils possessing a wide variety of geological origins and physical and geotechnical properties. Details of the microscopy techniques employed and the soils studied, are given, in later chapters. The various microfabric aspects so observed, were noted.

The characterisation system developed basically involves consideration of the following aspects:

(i) The nature of microfabric forms. Three main types of form are identified, as indicated by Table 3.1., these are I the Elementary Particle Arrangements; II the Particle Assemblages, and III the Pore Spaces. Each of these main form groups is sub-divided into a number of sub-forms and in certain cases sub-divisions of sub-forms are also introduced, Table 3.1.

(ii) The spatial organisation and interaction of the various microfabric forms to form the so called Composite Microfabric.

(iii) The apparent relative abundance of the sub-forms and sub-divisions.

(iv) Anisotropy within the composite microfabric.

Each of these aspects will now be dealt with separately and in detail.

3.2. THE NATURE OF MICROFABRIC FORMS.

Microfabric features which make up the composite microfabric are divided into three main forms:

I Elementary Particle Arrangements which involve essentially interaction between a small number of like constituent particles. Sub-forms and sub-divisions of sub-forms were identified on the basis of the size, nature and mutual organisation of the constituent particles, Table 3.1.

II Particle Assemblages which are units of particle organisation which have definable physical boundaries and consist of arrays of one or more forms of elementary particle arrangement or smaller particle assemblages. Sub-forms and sub-divisions of sub-forms are identified on the basis of their origin, mechanical function or general character, Table 3.1.

III Pore Spaces which are formed by and which occur within and between the microfabric forms types I and II. Again several sub-forms are identified in this case on the basis of the relationship or the absence of a relationship of pore space to the occurrence of specific microfabric form types I and II, Table 3.1.

Before dealing with each of these main forms consideration will first be given to the nature of the so called constituent particles.

3.2.1. Constituent Particles.

Constituent particles have been taken to be the basic or unit inorganic elements and organic constituents of the skeleton phase.

Inorganic Particles - Two basic types of inorganic particles were considered, the 'clay particles' and the 'granular particles'.

Clay particles are those which have a maximum effective diameter of ($\sim 2\,\mu$) or less, and are therefore usually clay minerals but not always. Three approximate size ranges are defined, 'coarse clay sizes' ($\sim 1\text{-}2\,\mu$), 'fine clay sizes' ($\sim 0.25\text{-}1\,\mu$) and 'very fine clay sizes' ($\sim 0.25\,\mu$). On the basis of the forms and shapes encountered in the soils studied, clay particles can be classified as follows:

(a) plate shaped individuals.
(b) rod shaped individuals.
(c) bulky shaped individuals. This is meant to be a broad term covering all shapes other than plate and rod.
(d) plate or crinkle shaped groups* wherein a small number of individuals or unit layers in the case of say montmorillonite have either face-face or edge-edge association, or both.

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* The term 'group' as used here, is a broad term meant to be equivalent to the terms packet, stack, discrete domain, book or quasi-crystal as in the case of say montmorillonite.

(e) clusters - these are more or less equidimensional and are composed of haphazardly arranged platey or bulky shaped individuals.

Identification of these particle categories in the scanning electron microscope was achieved with reference mainly to the observed external particle forms and on some occasions to their internal organisation. However, mineralogical and size distribution data, where known, was also used as an aid in identification.

Granular particles are those which have a maximum effective diameter greater than 2 μ . The silt, sand and gravel size range classifications as given by the A.S.T.M. scale, (Section 2.2.1.1.) has been adopted herein. It was deemed necessary however, for descriptive purposes, to subdivide the silt size fraction into fine ($\sim$ 2-6 μ), medium (6-20 μ) and coarse (20-74 μ) size ranges.

Regarding particle shape, five categories have been considered in accordance with the B.S.812 (1975) Table 2.1. These are rounded, irregular, angular, elongated and flaky. The elongated-flaky category was considered to be unnecessary for the purposes of the present study.

<u>Organic Constituents</u> - As well as the above inorganic particles, other organic constituents have been observed and described, e.g. micro-fossils, root remains, etc.

3.2.2. Elementary Particle Arrangements.

Elementary particle arrangements are defined as those arrangements which involve, essentially, interaction between a small number of like constituent particles. Two inorganic sub-forms and one organic sub-form are identified in Table 3.1. and these are described below.

3.2.2.1. Clay Particle Arrangements.

These are defined as arrangements which consist of a small number of clay particles. Three sub-divisions have been introduced as detailed in Table 3.1. namely random or parallel or partly discernible.

(a) Random Particle Arrangements.

These are defined as isotropic arrangements wherein clay particles are randomly orientated with respect to each other, are of such a shape or form, or they interact in such a manner so as to give an isotropic configuration, e.g. Fig.3.1. This broad term, if supplemented with information relating to the size and shape of constituent particles (Section 3.2.1.) accounts for many of the arrangements described in Section 2.2.1.2., e.g. honeycomb, non-salt and salt flocculation, cluster, stairstepped cardhouse, pinwheel, bookhouse and micro-aggregation. Usage of such a broad term as opposed to the more specific terms mentioned was considered to be sufficient and more appropriate for this or any other microscopy investigation since, to give a comprehensive account of the occurrence, relative proportions and degree of openness of these detailed arrangements would seem to be virtually impossible. In fact it could be argued that such an account would also be of little value, particularly so in this study where air-drying was used which undoubtedly induced changes in the openness of the clay particle arrangements viewed.

(b) Parallel Particle Arrangements.

These are defined as anisotropic arrangements wherein platey or wavy shaped particles are preferentially orientated with respect to each other, e.g. Fig. 3.2. This term accounts adequately for the 'dispersed' and 'parallel packet' arrangements described in Section 2.2.1.2. There may be a strong tendancy, especially where the more active clay minerals are involved, for edge-edge intergrowth (Fig. 2.12.) to occur in the plane of preferred orientation. In this event individual particle interaction will not be clearly discernible in the direction perpendicular to the plane of preferred orientation. That is to say, using the language of the next section, the configuration will be partly discernible when viewed in the direction perpendicular to the plane of preferred orientation.

(c) Partly Discernible Arrangements.

These arrangements are defined as configurations wherein the interaction of individual constituent particles are not clearly discernible no matter the direction of viewing in the scanning electron microscope. In certain cases some edges or boundaries were detected while in others few edges or boundaries were observable. Furthermore, those edges seen, displayed both crinkled and non-crinkled forms and are similar to the features described by Borst and Keller (1969). Their terminology however, is considered to be too specific for the purpose of the present study. Idealisations of these rather ill-defined systems are given in Fig. 3.3. These idealisation models are similar in concept to the indistinguishable clay-cement phase model presented by Mitchell and Jack (1966). Speculation as to the exact nature and origin of these observed forms will be made later in Part II of this Thesis.

3.2.2.2. Granular Particle Arrangements.

These are defined as arrangements which involve the interaction of a small number of granular particles of approximately the same order of size. Two sub-divisions have been identified, Table 3.1., the 'clean grain-grain contacts' which involve direct grain-grain contact and 'clothed grain-grain contacts' consisting of grains which are clothed in clay particles or some other material, Fig. 3.4. The 'clothed' model is similar to Dudley's model, previously cited, Fig. 2.13.

In order to complete the description of such arrangements information relating to the size, shape (Section 3.2.1.) and mode of packing of the grains has also been detailed in the description of particular microfabrics. Arrangements have been described, simply as being either relatively loosely or closely packed.

3.2.2.3. Organic Arrangements.

No specific organic arrangements are identified.

3.2.3. Particle Assemblages.

In an attempt to simplify and rationalise fabric description seven sub-forms have been introduced under two broad headings, the 'basic order particle assemblages' and the 'higher order particle assemblages', as detailed in Table 3.1.

3.2.3.1. Basic Order Particle Assemblages.

Such particle assemblages are considered to be associated with an essentially uninterrupted and uniform process of soil development. They have been recognised on the basis of their 'function', i.e. whether they form backgrounds or binders, linkages, independant units or interweaving units within the composite microfabric.

(a) Connectors.

These are assemblages which act as linkages between silt or sand grains, between aggregation assemblages, or between aggregations and the surrounding matrix, Fig. 3.5. They were seen to be variable in both extent and external physical form. Two sub-divisions are identified, namely 'bridges' and 'buttresses'.* It seems appropriate to refer to a network of connected grains as a 'connector system', Fig. 3.5. and to a network of connected or linked aggregations as a 'connector-aggregate system', Fig. 3.5.

At this point, it is perhaps relevant to note that from the

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* The ratio (c) of span length to some equivalent diameter of connector is referred to here. For bridge(c) $\gtrsim$ 1. For buttress (c) $\lesssim$ 1.

mechanistic viewpoint, connector systems must be thought of as 'multi-level' forms in so far as compression, deformation, etc, may occur at the assemblage level as well as the elementary particle arrangement level. These connector models account more than adequately for the previous models described in Section 2.2.1.4. (iii), and Fig. 2.20.

(b) Aggregations.

These are assemblages which act effectively as independant units within the composite microfabric. They are multi-level in the mechanistic sense. Aggregations may display a variety of sizes, up to silt and fine sand grades, a variety of shapes, internal organisations and modes of interaction. They have been sub-divided into 'irregular' or 'regular' forms, Table 3.1. Irregular aggregations were observed consisting generally of elementary particle arrangement arrays. They can display several modes of interaction including interaction between aggregates indirectly through connectors, and interaction via connectors of aggregates with the surrounding matrix, as shown in Fig. 3.5. Regular aggregations generally consist entirely of elementary particle arrangement arrays. In some cases they can be formed by connector systems. The modes of interaction of the regular aggregations with the other microfabric forms are of essentially two types: aggregates interacting directly with other aggregates or grains within essentially granular looking arrangements, Fig. 3.6.; aggregations interacting directly with the nearby clay matrix, Fig. 3.6.; aggregates interacting indirectly through connectors with other aggregates or the nearby matrix Fig. 3.5. These aggregate models account for the arrangements described in Section 2.2.1.4.(iii) and Fig. 2.21.

(c) Interweaving Bunches.

These assemblages are bunches or strands of elementary particle arrangement arrays, which act as interweaving units within the composite microfabric. The term 'interweaving bunches' was suggested previously by Barden and McGown (1973). They interact to form an interwoven system Fig. 3.7.(a). In certain cases the bunches also interwove between and around silt particles, as illustrated in Fig. 3.7.(b). These assemblages, like the connectors and aggregations, can be considered, mechanistically speaking, as multi-level in character.

(d) Particle Matrices.

These assemblages are three-dimensionally extensive, and consist of elementary particle arrangement arrays. Matrices will generally occupy the regions between and around large embedded grains or the other assemblage systems present, acting effectively as background or binding features, Fig. 3.8.(a). Where no large grains or other assemblage forms exist the matrices themselves are the entire fabric. In the mechanistic sense, a matrix is a 'single level' assemblage, i.e. compression, deformation, etc., can be thought of as occurring at essentially one level - the elementary particle arrangement level.

Between particle matrices and throughout any one matrix, a considerable variation in the type and complexity of elementary particle arrangement array may be found to exist. In order to achieve consistency in description therefore, matrices have been considered as being composed of 'regions' of various forms classified according to the relative proportions by volume, of their constituent arrays, Table 3.1. For each region type a number of array patterns have been identified. In any one matrix therefore, one or all types of region may exist and within regions of the same type a variety of patterns may exist. There is essentially no limit to the extensiveness of a matrix region and in fact where only one type of region occurs the whole matrix is one large single region.

Matrix Regions:

(1) Clay regions Fig. 3.8.(b) are defined as three-dimensional configurations within which there is a continuous array of clay particle arrangements, and where the interference from silt or sand size particles is either minimal or non-existent. The following terms and models have been used to account for the variety of 'clay particle array' patterns observed within such configurations.

(i) 'Parallel clay array' Fig. 3.8.(c), i.e. where clay arrangements are all of the parallel variety.

(ii) 'Predominently parallel clay array' Fig. 3.8.(d), i.e. where the majority of the clay arrangements are of the parallel variety.

(iii) 'Predominently random clay array' Fig. 3.8.(e), i.e. where most of the clay arrangements are of the random variety - (partly parallel clay array is an equivalent statement).

(iv) 'Random clay array' Fig. 3.8.(f), i.e. where all the clay arrangements are of the random variety.

(v) 'Partly discernible clay array' Fig. 3.8.(g), i.e. where all the clay arrangements are of the 'partly discernible variety'.

Furthermore, in each of the patterns (i) and (ii), the degree of preferred orientation of the parallel clay arrangements within any clay region, has been described as illustrated by Figs. 3.8.(c) and (d) respectively. The direction of preferred orientation has also been indicated, i.e. horizontal, inclined and vertical.

(2) Clay-granular regions Fig. 3.8.(h) are defined as three-dimensional configurations within which there is a more or less continuous array of clay particle arrangements but where there is significant interference either from embedded silt and sand size grains or the occasional isolated grain-grain

contact. In future developments a criterion may be introduced to enable a fairly consistent assessment of 'significant interference' to be made.

The clay arrangement arrays within these configurations are described using the same terminology as used for the clay regions, as given in (1) above and models as shown by Figs. 3.8.(c), (d), (e), (f) and (g).

Consideration is also given to the orientation of those embedded matrix grains with easily discernible directional characteristics, i.e. mainly the flaky and elongated grains. In this context, the degree of preferred orientation of the matrix grains within the clay-granular region, has been described as shown by Fig. 3.8.(i).

Regarding interaction between the matrix grains and the surrounding clay arrays, three models are put forward. Fig. 8(j) represents a situation where only those clay particles in the immediate vicinity of a grain are orientated in sympathy with the grain surface. Fig. 8(k) on the other hand illustrates a situation where parallel clay arrangements in the near vicinity of a grain are orientated in sympathy with the grain surface. Finally the model shown in Fig. 3.8.(l) is associated with partly discernible clay arrays and involves a sharp well defined array boundary which is sympathetically orientated to the grain surface. Unless otherwise stated, it should be assumed that these models apply for the respective clay array type (i.e. Fig. 8(j) - random; Fig. 8(k) - parallel; Fig. 8(l) - partly discernible).

(3) Granular regions Fig. 8(m) are defined simply as three-dimensional configurations wherein there is a continuous array of grain-grain contacts, either clothed or clean, or both. The degree of preferred orientation of directional grains within any granular region is described simply as 'complete', etc., as shown in Fig. 3.8(n). In certain cases

a more complex pattern may occur wherein two directions of preferred orientation in a cross-wise pattern, can be identified, Fig. 3.8(p).

Regardless of the pattern within the granular array itself, the flaky and elongated grains in the immediate vicinity of any larger grains are generally orientated in sympathy with the larger grain boundary, Fig. 3.8(q).

The various matrix models defined above and illustrated by Fig. 3.8. adequately account for the previous models described in Section 2.2.1.4. (parts (i) and (ii)), and Figs. 2.14. - 2.19.

3.2.3.2. Higher Order Particle Assemblages.

Such particle assemblages are considered to be associated with, either a non-uniform process of soil formation, e.g. micro-lenses, or disruptions (tectonic activity) or interruptions (e.g. lithological changes overall during deposition, and cessation of deposition) during the process of soil formation, e.g. 'micro-veins' and 'micro-layers' respectively.

(a) Micro-lenses.

These are particle assemblages which occur in the form of lenses within the composite microfabric as illustrated in Fig. 3.9. They may be of various thicknesses usually from around 200 μ to around 10 μ , and are surrounded by or embedded in a basic order assemblage network. Regarding internal organisation, they may consist entirely of clay or granular elementary particle arrangement arrays or mixtures of these. Mechanistically speaking, micro-lenses are described as single level assemblages.

(b) Micro-veins.

These are single level particle assemblages which occur in the form of planar veins within the composite microfabric. They may be composed either entirely of preferentially orientated silt particles or consist almost entirely of preferentially orientated parallel clay arrangements and embedded silt particles. Vein thickness may vary widely both along and between veins but generally may be around 50 μ or less in the case of granular veins; and 30 μ in the case of clayey veins. Several types of vein organisation may exist. Sometimes veins will occur as individuals, Fig.3.10(a) while in the case of clayey veins more complex patterns may be evidenced. These involve either 'forked systems' or 'cross-wise systems' as illustrated in Fig. 3.10(b). In all cases veins will be surrounded by or embedded in a basic order assemblage network. These vein models account fairly well for certain of the previous models described in Section 2.2.1.4. part (iii).

(c) Micro-layers.

These are assemblages which occur in the form of layers of such a thickness that they are not clearly visible with the naked eye (i.e. $\sim$ 200-300 μ or less).

They may consist entirely of elementary particle arrangement arrays, either clay or grain or both, in which case they are described as single level assemblages, Fig. 3.11.(a). These arrays have been defined as 'layer regions' which interact to form a 'region system' and are identical in character to matrix regions. They are in fact described using the same terminology as was given for matrix regions in section 3.2.3.1.(d). Moreover, although not included in Section 3.2.3.1., a region system qualifies as a basic order assemblage. In other cases, usually within thicker layers, layer regions interact with connector, aggregation or interweaving bunch systems to form the layers, in which case compression, deformation, etc., occurs not only at the elementary particle arrangement level, but also at the level of the connectors, etc., within the layers. Thus the layers often are in the mechanistic sense essentially multi-level in character, Fig. 3.11.(b).

3.2.4. Pore Spaces.

Four sub-forms of pore space have been introduced under two broad headings, 'basic pore space' and 'higher order pore space', Table 3.1.

This pore space classification is purely qualitative and does not specifically account for the size and shape of the pores, however, the nature of the classifications adopted implies to some extent both change in shape and increase in absolute size from intra-elemental to trans-assemblage pore spaces.

3.2.4.1. Basic Pore Space.

These are pores which have a specific relationship to the occurrence of the elementary particle arrangement arrays and particle assemblages. A schematic representation of the occurrence of these pore space types is given in Fig. 3.12.(a).

(a) Intra-elemental Pores.

These are pores occurring within the various elementary particle arrangements and include interindividual or inter-granular pores, i.e. those occurring between clay individuals or granular particles and inter-group or inter-cluster pores, i.e. those occurring between clay groups or clay clusters.

(b) Intra-assemblage Pores.

These are pores within particle assemblages occurring between sets of elementary particle arrangements. They are often responsible for particularly open honeycombed particle arrays.

(c) Inter-assemblage Pores.

These are pores occurring between individual basic order assemblages of any degree of complexity, i.e. connectors, aggregations and interweaving bunches.

3.2.4.2. Higher Order Pore Space.

These are essentially pores occurring without any specific relationship to the occurrence of particular microfabric forms, i.e. trans-assemblage pores. They were observed possessing both wavy or curviplanar and irregular shapes, Fig. 3.12.(b).

3.3. COMPOSITE MICROFABRIC.

The term 'composite microfabric' has been introduced to describe and account for the spatial organisation and interaction of the various microfabric forms occurring within a soil. It is necessary to discuss the meaning of this term in the context, firstly of non-layered soils, and secondly of layered soils. The notion or concept of 'total composite microfabric' is also presented.

3.3.1. Non-layered Soils.

Composite microfabric in this case refers to the organisation and interaction of the following assemblages; connector, aggregation and interweaving bunch systems; particle matrices with their various regions; and micro vein systems, along with the occurrence of trans-assemblage pores and large embedded grains which are not involved in any of the particle assemblages, to form the complete microfabric within the limits of the soil deposit boundaries. A schematic representation of a rather complex composite microfabric involving all these features is given in Fig. 3.13.(a). Of course not all composite models are as complex as the one illustrated.

3.3.2. Layered Soils.

In this case the term composite microfabric is applied in two senses, either the 'composite microfabric of individual layers', whether they be macro or micro layers, or the 'composite microfabric of the layered soil deposit'.

The composite microfabric of an individual layer may involve the organisation and interaction of the various basic order assemblages, trans-assemblage pores, plus the micro-vein and micro-lense assemblages, within the limits of the layer boundaries.

The composite microfabric of a layered soil deposit simply involves the summation of the composite microfabrics of the individual layers (both macro- and micro-) within the limits of the soil deposit boundaries, as shown schematically in Fig. 3.13.(b). The various types of layer interface, as observed at the micro-level, namely, 'sharp-straight', 'sharp-irregular' and 'ill-defined' are also illustrated.

3.3.3. The Total Composite Microfabric.

The concept of 'total composite microfabric' is a simplifying but convenient one introduced specifically for the purposes of the present investigation. The total composite microfabric is comprised of all the 'individual composite microfabrics' of the individual soil masses or soil layers which make up the engineering soil regime of the earth. A sub-division, namely the 'Total Composite Microfabric of the Transported Inorganic Soil Group', is identified, again for the purposes of the present investigation.

3.4. RELATIVE ABUNDANCE OF MICROFABRIC FORMS.

The relative abundance of certain of the microfabric forms within the individual composite microfabric, i.e. composite microfabric of non-layered soils and of individual layers within layered soils, is considered as part of the microfabric characterisation using a 'two-stage' approach. Firstly, the relative abundance of the various sub-forms of elementary particle arrangement, basic order particle assemblage and basic pore space are assessed to give the so called 'primary relative abundances'. Secondly, the relative abundance of the various elementary arrangement and basic order assemblage sub-divisions, is assessed to give the so called 'secondary relative abundances'. This two-stage approach is detailed and explained more fully below.

3.4.1. Primary Relative Abundance.

This term refers to the relative extent to which, in a volumetric sense, the sub-forms of elementary particle arrangement; basic order particle assemblage; and basic pore space are involved in the composite microfabric of non-layered soils and individual macro- or micro- layers.

Primary relative abundance, therefore, is taken to mean the relative extent to which, volumetrically speaking,

(i) clay and granular arrangements occupy the total elementary particle arrangement array within the composite microfabric.

(ii) matrix, connector, aggregation and bunch assemblages, occupy the total basic particle assemblage network within the composite microfabric.

(iii) intra-elemental, inter-assemblage and intra-assemblage pores occupy the total basic pore space within the composite microfabric.

A relative abundance scale has been introduced for the purposes of description and graphical illustration and analysis of microfabric character. This scale identifies five levels of abundance, as detailed in Table 3.2. As a way of illustrating the application of the primary relative abundance scale, Fig. 13(a) has been drawn with the basic order assemblages having the following abundances, matrix (4), aggregations (3), connectors (2) and bunches (1).

3.4.2. Secondary Relative Abundance.

This term has been introduced to account for the relative abundance of:

(i) parallel, random and partly discernible clay arrangements within the total clay arrangement array,

(ii) clean and clothed grain-grain contacts within the total granular arrangement array,

(iii) clay, granular and clay-granular regions within a matrix or a region system,

(iv) bridge and buttress connectors within the connector systems, etc.,

(v) irregular and regular aggregations within the aggregation systems, etc.

The relative abundance scale as described in Table 3.2., for primary relative abundance, has also been adopted for secondary relative abundance. For cases (i) and (iii) relative abundance refers to the relative extent to which, volumetrically speaking, the subdivision forms are involved within the corresponding sub-forms, an example being the relative abundances of the matrix regions in Fig. 3.13(a). For the other cases however, relative abundances refers to the relative numbers of each sub-division form.

3.5. ANISOTROPY WITHIN THE COMPOSITE MICROFABRIC.

Anisotropy within the composite microfabric of both non-layered soils and individual macro- and micro- layers within layered soils, is also considered. The aspects of degree of anisotropy and the feature or features inducing it along with the direction of preferred orientation are all included in the scheme.

The degree of fabric anisotropy is known to depend on the fabric level or size of field of view considered, e.g. Mitchell (1956), Smart (1966a). In an attempt to account for this fact three levels of fabric, namely the volumes of 5 μ, 50 μ and 500 μ sided cubes, have been considered in the present system. Choice of these three levels was governed by the granulometry and complexity of the observed microfabrics. The '5 μ level' was introduced to account for the clay arrangements and is not appropriate to granular arrangements. Introduction of a factor of ten to produce the '50 μ and 500 μ levels' seemed both logical and appropriate. The upper level of any such system should preferably be sufficiently large so as to include within it, a representative portion of the composite microfabric. The '500 μ level' appeared to satisfy this requirement, at least for the soils studied.

The basic approach adopted, involves firstly, reference to the individual composite microfabric model within which, the occurrence and where appropriate the relative abundance of the various microfabric forms is represented. The microfabric at each of the levels defined above is then considered in terms of degree of anisotropy, along with causal features plus direction of preferred orientation.

The degree of anisotropy is described using the anisotropy scale given in Table 3.3. which ranges from very high to nil degrees of anisotropy. Indication is made if, at the same level, certain 'volumes' displayed higher degrees of anisotropy than others and any predominance is also noted.

The features or feature inducing anisotropy are identified and noted. Degree of anisotropy within any particular 'volume' is observed to depend essentially on the occurrence and relative abundance, within that volume, of preferentially orientated parallel clay arrangements within the various clay arrays, preferentially orientated silt and sand grains and interweaving bunch assemblages. The occurrence of micro-lense and micro-vein assemblages may also induce anisotropy at the higher levels.

The direction of preferred orientation is described approximately using the terms 'horizontal', 'inclined' or 'vertical'. If at the same level a number of 'volumes' displayed a range of 'directions', the term 'full range' is applied.

The above aspects of anisotropy have been assessed on a qualitative basis only in this scanning electron microscopy study.

3.6. CONCLUDING SECTION.

The microfabric characterisation scheme developed in the present study and detailed in the foregoing sections is summarised schematically in Fig. 3.14.

The system devised satisfies fairly well, those basic requirements outlined in Section 3.1. It is comprehensive without being too specific, and the various elementary particle arrangements, particle assemblages and pore arrangements, account for most of the features both observed in the present study and described from previous studies. Also, it is consistent throughout all fabric levels and if necessary and where appropriate, its terminology could be easily applied to macrofabric features. Furthermore, it is both memorable and simple to use.

Apart from these basic qualities, the present system also embodies both geological and mechanistic classifications and is therefore truly 'geotechnical' in character.

A number of points require to be made as follows:

(a) It requires to be strongly emphasised and made clear that the characterisation scheme devised herein is intended to be independant of the technique of examination used.

(b) The present scanning electron microscope study has assessed the various aspects of the characterisation scheme qualitatively only.

(c) As was pointed out in Chapter 2 no thoroughly tested technique is available for quantitative work using the scanning electron microscope. Where available techniques have been applied mainly to artificially derived clay systems. Furthermore such techniques can only furnish information relating to the degree and direction of preferred orientation. No information is provided relating to (1) the nature and variety of microfabric forms present, (2) the relative abundance of microfabric forms or (3) the feature(s) responsible for any degree of anisotropy (at least in any detail).

(d) It is doubtful whether this or any other acceptable scheme for microfabric characterisation will ever be fully quantified due to the complex nature of natural microfabric and its extreme variability at all levels.

(e) It is not envisaged therefore that the scheme suggested herein need ever be wholly superseded but it may perhaps be supplemented by quantitative schemes, e.g. porosimetry data, x-ray diffraction or magnetic anisotropy data.

CHAPTER 4

TECHNIQUES ADOPTED FOR THIS SCANNING ELECTRON MICROSCOPY STUDY

4.1. INTRODUCTION.

As discussed in Chapter 2, Section 2.1. selection of the observation and specimen preparation techniques for a particular microfabric study will depend on a number of factors including the number, the nature and state of bulk materials, the characteristics and levels of microfabric to be examined and the type of assessment required. The present project required principally a qualitative examination, over a wide range of magnification from unity up to 20,000 x, for some 34 soils possessing a wide range of granulometries. In their natural states the bulk samples of the cohesive soils to be investigated ranged from very wet and soft to very dry and hard. The granular soil samples were either partly saturated or dry.

Considering then, these basic requirements and the time available, the scanning electron microscope was chosen as the observation tool for the present investigation. This technique enables a direct, high contrast stereoscopic image of the fracture surface of small block specimens to be obtained over a wide range of magnifications. Where required dehydration of samples for microscopy was facilitated using the process of air-drying which was selected because of its simplicity and because it could be applied to all soil types, providing that only a qualitative assessment of microfabric was needed. Air-drying can induce considerable shrinkage if the moisture content of a soil is high compared to its shrinkage limit and in an effort to evaluate the problems of air drying an alternative but more elaborate technique, Critical Point Drying was used in a limited series of tests.

As pointed out in Section 2.1., one of the greatest difficulties to be encountered in scanning electron microscopy is met when an attempt is made to obtain a realistic and representative assessment of the microfabric of even a small specimen. This vitally important aspect, perhaps the most important one, was therefore given a great deal of consideration and a routine procedure for microfabric assessment in the scanning electron microscope was developed.

This Chapter then, is divided into three main sections as follows: (1) a short section on the scanning electron microscopy techniques employed, (2) a detailed account of the specimen preparation procedures adopted and, (3) a detailed account of the microscopy procedure developed for microfabric assessment.

4.2. SCANNING ELECTRON MICROSCOPY.

4.2.1. Scanning Electron Microscope.

Detailed accounts of the historical background, fundamental techniques of operation and scope of application of the scanning electron microscope has been given by Oatley et al (1965), Roscoe (1967), Tovey (1970 and 1973c), and many others.

The fundamental principle behind the operation of the scanning electron microscope is the use of a primary electron beam which passes through a high vacuum (1×10^{-5} Torr) and strikes the surface of a block specimen. At this point, some electrons are reflected and others cause the emission of secondary electrons, and in the reflective / emissive mode a proportion of these reflected and secondary electrons are collected in the collector. From this collector the signal is amplified, and fed to modulate the intensity of the spot on a cathode ray tube display screen. Beams in the microscope and cathode ray tube are scanned in synchronism so that each point on the latter corresponds to the equivalent point on the specimen. The contrast of the picture so obtained on the display screen is a function of the relative proportions of the reflective and emissive electrons which leave different regions of the specimen, which in turn depends on the topography of the surface and the atomic number (Z) of the components, Stoops (1973). Generally, resolution is about 100-200 Å

(50 Å for the new microscopes) and the magnifications range from x 20 to x 50,000. Although the reflective and emissive modes are the norm, the scanning electron microscope can also be operated in the cathodluminescent, absorbtive, transmissive and x-ray modes. Stereopair photographs are readily taken by tilting the specimen through several degrees. The particular instrument model used in the present study was the Cambridge Instruments Co. STEREOSCAN MK $\overline{\underline{11}}$ A and this was operated in the normal reflective / emissive mode. The routine operational procedures adopted to obtain optimum instrument performance were those laid down in the manufacturer's handbook. Recommendations given by Tovey (1970, 1973c) which relate specifically to the application of the S.E.M. to the study of soils were also closely adhered to.

4.2.2. Microphotography Techniques.

4.2.2.1. General.

In the early part of the project polaroid micrographs were taken but while these proved to be extremely useful from the point of view of interpretation their cost proved prohibitive for routine use. Again the recommendations given by Tovey (1970, 1973c) relating to the procedures for obtaining optimum photographic results were closely followed.

4.2.2.2. Stereo Microphotography.

Stereopair micrographs were taken using an angle of tilt of around 7 to 10°. In order to maintain constant magnification focussing was carried out using the specimen height control. An attempt was also made to maintain constant contrast and brightness conditions.

4.2.2.3. Overlapping Photography.

Overlaps were taken involving arrays of 2 x 2, up to 6 x 4 micrographs. A minimum overlap of ~10 percent at each boundary was adopted although for particularly difficult cases 20 percent or more overlap was used. Alignment, both horizontal and vertical, was checked using a 1 cm. square grid on a transparent sheet mounted on the microscope viewing screen. Again constant magnification was achieved by focussing with the specimen height control, although in cases where a particularly rough surface was being photographed both the height control and the electronic focussing controls were used in an attempt to obtain a good match between the successive micrographs.

4.2.2.4. Mounting Micrographs for Analysis.

Following the recommendations of the Third Annual Symposium on Scanning Electron Microscopy (1970), scale was indicated by specifying the width of the micrographs. The units used were mm or μ for low magnification and μ for high magnification. Magnification was given as the real magnification, i.e. as the electronic plus any photographic enlargement or reduction.

4.3. SPECIMEN PREPARATION

The sample preparation routine adopted for the present study is detailed in the following sections.

4.3.1. Air Drying of Bulk Samples.

Bulk soil samples were dried slowly in a constant ambient temperature of approximately 20°C over a period of one to six weeks. The time required for the drying procedure being dependant on the nature and water content of the sample under consideration. Bulk samples varied in character and size approximately 25 mm - 100 mm diameter with some being very soft or friable and others being fairly stiff or even hard. The problem of shrinkage therefore was met in only certain cases, i.e. essentially only where very soft or soft bulk samples were being air dried. To aid the drying process in these cases bulk samples were carefully trimmed down using cheese wire into smaller samples.

4.3.2. Specimen Selection for Microscopy.

Careful consideration was given to the selection of small specimens from the dried bulk samples with the chief aims being to achieve minimum sample disturbance and representativeness. Prismatic specimens approximately 1 cm. cross section and 3 cm. in length were carefully sculptured out of the bulk specimen using a sharp modelling knife and in the case of the very hard samples a fine hacksaw proved useful for coarse trimming. In the case of the friable samples prismatic samples could not be obtained and finger pressure was sufficient to obtain small or bulk specimens for fracture. Regarding the number of specimens taken, six was deemed to be an optimum number. Usually two of these would be selected such that the long axis was orientated in a vertical direction while the remaining four specimens were selected such that their long axis was orientated in a horizontal direction. Upon fracturing therefore two horizontal surfaces and four vertical surfaces were obtained.

4.3.3. Fracturing of Specimens.

Fracturing of specimens was carried out by cutting a V - shaped groove around the middle of the specimen and applying a combined bending and pulling action after Smart (1967). In the case of friable specimens a surface for viewing was obtained by applying a similar action to the small bulk specimens. As pointed out by Barden and Sides (1971) a fracture surface may prefer to follow a plane of weakness or preferred orientation and this has to be kept in mind when fracturing is carried out.

4.3.4. Mounting of Specimens.

Once the specimens were fractured they were carefully trimmed to approximately 1 cm. cube and care was taken not to disturb the fresh fracture surface during this operation. Small forceps proved invaluable here. The back of the specimens so obtained were trimmed flat and then fixed firmly to clean microscope stubs using Durofix glue, Barden and Sides (1971).

4.3.5. Preparation of Specimen Surfaces for Viewing.

After mounting, the fracture surfaces were peeled using up to 100 applications of cellotape in order to produce a cleaned and representative surface, Barden and Sides (1971). For the extremely clayey soils included in the study a very large number of cellotape applications was required. However, in the case of the coarse granular and friable soils included, peeling often appeared to induce disturbance due to the plucking out of a large number of soil grains and was therefore omitted. In such cases a low powered air-blast was adopted as a method for removing surface debris, McGown (1975). For those soils with a granulometry between extremely clayey and extremely granular an intermediate number of peels was applied.

To provide a check on the success or otherwise of the peeling or air-blasting techniques the texture of the prepared surface was examined. In the earlier stages of the project this was facilitated using simply a hand lens but in the latter stages a simple optical stereomicroscope did indeed prove useful, Stoops (1973).

4.3.6. Rendering Specimens Conductive.

The prepared surface of each specimen was vacuum coated with a layer of gold palladium (200 - 300 Å) thick to prevent charge build up on the specimen. Surfaces not requiring examination were painted with colloidal silver in order to improve the electrical contact between the specimen and stub.

4.3.7. Handling and Storage of Specimens.

In order to avoid contamination direct handling of specimens was kept to a minimum by the use of several types of forcep. Contamination of the specimens from the surrounding environment was reduced to a minimum by storing the specimens in sealable plastic containers or bottles.

4.3.8. Preliminary Investigation of the Critical Point Drying Technique.

4.3.8.1. Introduction.

A preliminary investigation using the technique of critical point drying was undertaken as part of the overall project in order to gain some idea of the effects that air-drying may have had on soil fabrics viewed in the present microfabric study.

The critical point drying method relies on the fact that at a temperature and pressure above a certain critical point, the physical properties of a liquid and its vapour become the same. As the interface no longer exists surface tension damage is therefore eliminated. The critical values of temperature and pressure for water are 374°C and 217.7 atm, respectively. Such high critical values however, may have an adverse affect on the structure of the clay particles. To avoid this a two stage procedure involving first the replacement of pore water with methanol, followed by the replacement of methanol with liquid carbon dioxide which is then taken to its critical point (critical $T = 31.1^{\circ}C$ and $P = 71$ atm) has been recommended Greene-kelly (1973). Such a two stage approach was adopted in the present preliminary investigation. The test apparatus and procedures are described in detail in Appendix B, Sections B.1. and B.2. respectively.

Unfortunately it was not possible to use soils from the main part of the microfabric investigation since the soil samples to which critical point drying would have been particularly appropriate, i.e. the soft marine, estuarine, and lacustrine deposits were already in the air-dried state by the time the critical point drying apparatus became available.

Five samples of suitable material were however available these being four natural water laid and saturated clays and a laboratory consolidated illite. Their general background properties are given in Table B.1. The natural soils were chosen because their general character resembled that of the soft water laid clays included in the main investigation. The illite clay seemed appropriate due to the fact that the four natural deposits were strongly illitic in character.

Lake Portchartrain clay was looked at early in the investigation and specimens were prepared by critical point drying (replacement of pore water directly with concentrated methanol) air-drying and oven drying methods. Later for the remaining four samples it was decided to consider only air drying and critical point drying, (with both concentrated and graded methanol impregnation).

It has been inferred by Greene-kelly(1973) that direct impregnation with concentrated methanol while being far simpler can induce damage due to high concentration gradients. On the other hand graded substitution involves introduction of water to the specimen and this also may have adverse effects.

Macroscopic observations of the degree of overall shrinkage or swelling and the more general characteristics such as shape and texture were made on all specimens dried by the various methods, and these are presented in Appendix B, Section B.3. For the Lake Portchartrain, microscopic examinations were also undertaken and these are given in Section B.4. Lack of time however made it impossible to extend the microscopic investigation to the other four soils.

It required to be emphasised that it was intended here to identify only general trends, i.e. to obtain a global view and therefore highly detailed macroscopic and microscopic examinations and assessment were not carried out.

4.3.8.2. Discussion of Results.

1. The limited macroscopic observations seem to indicate that:

(a) Slow air-drying, as might be expected, induces considerable linear and volumetric shrinkage in wet clay soils.

(b) Critical point drying reduces the degree of linear and volumetric shrinkage to a very low value. The magnitude of the reduction measured in the present study appears to be of the same order as that obtained by Greene-kelly (1973). The magnitude of the linear shrinkage (0 - 2.8%) however is slightly higher than reported by Tovey and Wong (1973 a), (< 0.5%). Differences in specimen volumes may be one of the factors responsible for this discrepancy.

(c) Preferred orientation of particles at the micro level due to drying is negligible since differential linear shrinkage (i.e. horizontal versus vertical) for both the critical point and air dried specimens seems on balance to be minimal.

(d) No statement can be made as to the relative merits of the graded or concentrated methanol impregnation methods for critical point drying since shrinkage after drying was greater for the former in two of the soils while being greater for the latter for the other two soils.

(e) There is a strong tendancy for methanol impregnation, whether it be by the graded or concentrated method, to induce cracking of specimens. This of course makes specimen preparation for microscopy more difficult.

(f) For soft uncemented clays, e.g. the laboratory prepared illite, San Francisco Bay Mud and Lake Portchartrain clays, the process of critical point drying may itself be responsible for producing a relatively weak and rather delicate skeleton as evidenced by, e.g. tendancy for surface flaking. This again presented problems in preparation for microscopy compared with that provided by say air-drying.

(g) The perforated specimen containers were useful for discouraging specimen distortion and to a large extent swelling during methanol impregnation. Significant swelling through the perforations was prevalent in the specimens of illite and this may be associated with the artificial nature of the soil structure.

2. The biggest problem in assessing the effects of specimen dehydration by the various methods at the microscopic level is that the 'natural' fabric is an unknown quantity and therefore damage, or the absence of damage, cannot be inferred from microscopic examination of dried specimens, Greene-kelly (1973). For example the most open and particulate and random fabric may not necessarily be the natural fabric, e.g. freeze drying has induced overall swelling at the macroscopic (and presumably the microlevel) Tovey (1970) and it has been suggested that critical point drying could possibly induce particle breakup.

Bearing this in mind, and on the basis of macroscopic observations, and the limited microscopic observations made on the Lake Portchartrain specimens, the following tentative conclusions are submitted relating to illitic or kaolinitic clays.

(a) Critical point drying produces a more realistic view of the character of natural microfabric of a wet soil than does either air or oven-drying. Certain artefacts however may be introduced, namely, a slightly more particulate and open clay array due to some packet breakdown, and a more porous looking fabric due to the presence of planar trans-assemblage pores (introduced probably during methanol impregnation) and an extremely large number of grain cavities. Moreover, if as suggested in 1.(f), above critical point drying does, due to the fact that plucking appears to be highly prevalent, tend to produce a relatively weak skeleton then it would seem that the post drying procedures of fracturing, mounting, peeling, etc. must induce some sort and degree of internal disturbance.

(b) Air drying produces a denser but not necessarily a more anisotropic clay array than the 'natural' one. Some clay group formation or extension is also probable. Artefacts such as trans-assemblage cracks seem unlikely and grain cavities, because of the shrinkage of clay arrangements around grains, are liable to be less abundant than in the case of critical point drying. There is no evidence to suggest that air drying produces, e.g. aggregations, connectors or bunches or alternatively breaks down such assemblages.

(c) Oven drying also produces a denser but again not necessarily a more anisotropic clay array overall although local collapse and preferred orientation of clay particles may occur. Again, clay group formation and extension, possibly more profound than in the case of air drying, may be induced and artefacts in the form of cracks, grain cavities and assemblage formation or destruction will be minimal.

3. The recommendation of the present preliminary investigation therefore, is that for routine drying of specimens of wet illitic or kaolinitic clays, critical point drying and air drying should be used, and a judgement made of the character of the natural microfabric on the basis of the information provided by each of these methods.

4.4. MICROSCOPY PROCEDURE ADOPTED FOR MICROFABRIC INVESTIGATION.

4.4.1. Introduction.

Natural soil fabric may be expected to be highly variable in character in many cases and it is necessary therefore, to employ a rational and consistent approach when using scanning electron microscopy for the investigation of soil microfabric, otherwise realistic and reproducable results may not be obtained.

For the present investigation a basically two stage approach was developed involving a preliminary microfabric assessment followed by a detailed microfabric assessment. In both stages the specimens were viewed and examined carefully in the S.E.M. and a large number of carefully selected micrographs taken. At the very least, 50 micrographs and generally more than 200 micrographs were taken for each specimen, the actual number being a function of the fabric complexity and specimen granulometry. Monomicrographs were usually taken only at low magnification ($\leq$ x 250) while stereopair and overlapping micrographs were usually only taken at higher magnifications.

Stereopair microphotography was employed whenever possible in order that anomalies could be easily identified and an appropriate allowance made, Tovey (1970, 1973c). Tovey has highlighted the errors in interpretation of particle alignment which can occur if fabric is viewed monoscopically. Stereoscopic viewing proved invaluable in this project as a means of guarding against misinterpretation of particle configuration. For example, cavities left by grains plucked out during preparation can be mistaken for pores if viewed monoscopically. Also, matrix 'projections' can be mistaken for aggregations, connectors or interweaving bunches. The internal organisation and the character of constituent grains can also be better assessed stereoscopically.

Overlapping photography was employed to assist in the detailed assessment of microfabric. Such a technique allows for better recognition of individual and multi-level microfabric forms and for a better appreciation of the degree of variability of microfabric form which exists.

Overlaps proved particularly useful for tracing clearly the pattern displayed by higher order vein assemblages across a specimen and for showing clearly the interaction and interface between the layers of a layered system.

Assessment of microfabric character was carried out on a purely qualitative basis since few quantitative techniques are available for scanning microscopy and as mentioned in Section 2.1. those that have been developed give limited information and as yet have not been thoroughly tested on natural soil fabrics.

Early in this project, an exploratory investigation was undertaken of the applicability of the Quantimet 720 image analysis computer to quantification of scanning electron micrographs. However, it was concluded that such an instrument cannot be applied successfully to scanning electron micrographs since unlike transmission electron micrographs of thin sections, they contain a multi-phase system wherein particles generally have a wide range of tone densities. These findings are in agreement with Tovey (1973a), who also stated that 'on line' processing, which eliminates the photographic step may partly assist in reducing this problem.

4.4.2. Preliminary Assessment.

Five steps are identified as follows:-

1) The specimens are placed in the specimen chamber of the S.E.M. such that the surface to be viewed is laid as close to the horizontal plane as possible and therefore approximately normal to the electron beam. This results in a better perspective monoscopic image than that obtained by oblique viewing although high quality micrographs are more difficult to obtain, Tovey (1973c).

2) The surfaces are then scanned at low magnification (x 25 - coarse grained soils; up to x 250 - fine grained soils) and their texture examined. Areas where surface preparation appears to have been ineffective are identified, i.e. areas where either charging or a fluffy appearance is evident. Reference should be made at this point to the information gained at the surface preparation stage.

3) A rough assessment is made of the degree of uniformity and coarseness of texture for each surface and this is noted. Representative areas are then identified on the basis of tex-

ture. Monomicrographs are taken of these areas at low magnification for the purposes of surface mapping and assessment. Stereopair micrographs may also be taken in the case of a coarse grained soil. Polaroid prints are extremely useful at this stage.

4) Each of these representative areas is then carefully examined in turn by carrying out a 'zooming action' from low to high magnification at many points within the area. A number of sets of stereopair micrographs are taken at various selected magnifications at selected points.

5) At this stage 'first impressions' of the microfabric character of each specimen should be formulated and recorded. The types of Elementary Particle Arrangements, and Basic and Higher order Particle Assemblages present and Pore Spaces and the organisation of the Composite Microfabric should be assessed along with some comment on the degree of anisotropy displayed.

4.4.3. Detailed Microfabric Assessment.

Two main steps are identified.

1) The sets of sequential stereopair micrographs taken at stage 4) above are mounted for viewing and carefully examined. Representative features are identified and more detailed notes made confirming or altering the 'first impressions'. Higher magnification stereopair sequences and overlaps are taken where necessary at appropriate levels of magnification.

2) In this, the final stage, a detailed account of the following aspects are made first for each specimen, and then for the bulk sample:
1) the nature of microfabric forms present, (ii) their spatial organisation and interaction to form the composite microfabric, (iii) the relative abundance of the various

microfabric forms within the composite microfabric and (iv) the nature of any anisotropy within the composite microfabric.

CHAPTER 5

A CATALOGUE OF NATURAL SOIL MICROFABRIC

5.1. INTRODUCTION.

The soils investigated display a wide range of geological origins but on the whole belong to the Transported Inorganic Soil Group. The individual soils are in fact, in most cases, highly representative of either a particular geological or geotechnical soil group. This chapter reports on the geological and geotechnical background of the soils studied and on the findings of the present scanning electron microscopy investigation of their microfabrics. A 'catalogue of natural soil microfabric' is presented and five main sections have been identified. Section I deals with the data for water laid deposits and is sub-divided into three parts dealing with marine, brackish water and fresh water deposits. Sections II, III and IV deal with the data for wind borne, ice laid and residual deposits. A summary is presented in Section V. Table 5.1. gives details of some of the basic geotechnical properties and also the source or authoritative reference for the particular soils included.

The soil samples were all examined in the air-dried state using the microscopy techniques described in Chapter 4, and the microfabrics so observed were characterised according to the system developed for the present study and detailed in Chapter 3. The various aspects of the characterisation system however, could only be assessed on a qualitative basis in this investigation.

Several ways of presenting the microfabric characterisation data were considered. The approach adopted in the present study includes for each soil, a well detailed descriptive text together with a number of selected micrographs illustrating the principal features in vertical section, and certain summary figures.

SECTION I - WATER LAID DEPOSITS

Part (a) Marine Deposits

5.2. GRANGEMOUTH, U.K.

5.2.1. General Background.

A bulk sample of soil from the site of a new lock construction, located on the flat alluvial plain of the River Forth, has been included. Evidence, both geological and structural suggests that this deposit is glacio-marine in origin and was formed during late-glacial times in arctic seas, Sissons (1970). Such marine deposits in the Grangemouth region are variable in thickness exceeding 30 m in places and display a range of macrofabrics including laminated, possibly even varved in cases, pedal or non-stratified with sand lenses. The bulk sample selected for the present study was found to have a non-stratified macrofabric wherein irregular shaped sandy or silty lenses were visible. It was found to be a soft-very soft, saturated clayey silt with a measured salinity of 27 g/1, Gabr (1975). Geotechnically speaking, it is classified as a normally consolidated ($p'_c \approx p'_o \approx 110$ kN/m^2) inorganic medium sensitive ($S_t = 2.5$) clay of high plasticity.

5.2.2. Microfabric Characterisation.

(a) <u>Elementary particle arrangements - Fig. 5.1.(a)</u>: clay arrangements appeared to be the only arrangements present and these were predominantly random in character. Parallel configurations were also occasionally in evidence with partly discernible particle arrangements displaying some crinkled edges only rarely observable. The discernible clay arrangements consisted both of plate shaped individuals of mainly coarse clay size, and plate shaped groups with fine-coarse clay sizes as indicated by Mic. 5.1.(a) which shows a random configuration at high magnification.

(b) Particle assemblages - Fig. 5.1.(b): a rather complex assemblage network was apparent within which a clay-granular matrix predominated and aggregations and interweaving bunches were each occasionally in evidence. The embedded matrix grains overall were haphazardly orientated with medium-fine silt sizes and flaky, elongated, angular and irregular shapes, otherwise the matrix consisted of an essentially random clay array. A typical clay-granular matrix region is shown in Mic. 5.1.(b). The aggregations present were more or less regular in shape; of medium silt size; consisted of clay arrays and were observed interacting directly with each other or the surrounding matrix. The typical nature of these assemblages is illustrated by Mic. 5.1.(c). The bunches interwove haphazardly between and around silt grains and were seen consisting mainly of parallel clay arrays. A horizontal bunch is shown in Mic. 5.1.(d). A significant number of fossil particles were also to be found interacting with and incorporated within the various assemblages. This is particularly well shown by Mic. 5.1.(e).

(c) Basic pore spaces - Fig. 5.1.(c): the intra-elemental pores associated with the clay arrangements, Mic. 5.1.(a), appeared to dominate the pore space although a considerable contribution from the various inter-assemblage pores, e.g. Mic. 5.1.(c), was also in evidence. Only a small proportion of the pore space seemed to be accounted for by intra-assemblage pores.

(d) Composite microfabric: the general nature and fairly uniform texture of the composite microfabric are clearly shown by Mic. 5.1.(f).

(e) Anisotropy within composite microfabric - Fig. 5.1.(d): the microfabric appeared to be isotropic at the 500 μ and 50 μ levels. This was also the case for the major portion of the microfabric at the 5 μ level.

5.3. OSLO FJORD, NORWAY.

5.3.1. General Background.

Four bulk samples of the well known sensitive Norwegian marine clays from the Drammen Valley and Oslo regions, Norway, have been included. The geological history and geotechnical properties of these deposits have been discussed in detail by Bjerrum (1967, 1973), Kazi and Moum (1973) and others, and summarised below.

Three of the deposits from Solbergelva and Sundland in the Drammen region and Ellingsgrud, Oslo, are glacio-marine in origin deposited during late-glacial times. The Drammen Town deposit however was laid down in early post glacial times. From the geological point of view, all these Norwegian sediments are normally consolidated. ($p'_c \approx p'_o \approx 84$ kN/m^2 for the Solbergelva and Sundland deposits). The Drammen Town and Ellingsgrud deposits however, have developed reserve resistance to compression as a result of the large delayed compression to which it has been subjected, and therefore displays some apparent pre-consolidation, (e.g. for Drammen Town $p'_c \approx 1.6\ p'_o \approx 107$ kN/m^2). Post-depositional leaching by freshwater occurred in varying degrees within the four deposits following isostatic uplift as indicated by the measured soluble salt contents of the samples (Drammen Town - 27 g/l; Solbergelva - 15 g/l; Sundland - 2 g/l and Ellingsgrud - 1 g/l.) All four samples were found to have water contents approaching or above their liquid limits and were grey in colour, homogeneous, intact and saturated in the undisturbed state. The Drammen Town soil has been described as an inorganic highly plastic clay while the late-glacial Drammen deposits have been described as inorganic clays of low plasticity, i.e. 'lean clays'. The Ellingsgrud deposit has been described as an inorganic silt of low plasticity despite its significant clay content of 38%. Typically the clay fraction of Norwegian marine clays has been reported as consisting mainly of illite, chlorite along with significant amounts of quartz and feldspar. The Norwegian marine deposits are renowned for their unusual and often extreme mechanical properties, particularly their sensitivity which is defined as the ratio of undisturbed to remoulded strength and which has been well correlated with the degree of salt leaching. The samples selected for this study display a range of sensitivities, the Ellingsgrud is classed as extra quick, ($S_t = 70$) the Sundland as medium quick, ($S_t = 17$) and those from Drammen Town and Solbergelva are very sensitive, ($S_t = 8$).

5.3.2. Microfabric Characterisation.

5.3.2.1. Drammen Town.

(a) Elementary particle arrangements - Fig. 5.2.(a): clay arrangements were observed predominating over clean grain-grain contact arrangements which were also frequently in evidence. The former arrangements were predominantly random in character and the clay particles comprising these arrangements appeared to be both plate shaped indidivuals of mainly coarse clay size and plate shaped groups of mainly fine clay size. Mic. 5.2.(a) shows a random configuration wherein clay individuals are prominent. Rarely the clay arrangements were partly discernible in character. The grains involved in the grain-grain contacts were mainly finer silt sizes, flaky and elongated shapes, and were generally loosely packed.

(b) Particle assemblages - Fig. 5.2.(b): A matrix appeared to be the dominant assemblage present, and aggregations and connectors were only rarely abundant. Within the matrix which was very open in places, clay-granular regions were observed dominating over clay regions which were occasionally present. Embedded matrix grains were haphazardly orientated medium-fine silt sizes with mainly flaky and elongated shapes, otherwise the matrix consisted of a random clay array with isolated grain-grain contacts. Mic. 5.2.(b) illustrates the typical internal organisation of the various matrix regions. Two clay-granular regions are shown with one being more open and less clayey than the other. In contrast to these clay-granular regions, a clay region is also shown.

The aggregations were irregular in shape, silt sized and associated with the surrounding matrix via bridge connectors. The latter assemblages consisted of mixtures of random clay and grain-grain arrangements. The nature of the irregular aggregations and their linkages with the surrounding matrix may be taken as being similar to that shown in Mic. 5.3.(b) for the Sundland soil.

(c) Basic pore spaces - Fig. 5.2.(c): the intra-elemental pores associated with both the clay arrangements, e.g. Mic. 5.2.(a) and grain arrangements appeared to dominate the pore space although an appreciable contribution was also in evidence from the intra-assemblage pores associated with the open matrix regions, e.g. Mic. 5.2.(b). Overall, only a small contribution was apparent from inter-assemblage pores.

(d) Composite microfabric: the general nature and fine texture of the composite microfabric are clearly shown by Mic. 5.2.(c).

(e) Anisotropy within composite microfabric - Fig. 5.2.(d): the microfabric appeared to be isotropic at the three levels considered.

5.3.2.2. Sundland.

(a) Elementary particle arrangements - Fig. 5.3.(a): both clay and clean grain-grain contact arrangements were observed to be frequently abundant. The former arrangements were predominantly random in character and appeared to consist of both bulky shaped individuals of mainly coarse clay size, and plate shaped groups of mainly fine clay size, as indicated in Mic. 5.3.(a). Rarely, the clay arrangements were partly discernible in character. The grains involved in the grain-grain contacts were mainly finer silt sizes with flaky, elongated and angular shapes, Mic. 5.3.(b). Both loosely and closely packed arrangements were apparent.

(b) Particle assemblages - Fig. 5.3.(b): a rather complex assemblage network was apparent within which connectors appeared to be predominant and aggregations were frequently observable. The connectors bridged and buttressed medium-fine silt grains and were observed to generally consist of both random clay arrangements and grain-grain contacts, with the proportions of each arrangement present varying between connectors. A connector system is shown in Mic. 5.3.(a). In some cases, grain connectors were actually present within larger connectors. Connectors also served to link aggregations, both with each other, in connected aggregate systems, and with the surrounding grain connector system. The aggregations were silt sized and irregularly shaped and consisted of mixtures of clay arrangements and grain-grain contacts. Mic. 5.3.(b) serves to illustrate the nature and organisation of an irregular aggregation and its linkages. No preferred orientation of the assemblage grains was apparent.

(c) Basic pore spaces - Fig. 5.3.(c): the inter-assemblage pores formed by the connector systems, e.g. Mic. 5.3.(a) and (b) appeared to dominate the pore space with an appreciable contribution coming also from the intra-elemental pores associated with both the clay and grain arrangements. Only a small contribution was in evidence from intra-assemblage pores.

(d) Composite microfabric: the rather open and grain like appearance of the composite microfabric is quite apparent from Mic. 5.3.(c).

(e) Anisotropy within composite microfabric - Fig. 5.3.(d): the microfabric appeared to be isotropic at the three levels considered.

5.3.2.3. Solbergelva.

(a) Elementary particle arrangements - Fig. 5.4.(a): clay arrangements were observed to be the dominant arrangement present and clean grain-grain contacts were only rarely observable. The former arrangements were random in character and appeared to consist of both plate shaped individuals of mainly coarse clay size, and plate shaped groups with fine-coarse clay sizes as shown by Mic. 5.4.(a). Fine silt size particles with mainly flaky and angular shapes were involved in the grain-grain arrangements which were relatively loosely packed.

(b) Particle assemblages - Fig. 5.4.(b): a clay-granular matrix appeared to be the dominant assemblage present whilst connector systems were also occasionally in evidence. The embedded matrix and connected grains were mainly medium silt size with irregular, elongated and angular shapes displaying no preferred orientation. Within the matrix, the silt grains were set against a random clay array as shown by Mic. 5.4.(b) and a few isolated grain-grain contacts were in evidence. The connectors were of the bridge type and were observed consisting of random clay arrays as indicated in Mic. 5.4.(c). Some fossil particles were also to be found interacting with and incorporated within the various assemblages.

(c) Basic pore spaces - Fig. 5.4.(c): the intra-elemental pores particularly those associated with the clay arrangements, Mic. 5.4.(a) appeared to dominate the pore space, although an appreciable contribution was also in evidence from the inter-assemblage pores of the connector systems, Mic. 5.4.(c). Only a small contribution was apparent from intra-assemblage pores.

(d) Composite microfabric: the general nature and texture of the composite microfabric can be appreciated from Mic.5.4.(d).

(e) Anisotropy within composite microfabric - Fig. 5.4.(d): the microfabric appeared to be isotropic at the three levels considered.

5.3.2.4. Ellingsgrud.

(a) Elementary particle arrangements - Fig. 5.5.(a): clay arrangements appeared to be the only arrangements present. These were random in character and seemed to consist of both plate shaped individuals of mainly coarse clay size and plate shaped groups, with fine-coarse clay sizes, as indicated in Mic. 5.5.(a).

(b) Particle assemblages - Fig. 5.5.(b): a clay-granular matrix was observed to be the dominant assemblage present with connector and aggregations being respectively, occasionally or only rarely in evidence. The embedded matrix grains were medium-fine silt sized and angular, flaky and elongated in shape, and otherwise the matrix consisted of a random clay array as shown by Mic. 5.5.(a). A medium degree of preferred orientation of matrix grains towards the horizontal can also be seen. The connector assemblages were found either bridging and buttressing silt grains, or linking the irregular shaped aggregations with the surrounding matrix. The aggregations were of finer silt size and like the connectors were composed of the clay arrays and sometimes incorporated very fine silt grains.

(c) Basic pore spaces - Fig. 5.5.(c): the intra-elemental pores associated with the random clay arrangements, Mic. 5.5.(a), appeared to dominate the pore space. An appreciable contribution was however, also in evidence from the inter-assemblage pores of the connector and aggregation systems whereas only a small proportion of the pore space appeared to be accounted for by intra-assemblage pores.

(d) Composite microfabric: the general nature and texture of the composite microfabric can be appreciated from Mic. 5.5.(b).

(e) Anisotropy of composite microfabric - Fig. 5.5.(d): the microfabric appeared to be isotropic throughout at the 5 μ

level but displayed a low degree of anisotropy at both the 50μ and 500μ levels.

5.4. JACKSON, U.S.A.

5.4.1. General Background.

A bulk sample of Yazoo Marine clay from Jackson, Mississippi, a member of the Jackson Group of the Tertiary (Eocene) system has been included. The Yazoo clay was formed late in Eocene period by large amounts of clay material deposited in the sea by a river or several rivers, Monroe (1954). Overlying deposits some 100 metres thick were eroded in the Pleistocene period leaving a flat surface of the Yazoo clay which is therefore highly over consolidated. The upper 6 metres of the deposit were subsequently weathered and the sample selected for the present study was taken from within the weathered zone. In appearance it has been described as a stiff, tan and grey clay, containing some slickensides with reddish staining from hematite in certain cases. In places black specks were observable and these it seems are possibly concentrations of organic matter. It is classified as an inorganic highly plastic clay with a high degree of saturation. The clay fraction contains mainly kaolinite groups and montmorillonite minerals, Buck (1956). A number of field and laboratory studies have shown the Yazoo clay to be potentially a high expansive soil, Gromko (1969) and Johnson et al (1973).

5.4.2. Microfabric Characterisation.

(a) Elementary particle arrangements - Fig. 5.6.(a): clay arrangements appeared to be the only arrangements present and these were found to be predominantly of the parallel type, Mic. 5.6.(a), with more random arrangements, Mic. 5.6.(b) also occasionally in evidence. The clay particles comprising these arrangements, were apparently coarse clay groups, wavy and occasionally almost transparent in appearance.

(b) Particle assemblages - Fig. 5.6.(b): a matrix consisting essentially of clay regions appeared to be the only assemblage present. Overall, a predominently parallel clay array displaying strong preferred orientation was in evidence. Mic. 5.6.(c) shows a parallel clay array within a clay region while in contrast, Mic. 5.6.(d) shows a clay region wherein a predominently random clay array exists. Those embedded matrix grains observable were of mainly medium-fine silt size with angular and flaky shapes. The flaky grains were generally horizontally orientated and occasionally almost transparent. A variety of fossil particles were also in evidence and these tended to occur as concentrations within the matrix. In some cases they appeared to be in a state of decomposition.

(c) Basic pore spaces - Fig. 5.6.(c): the pore space appeared to be dominated by the intra-elemental pores, Mic. 5.6.(a) and (b), although it seemed that a small contribution from intra-assemblage pores was also in evidence.

(d) Composite microfabric: the general nature and texture of the composite microfabric are illustrated by Mic. 5.6.(e). A horizontally orientated gravel particle and a fossil particle are shown embedded in this composite microfabric.

(e) Anisotropy within composite microfabric - Fig. 5.6.(d): the microfabric at the 500 μ level appeared to possess a high degree of anisotropy while at the lower levels, degrees of anisotropy ranging from nil to very high were in evidence, with the latter being predominant. Preferred orientation was towards the horizontal in all cases.

5.5. LUANDA, ANGOLA.

5.5.1. General Background.

A bulk sample of a Tertiary (Miocene) marine clay from the River

Cuanza sedimentary basin in the Luanda region of Angola has been included. According to Novias-Ferreira and Horta da Silva (1973), the clay was deposited in the hypersaline waters of an enclosed sea, following which it densified by overlying sediments and diagenisis phenomenon. Subsequently the miocene clay and the overlying sediments were subjected to intense desiccation and locally were partly eroded. The deposit is some 30 m thick, partly saturated, heavily overconsolidated and fissured. The sample selected for the present study was light grey in colour and is classified as inorganic clay of high plasticity. The clay fraction is reported as consisting mainly of montmorillonite with significant amounts of kaolinite and micaceous minerals. Laboratory studies Novias-Ferreira and Horta da Silva (1973) have confirmed that the Luanda clay is potentially a high expansive deposit.

5.5.2. Microfabric characterisation.

(a) Elementary particle arrangements - Fig. 5.7.(a): clay arrangements appeared to be the only arrangements present and these were found to be predominantly of the parallel type, Mic. 5.7.(a), with random arrangements rarely in evidence. The clay particles comprising these arrangements were considered to be wavy shaped fine coarse clay size groups.

(b) Particle assemblages - Fig. 5.7.(b): a matrix, wherein clay-granular regions predominated over clay regions which were occasionally in evidence, was found to be the only assemblage present. Overall, a predominently parallel clay array displaying medium degree of preferred orientation towards the horizontal, was in evidence. The embedded matrix grains were haphazardly orientated silt sizes with mainly irregular but also elongated shapes. Mics. 5.7.(b), (c) and (d) serve to illustrate the internal nature and organisation of the particle matrix. The first shows a predominantly parallel array displaying weak preferred orientation and the second illustrates the clay-granular region in which this array is located. The nature and spatial orientation of the matrix grains can be easily appreciated. The third shows a clay region wherein a parallel clay array displaying strong preferred orientation is in evidence.

(c) Basic pore spaces - Fig. 5.7.(c): the pore space appeared to be dominated by the intra-elemental pores of the clay arrangements, Mic. 5.7.(a), and only a relatively small contribution from intra-assemblage pores was apparent.

(d) Composite microfabric: the general nature and texture of the composite microfabric are illustrated by Mic. 5.7.(e).

(e) Anisotropy within composite microfabric - Fig. 5.7.(d): the microfabric at the 500 μ level appeared to possess a slightly less than medium degree of anisotropy. At the 50 μ level the major portion of the microfabric displayed a low degree of anisotropy with the remainder showing a high degree of anisotropy. The vast majority of the fabric at the 5 μ level possessed very high degrees of anisotropy.

Part (b) Brackish Water Deposits

5.6. UPPER CLYDE ESTUARY, U.K.

5.6.1. General Background.

Bulk samples from three sites along the Upper Clyde Estuary at Renfrew, Laurieston and Gallowgate have been included. A detailed account of the geological history and profiles, and the geotechnical properties of the soils at these sites has been given by Gabr (1975). These are estuarine deposits which were formed under sub-arctic conditions in late-glacial times and which constitute the belt of drumlin free ground bordering the River Clyde. Geological evidence suggests that the Renfrew soil was deposited in a brackish-marine environment and the Laurieston and Gallowgate were formed in a brackish-freshwater environment. The measured soluble salt contents of all three soils however, is very low (< 2 g/l). The Renfrew and Gallowgate deposits are normally consolidated ($p'_c \approx p'_o \approx 110$ kN/m^2) and ($p'_c \approx p'_o \approx 120$ kN/m^2) respectively, and the Laurieston is slightly over consolidated ($p'_c \approx 2p'_o \approx 110$ kN/m^2). The bulk samples selected were all brown in colour, fully saturated and displayed a range of consistencies; soft-very soft for Renfrew; soft-firm for Laurieston; and firm for Gallowgate. The Renfrew and Laurieston samples are classified as inorganic silty clays of low plasticity whereas the Gallowgate is classified as an organic clay of high plasticity. They are all classified as medium sensitive ($S_t = 2 - 4$). With regard to the macrofabrics of the samples, Renfrew and Laurieston were very finely and finely laminated respectively, and were found therefore, to be representative of the respective deposits. Although the Gallowgate deposit has been found to be finely laminated in places, no layering effects were visible in the present bulk sample.

5.6.2. Microfabric Characterisation.

5.6.2.1. Gallowgate.

(a) Elementary particle arrangements - Fig. 5.8.(a): clay arrangements were observed to be the dominant arrangements present although clean grain-grain contacts were also occasionally in evidence. The vast majority of clay arrangements were of the parallel type and random configurations were only rarely observable. The clay particles involved in these arrangements seemed to be mainly fine-coarse clay size plate shaped groups although plate shaped individuals of mainly coarse clay size were also present. Mic. 5.8.(a) serves to illustrate the nature of these clay particles. The grain-grain arrangements were observed to involve medium-fine silt sized flaky and elongated shaped grains which were generally relatively closely packed with a parallel association of grains observable in many cases, Mic. 5.8.(d).

(b) <u>Particle assemblages - Fig. 5.8.(b)</u>: a particle matrix appeared to be the only basic assemblage present. Within this matrix, clay-granular regions were found predominating over purely clay or granular regions which were both occasionally observed. Within the clayey part of the matrix a parallel clay array, displaying haphazard orientation was in evidence. Parallel clay arrangements were orientated in sympathy with the matrix grain surfaces. Overall the matrix grains were haphazardly orientated silt sizes with mainly elongated and flaky shapes. The internal nature and organisation of the various matrix regions are clearly illustrated by Mics. 5.8.(b), (c) and (d), which show clay-granular, clay and granular regions respectively and the haphazard organisation of the constituent arrays. The particle matrix was disrupted in places by higher order vein assemblages consisting, as indicated in Mic. 5.8.(g) of parallel clay arrays and silt grains. Forked systems were generally observed. Individual veins within the system were obliquely orientated and limited in extent relative to the specimen boundary. Mics. 5.8.(e) and (f) show the general nature and internal organisation of the veins. The well defined vein boundaries are also clearly illustrated by the latter.

(c) <u>Basic pore spaces - Fig. 5.8.(c)</u>: the intra-elemental pores particularly those associated with the parallel clay arrangements, Mic. 5.8.(b), appeared to dominate the pore space and only a relatively small contribution was apparent from intra-assemblage pores. No inter-assemblage pores were in evidence.

(d) *Composite microfabric*: the fine and somewhat patchy texture of the composite microfabric is clearly illustrated by Mic. 5.8.(g). The prominence of the vein assemblages is also well demonstrated.

(e) *Anisotropy within composite microfabric - Fig. 5.8.(d)*: the vast majority of the microfabric at the 500µ level appeared to be isotropic in character with a small proportion displaying a low degree of anisotropy. The microfabric was almost isotropic throughout at the 50µ level, while in contrast very high degrees of anisotropy were displayed by the vast majority of the fabric at the 5µ level.

5.6.2.2. Laurieston

Three types of layer were identified from within the finely laminated system, and both macro and microlayers were in evidence.

(a) *Elementary particle arrangements - Fig. 5.9.(a)*: in layer type I, parallel clay arrangements appeared to be the only arrangements present while in layer type II, these dominated over random clay configurations which were occasionally in evidence. The clay particles comprising these arrangements were considered to be mainly coarse clay size plate shaped groups. The nature of the parallel clay arrangements and their constituent particles can be appreciated from Mic.5.9.(a).

In layer type III, clean grain-grain contacts were observable dominating with the grains involved being medium-fine silt sized and elongated flaky and angular in shape. They were generally relatively closely packed.

(b) Particle assemblages - Fig. 5.9.(b): a region system appeared to be the only assemblage present in each of the three layer types although the internal organisation in each was observed to be different.

In layer type I, clay regions were to be found, within which a parallel clay array, displaying complete preferred orientation towards the horizontal, was in evidence as illustrated by Mic. 5.9.(b).

Layer type II was observed consisting entirely of clay-granular regions and overall, a predominently parallel clay array displaying strong preferred orientation towards the horizontal, was in evidence as illustrated by Mic. 5.9.(c). As shown, the grains within the region were medium-fine silt sizes with elongated, flaky and angular shapes and were also preferentially orientated towards the horizontal.

In contrast to these types, layer type III was observed consisting entirely of granular regions, with once again a marked tendancy for horizontal orientation of the elongated and flaky grains involved in the clean grain-grain contacts, Mic. 5.9.(d).

(c) Basic pore spaces - Fig. 5.9.(c): in all three layer types, the intra-elemental pores appeared to dominate the pore space and these were associated with the clay arrangements in layer types I and II, Mic. 5.9.(a), and with grain arrangements in layer type III, Mic. 5.9.(d). Only a small contribution was evident from intra-assemblage pores in each case.

(d) Composite microfabric: the general nature and differing textures of the composite microfabrics of layer types I, II and III are illustrated by Mics. 5.9.(e), (f) and (g) respectively. A portion of the composite microfabric of the layered system, consisting of microlayers, is given in Mic.

5.9.(h). Layer interfaces were essentially sharp and straight in character.

(e) Anisotropy within composite microfabric of layers - Fig.5.9.(d): within layer type 1, the microfabric appeared to be very highly anisotropic at all levels. Within layer type 11, the microfabric displayed high degrees of anisotropy at both the 500 μ and 50 μ levels. At the 5 μ level the major portion of the microfabric was very highly anisotropic with the remainder displaying isotropy. Within layer type 111, a medium degree of anisotropy was apparent at the 500 μ and 50 μ levels. Clay arrangements were absent and the 5 μ level therefore was not appropriate. Preferred orientation was towards the horizontal in all cases.

5.6.2.3. Renfrew.

Three types of layer were identified from within the very finely laminated system, and both macro and microlayers were in evidence.

(a) Elementary particle arrangements - Fig. 5.10.(a): within layer type 1, clay arrangements appeared to be the only arrangements present while in layer type 11, these dominated over clean grain-grain contacts which were however, only rarely discernible. The clay arrangements in both layers were predominantly random in character although parallel configurations were frequently and occasionally in evidence in layer types 1, and 11 respectively. The arrangements appeared to be composed generally of coarse clay size plate shaped groups and often incorporated fine silt particles, as indicated by Mic. 5.10.(a) which shows a random clay arrangement.

Within layer type 111, grain-grain contacts predominated over clay arrangements which were occasionally in evidence. The former arrangements involved medium-fine silt sizes and flaky, elongated and angular shapes; were both clothed and clean and generally relatively closely packed. Random and parallel clay arrangements were both frequently observable.

(b) Particle assemblages - Fig. 5.10.(b): within layer type I, a region system appeared to be the only assemblage present, within which clay-granular regions were observed predominating over clay regions which were also frequently in evidence. The embedded region grains were mainly medium-fine silt sizes with flaky and elongated shapes. A strong tendancy for preferential orientation of the embedded grains towards the horizontal was apparent, as demonstrated by Mic. 5.10.(b). A detailed view of the region system is presented in Mic. 5.10.(c).

Within layer type II, a more complex assemblage network was observed wherein a region system, consisting entirely of clay-granular regions predominated over connectors, aggregations and interweaving bunches which each appeared to be rarely abundant. The region system, overall, involved a predominantly random clay array and the region grains were haphazardly arranged silt sizes with mainly flaky and angular shapes, as illustrated by Mic. 5.10.(d) which shows a typical view of a clay-granular region. The aggregations were irregular in shape and coarse silt sized and were observed generally interacting with each other and the nearby regions via bridge connectors as shown by Mic. 5.10.(e). Both these assemblages consisted of confused mixtures of random and parallel clay arrangements. The interweaving bunches were preferentially orientated towards the horizontal and composed of parallel clay arrays and occurred in interwoven systems.

Within layer type III, a connector system was observed predominating over granular regions which were at the occasional level of abundance. Both bridge connectors, consisting of parallel clay, and buttress connectors composed either of random or parallel clay appeared to be equally abundant, Mic.

5.10(f). The connector and region grains were mainly medium-fine silt sizes with flaky and angular shapes and overall a tendancy for preferential orientation towards the horizontal was apparent, as demonstrated by Mic. 5.10.(g).

(c) Basic pore spaces - Mic. 5.10.(c): within layer types I and II, intra-elemental pores associated with the various clay arrangements appeared to dominate the pore space while an appreciable contribution from intra-assemblage pores was also in evidence. An appreciable proportion of the pore space in layer 11 was also accounted for by the various inter-assemblage pores present.

Within layer type 111, the majority of the pore space appeared to be accounted for by the inter-assemblage pores associated with the connector systems. An appreciable proportion was also provided by the intra-elemental pores of the grain-grain arrangements.

(d) Composite microfabric: the general nature and differing textures of the composite microfabrics of the individual layer types are illustrated by Mic. 5.10.(h). Two general views of the composite microfabric of the layered system are presented in Mic. 5.10.(j). As indicated, layer interfaces were found to be sharp and straight, sharp and wavy and in other cases ill-defined in character.

(e) Anisotropy within composite microfabric of layers - Fig. 5.10.(d): the microfabrics within layer types 1, 11 and 111 appeared to possess medium, nil and less than medium degrees of anisotropy respectively at the 500 μ level. At the 50 μ level the major portion of the microfabric within layer 1 displayed a low degree of anisotropy with the remainder displaying high anisotropy. At the 50 μ level within layer 11, isotropy was in evidence. The microfabric of layer III at the 50 μ level possessed both nil and medium degrees of anisotropy. At the 5 μ level the major proportion of microfabrics displayed nil anisotropy with the remainder displaying very high anisotropy.

5.7. SHANNON ESTUARY, EIRE.

5.7.1. General Background.

Two bulk samples of recent estuarine deposits from a site on the southern bank of the Shannon Estuary near the town of Foynes are included. The estuarine deposits are predominantly very loose homogeneous clayey silts often sandy and in some cases slightly organic, and shelly. In general there is a thickening of deposits towards the north west up to about 28 metres. They have proved to be extremely troublesome foundation deposits, the samples selected for this study will be referred to hereafter as Shannon A and B. Sample A was a very loose, grey sandy clayey silt and is classified as inorganic soil of low plasticity. Sample B however, was less typical of the deposits and was a soft silty clay, being classified as inorganic clay of high plasticity. Both samples were fully saturated. The clay fractions consist mainly of illite and kaolinite.

5.7.2. Microfabric Characterisation.

5.7.2.1. Shannon A.

(a) <u>Elementary particle arrangements - Fig. 5.11.(a)</u>: grain-grain contacts were observed to be the dominant arrangements present and both clothed and clean arrangements appeared to occur equally as frequently. The grains involved were fine sand and silt sizes with elongated, flaky, irregular and angular shapes. The arrangements appeared to be both closely and loosely packed. A number of grain-grain contacts are indicated on Mic. 5.11.(e). Clay arrangements were also occasionally observable and both partly discernible particle arrangements and random arrangements appeared to be equally abundant. The former were observed displaying some non-crinkled edges, Mic. 5.11.(a) while the latter arrangements were considered to be composed of fine-coarse clay sized plate shaped individuals and groups, Mic. 5.11.(b).

(b) Particle assemblages - Fig. 5.11.(b): a rather complex assemblage system was apparent within which granular matrix and aggregation assemblages were frequently observable and connectors were occasionally in evidence. The aggregations were fine sand and silt sized and were generally more or less regular in shape, Mic. 5.11.(c). They appeared to consist mainly of clay arrays and sometimes silt grains and were observed having several modes of interaction, including interaction with each other and with the matrix grains either directly, or indirectly via connectors, Mic. 5.11.(c). The connector assemblages, which also spanned sand and silt grains, were in the form of bridges and buttresses and consisted of clay arrays. Mic. 5.11.(d) illustrates the nature and occurrence of a buttress connector. As indicated in Mic. 5.11.(e), a large number and variety of fossil particles were also to be found interacting with and incorporated within the various assemblages, and overall, no preferred orientation of the various assemblage grains was apparent.

(c) Basic pore spaces - Fig. 5.11.(c): the intra-elemental pores, particularly those associated with the grain-grain contacts, Mic. 5.11.(e), and the inter-assemblage pores, e.g. Mic. 5.11.(c) and (d), were each considered to account for a considerable proportion of the pore space. A relatively small contribution from intra-assemblage pores was also in evidence.

(d) Composite microfabric: the nature of the composite microfabric is clearly illustrated by Mics. 5.11.(e) and (f). The former gives a detailed view of the composite microfabric and shows the nature, occurrence and interaction of the various microfabric forms. The latter gives a more general view of the composite microfabric at low magnification.

(e) Anisotropy within the microfabric - Fig. 5.11.(d): the microfabric appeared to be isotropic at all the levels considered. Due to the grain sizes involved within the microfabric the 50 µ level was inappropriate in many cases.

5.7.2.2. Shannon B.

(a) Elementary particle arrangements - Fig. 5.12.(a): clay arrangements appeared to be the only arrangements present and these were found to be predominantly random in character with parallel arrangements also occasionally in evidence. The clay particles comprising these arrangements were mainly fine clay sized and were considered to be both plate shaped individuals and groups. In some cases bulky individuals were in evidence. The typical nature of the clay arrangements and their constituent particles is illustrated by Mics. 5.12.(a) and (b), which show random and parallel configurations respectively.

(b) Particle assemblages - Fig. 5.12.(b): a complex assemblage system was apparent within which a particle matrix predominated and connectors and aggregations were rarely and occasionally observable, respectively. A large number and variety of fossils were also to be found interacting with and incorporated within the various assemblages. Within the matrix, clay-granular regions predominated over clay regions which were frequently observed and overall, a predominantly random clay array was in evidence. The matrix grains were haphazardly orientated and were mainly silt sized with elongated flaky, angular and irregular shapes, Mic. 5.12.(c) serves to illustrate the typical nature and internal organisation of the matrix. The aggregations were of silt size and regular in shape, and were composed mainly of clay arrays. They interacted indirectly with each other and the matrix via bridge connectors as indicated by Mic. 5.12.(d).

(e) Basic pore spaces - Fig. 5.12.(c): the intra-elemental pores associated with the various clay arrangements, e.g. Mics. 5.12.(a) and (b), appeared to dominate the pore space. Small and appreciable contributions were in evidence from the intra-assemblage pores and inter-assemblage pores, Mic. 5.12.(d), respectively.

(d) Composite microfabric: a general view of the composite microfabric is given in Mic. 5.12.(e).

(e) Anisotropy within composite microfabric - Fig. 5.12.(d): the microfabric appeared to be isotropic in character at both the 500 μ and 50 μ levels. This was also the case for the major portion of the microfabric at the 5 μ level with the remainder displaying very high anisotropy.

5.8. CHAMPLAIN SEA, CANADA.

5.8.1. General Background.

Two bulk samples of the well documented and highly sensitive Champlain Sea deposits from sites at Saint Alban and Saint Jean Vianney in Eastern Canada have been included. The deposit from Saint Alban in the Saint-Laurent Lowlands in the fringe of the Champlain Sea deposits, is thought to have been laid down in a brackish water environment, and possibly leached subsequently by the upward flow of freshwater La Rochelle et al (1974). The Saint Jean Vianney site, the scene of a disastrous landslide in 1971, as described by Tavenas et al (1971), is situated in a region which was flooded by brackish-fresh-water some 9,000 years ago by an extension of the Champlain Sea, the so called Laflamme Sea. Deep layers of clay were subsequently formed in this environment, Larochelle (1974). The samples selected for the present study were found to be quite fine, homogeneous, apparently intact and fully saturated with measured salt contents of less than 1 g/l. They are classified as inorganic silty clays of low plasticity. The very low plastic clay from Saint Jean Vianney is known to be very strongly cemented, Bjerrum (1973). The clay fraction of the

Champlain Sea deposits is reported consisting mainly of illite and chlorite with significant amounts of quartz and feldspar.

These Canadian deposits, like the Norwegian marine clays, are well known for their extreme sensitivity. Unlike the Norwegian deposits however, this has been strongly associated with the presence of cementing bonds. Saint Alban is classified as medium quick (S_t = 22) and Saint Jean Vianney is classified as extra quick (S_t = 500 to infinity). The Saint Alban and Saint Jean Vianney clays are apparently lightly over-consolidated ($p'_c \approx 2\ p'_o \approx 77$ kN/m^2) and fairly heavily over-consolidated ($p'_c \approx 1000$ kN/m^2) respectively. The influence however, of cementing agents is known to have been considerable, particularly in the case of the latter. Hence despite the significant overburden pressures which have existed, particularly in the case of Saint Jean Vianney, an open structure with an exceptionally high water content, appears to have been preserved due to the action of the cementing agents.

5.8.2. Microfabric Characterisation.

5.8.2.1. Saint Alban.

(a) Elementary particle arrangements - Fig. 5.13.(a): clay arrangements appeared to be the only arrangements present and were found to be entirely random in character. Their constituent particles were plate shaped and mainly fine clay size and in certain cases were extremely thin and appeared almost transparent. Clay groups and clusters were seemingly infrequently present. In certain cases amorphous material was possibly present at the points of contact between clay particles. Mics. 5.13.(a) and (b) serve to illustrate the typical character and constituent particles of these random clay arrangements.

(b) Particle assemblages - Fig. 5.13.(b): a matrix appeared to be the only assemblage present. Within this matrix clay-granular regions were observed predominating over clay regions which were occasionally in evidence. Random clay arrays were in evidence within these regions as shown by Mic. 5.13.(b). The matrix grains overall were haphazardly arranged with mainly silt but also some fine sand sizes and elongated, irregular, flaky and angular shapes. Also, the grain sizes were not evenly distributed and some clay-granular regions contained coarser grains than others, as shown by Mic.5.13.(c).

(c) Basic pore spaces - Fig. 5.13.(c): the intra-elemental pores associated with the clay arrangements, e.g. Mic.5.13.(b), were observed dominating the pore space and only a small contribution from intra-assemblage pores was apparent. No inter-assemblage pores were in evidence.

(d) Composite microfabric: Mic. 5.13.(d) serves to illustrate the typical nature and rather patchy texture of the composite microfabric.

(e) Anisotropy within composite microfabric - Fig. 5.13.(d): the microfabric appeared to be isotropic at each of the levels considered.

5.8.2.2. Saint Jean Vianney.

(a) Elementary particle arrangements - Fig. 5.14.(a): clay arrangements appeared to be the only arrangements present and were found to be entirely random in character. The clay particles comprising these arrangements were bulky shaped and of fine clay size. Coarse clay size particles appeared to be individuals which generally had some form of material uniformly coated on their surfaces. Within the fine clay size range the particles appeared to be in the form of both individuals and clusters. The latter seemed to be composed of bulky shaped individuals as shown by Mic. 5.14.(a). Mic. 5.14.(b) serves to illustrate the typical character and constituent particles of the random clay arrangements.

(b) Particle assemblages - Fig. 5.14.(b): a particle matrix appeared to be the only assemblage present. Within this matrix clay regions were observed predominating over clay-granular regions which were frequently in evidence. Random clay arrays were in evidence within these regions and the matrix grains were mainly finer silt sizes with angular and elongated shapes. Overall, a slight tendancy for horizontal orientation of the elongated silt grains was just detectable. Mics. 5.14.(c) and (d) present detailed views of the matrix and both clay and clay-granular regions can be clearly identified.

(c) Basic pore spaces - Fig. 5.14.(c): the intra-elemental pores associated with the clay arrangements, e.g. Mics. 5.14.(a) and (b), were observed dominating the pore space and only a small contribution from intra-assemblage pores was apparent.

(d) Composite microfabric: Mic. 5.14.(e) serves to illustrate the uniform and fine texture of the composite microfabric.

(e) Anisotropy within composite microfabric - Fig. 5.14.(d): the microfabric appeared to be isotropic at each of the levels considered.

5.9. BOSTON, U.S.A.

5.9.1. General Background.

A bulk sample of the Boston Blue Clay deposits from Cambridge, Massachussetts has been included. These deposits were formed in late-glacial times when material was transported by streams of melting Pleistocene glaciers and deposited in the quite marine-brackish waters of the Boston Basin, in post-depositional times the clay deposits were elevated by isostatic uplift, subjected to weathering and erosion and subsequently resubmerged, Crosby (1934), Skempton (1948). The Boston Blue deposit is typically 25 m thick and varies from being stiff and often weathered yellow at the top to being soft homogeneous and blue in colour at depth. The sample selected is a typical example of the soft blue clay and is classified as a lightly over consolidated, inorganic clay of high plasticity. The clay fraction of the blue clay is reported to consist of mainly illite, with significant amounts of chlorite and quartz, Mitchell (1956).

5.9.2. Microfabric Characterisation.

(a) Elementary particle arrangements - Fig. 5.15.(a): clay arrangements were observed to be the dominant arrangements present and both the random and parallel types appeared to be equally abundant. The clay particles comprising these arrangements were both plate shaped groups and individuals with fine and coarse clay sizes. Detailed views, illustrating the typical nature and constituent particles of the clay arrangements are given in Mics. 5.15.(a), and (b). The former shows a predominantly parallel array whereas the latter shows a predominantly random array. Clean grain-grain arrangements were occasionally in evidence, e.g. Mic. 5.15.(b) with the grains involved being the finer silt sizes with flaky, elongated and angular shapes.

(b) Particle assemblages - Fig. 5.15.(b): a matrix appeared to be the only assemblage present and within this assemblage, clay-granular regions predominated over clay regions which were frequently observable. Within the regions, no predominance of either random or parallel clay arrays was in evidence, and isolated grain-grain contacts were occasionally observable. Where present the parallel arrays displayed strong preferred orientation towards the horizontal. The matrix grains were medium and fine silt sizes with flaky, elongated and angular shapes, and were strongly orientated towards the horizontal. Mic. 5.15.(c) presents a detailed view of the matrix to illustrate these various features.

(c) Basic pore spaces - Fig. 5.15.(c): the intra-elemental pores particularly those associated with the clay arrangements, e.g. Mics. 5.15.(a) and (b), appeared to dominate the pore space. A relatively small contribution from intra-assemblage pores was also in evidence.

(d) Composite microfabric: the typical character and texture of the composite microfabric at two levels of magnification are clearly illustrated by Mics. 5.15.(d) and (e).

(e) Anisotropy within composite microfabric - Fig. 5.15.(d): the microfabric at the 500μ level and 50μ level appeared to possess a medium degree of anisotropy. At the 5μ level more or less half the microfabric appeared to possess nil anisotropy, while the rest appeared to possess very high anisotropy. The direction of preferred orientation was horizontal in all cases.

Part (c) Freshwater Deposits

5.10. TUCSON, U.S.A.

5.10.1. General Background.

A bulk sample of a recent alluvial floodplain deposit from Tucson, Arizona, has been included. This deposit was formed as an outwash floodplain between the Santa Cruz River and the Tucson Mountain foothills, and in the present arid to semi-arid climate the water table is at a considerable depth below ground level, Sultan (1969). The shallow deposits are therefore desiccated and over consolidated and contain small desiccation cracks or fissures at the surface. The sample selected was a stiff, brown, calcareous silty clay and is classified as an organic clay of high plasticity. The clay fraction consists mainly of montmorillonite. Laboratory studies have shown that the Tucson silty clay has low compressibility in the undisturbed state, and is potentially capable of exhibiting the dual behaviour of expansion and collapse, Sultan (1969).

5.10.2. Microfabric Characterisation.

(a) Elementary particle arrangements - Fig. 5.16.(a); clothed grain-grain contacts were observed to be the predominant arrangements present although clay arrangements were also more than occasionally in evidence. The grains involved in the former arrangements were fine sand and silt sizes with mainly irregular and elongated shapes. Both closely and relatively loosely packed arrangements were apparent. The clay arrangements present were predominantly of the partly discernible type generally displaying some crinkled edges. Random clay arrangements composed of bulky shaped coarse clay size individuals were occasionally observable.

(b) Particle assemblages - Fig. 5.16.(b): a complex assemblage network was apparent with matrix, connector and aggregation systems all frequently observable. The matrix was found to be predominantly granular, although clay regions consisting of random clay arrays were rarely observable. No preferred orientation of the matrix grains was apparent. The connector assemblages were found bridging and buttressing sand and silt particles and consisting mainly of partly discernible particle arrays. Regular silt and fine sand size aggregations were observed consisting generally either of a confused mixture of grain and clay arrangements or of partly discernible particle arrangements alone. Sometimes aggregations were present within larger aggregations. Aggregations were found interacting directly with each other and with both matrix and connected grains.

(c) Basic pore spaces - Fig. 5.16.(c): the inter-assemblage pores associated with the occurrence of the aggregation and connector assemblages were found dominating the pore space. The intra-elemental pores, however, and in particular those associated with the granular arrangements appeared to account for a considerable proportion of the pore space.

(d) Composite microfabric: Detailed and general views of the composite microfabric are given in Mics. 5.16.(a) and (b) respectively. A wide variety of microfabric forms including two irregular shaped trans-assemblage pores are present, and these are clearly indicated.

(e) Anisotropy within composite microfabric - Fig. 5.16.(d): the microfabric was apparently isotropic at each of the levels considered. The 50 μ level was inappropriate to the grain arrangements in many cases due to the grain sizes involved.

5.11. MARICOPA, U.S.A.

5.11.1. General Background.

A bulk sample of a mudflow deposit from a site at Maricopa in the San Joaquin Valley, California, has been included. This deposit is typical of the mudflow deposits found in the general area of the western and southern parts of the San Joaquin Valley and described by Bull (1964) and Dudley (1970). It was deposited in recent times by a viscous mudflow derived from a small water shed, subject to cloud bursts at infrequent intervals. The slurry so formed subsequently dried out and the deposit is therefore highly over consolidated and desiccated. The sample selected was a yellow homogeneous poorly sorted clayey, silty, sandy material containing roots and some preferentially orientated flaky or elongated gravel particles. The clay fraction is reported to consist predominently of montmorillonite. The deposit is classified as an inorganic soil of low plasticity. The Maricopa deposit is also a typical example of the collapsing soils which are frequently encountered in the San Joaquin Valley, Dudley (1970).

5.11.2. Microfabric Characterisation.

(a) Elementary particle arrangements - Fig. 5.17.(a): grain-grain contacts were observed to be the dominant arrangements present and both the clothed and clean types appeared to be equally abundant. The grains involved were mainly silt sized with flaky, elongated and irregular shapes and both closely and relatively loosely packed arrangements were apparent, as illustrated by Mics. 5.17.(a) and (b). Clay arrangements were also occasionally observable and both partly discernible particle arrangements and random particle arrangements composed of coarse clay size individuals appeared to be equally as prominent. Within the former arrangements generally, relatively few edges were apparent but where present, these appeared to be non crinkled in nature. The general nature of the various clay arrangements can be appreciated from Mic. 5.17.(c).

(b) Particle assemblages - Fig. 5.17.(b): a matrix, wherein granular regions predominated over clay regions which were rarely observable, was observed to be the dominant assemblage present. The grain regions were variable in texture and sometimes consisted of closely packed clothed grain-grain contacts, Mic. 5.17.(a), and in other cases of loosely arranged clean grain-grain contacts, Mic. 5.17.(b). No preferred orientation of the grains was apparent. The clay regions were comprised of random and partly discernible clay arrays and their typical character may be appreciated from Mic. 5.17.(c). A rather open clay region is also shown in Mic. 5.17.(d). Aggregations, more or less regular in shape, were also frequently in evidence and these were found interacting directly with each other and also the matrix grains and consisting of a confused mixture of clay arrangements as indicated by Mic. 5.17.(e).

(c) Basic pore spaces - Fig. 5.17.(c): the intra-elemental pores, and in particular those associated with the grain-grain arrangements, e.g. Mic. 5.17.(a) and (b), appeared to dominate the pore space. The inter-assemblage pores formed by aggregate interaction, Mic. 5.17.(e) also accounted for a considerable proportion of the pore space. Intra-assemblage pores associated mainly with the rather open clay regions, Mic. 5.17.(d), were considered to account for a small proportion of the pore space.

(d) Composite microfabric: the general nature and texture of the composite microfabric are illustrated by Mic. 5.17.(f).

(e) Anisotropy within composite microfabric - Fig. 5.17.(d): the microfabric was apparently isotropic at each of the levels considered. The 50 μ level was sometimes inappropriate to the grain arrangements due to the grain sizes involved.

5.12. LYDDA, HOLON, AFULAH, ISRAEL.

5.12.1. General Background.

Bulk samples of three recent alluvial floodplain deposits from Lydda and Holon in the west of Israel, and Afulah in the north, are included. They were derived from the weathering of limestone or basaltic rocks on the adjacent hills and under the present humid to sub-humid mediterranean climate a deep groundwater level ordinarily exists and the deposits have been over consolidated and desiccated, Kassiff et al (1965). The Lydda, Holon and Afulah samples were found to have degrees of saturation of around 75%, 93% and 97% respectively, and were fairly stiff calcareous (12, 17 and 16% $CaCo_3$), light to dark brown in colour, slickensided and contained some small limestone nodules. Their clay fractions are known to consist predominently of montmorillonite. From the geotechnical point of view, the Lydda sample is classified as an inorganic silty clay of low plasticity and the Holon and Afulah samples are classified as inorganic clays of high plasticity. A number of field and laboratory studies, Komornick et al (1969), Frydman (1972) have shown that the three deposits are representative of the well known Israeli expansive soils.

5.12.2. Microfabric Characterisation.

5.12.2.1. Lydda.

(a) Elementary particle arrangements - Fig. 5.18.(a): clay arrangements were observed to be the dominant arrangements present, with clothed grain-grain contacts also occasionally observable. The clay arrangements were partly discernible in character with some arrangements displaying relatively few edges and others showing numerous edges. These edges where present, possessed crinkled forms generally. The general nature of these arrangements may be taken to be similar to that illustrated by Mic. 5.19. of the Holon deposit. The grain-grain contacts appeared to involve mainly fine sand and coarse silt size particles which were mainly irregular but also rounded and elongated in shape as indicated by Mic. 5.18.(b). Both relatively loosely and closely packed arrangements were apparent.

(b) Particle assemblages - Fig. 5.18.(b): a complex assemblage system was apparent which was dominated by a matrix and within which connectors were occasionally and aggregations were rarely to be found. Within the matrix clay-granular regions, very open in places, were found predominating over grain regions which were occasionally in evidence. Typical examples of these regions are given in Mic. 5.18.(a) and (b) respectively. The clayey parts of the matrix consisted of the partly discernible clay arrays and the embedded matrix grains were medium-fine sand sizes with mainly irregular but also rounded and elongated shapes. The connector assemblages were found bridging and buttressing fine sand and silt particles and composed generally of partly discernible particle arrays as indicated by Mic. 5.18.(c). The regular fine sand size aggregations were found generally interacting directly with the nearby matrix and consisting of connector systems, as shown by Mic. 5.18.(d).

(c) Basic pore spaces - Fig. 5.18.(c): the pore space appeared to be dominated by the intra-elemental pore arrangements associated with the clay arrangements and the grain arrangements. The intra-assemblage pores present in the open clayey regions were considered to account for an appreciable proportion of the pore space. Only a relatively small contribution was apparent from inter-assemblage pores, Mic. 5.18.(c).

(d) Composite microfabric: detailed views of two portions of the composite microfabric, which display contrasting coarse and relatively fine textures, are presented in Mic. 5.18.(e). The occurrence of irregular trans-assemblage pores is apparent in the fine textured region.

(e) Anisotropy within composite microfabric - Fig. 5.18.(d): the microfabric appeared to be isotropic in character at each of the levels considered.

5.12.2.2. Holon.

(a) Elementary particle arrangements - Fig. 5.19.(a): clay arrangements appeared to be the only arrangements present and these were found to be predominantly partly discernible in character with some arrangements displaying relatively few edges, Mic. 5.19.(a) and others displaying numerous edges, Mic. 5.19.(b). These edges were crinkled in form generally. Random clay arrangements were observable, although relatively rarely, and where present appeared to be composed of fine-coarse clay sized bulky shaped individuals.

(b) Particle assemblages - Fig. 5.19.(b): a matrix appeared to be the dominant assemblage present with aggregations also occasionally observable. Within the matrix, clay regions, often very open, as indicated by Mic. 5.19.(c), were found to be predominant although clay-granular regions were also frequently present. The various regions consisted essentially of partly discernible clay arrays and the embedded matrix grains were silt and fine sand sizes with mainly irregular and almost rounded shapes. The rather homogeneous nature of the matrix is demonstrated by Mics. 5.19.(d) and (e) which show at the same level of magnification, an open clay region and a dense clay-granular region respectively. The regular silt and fine size aggregations consisted mainly of partly discernible particle arrays and were found interacting directly with each other and also the surrounding clayey matrix, as shown by Mic. 5.19.(f).

(c) Basic pore spaces - Fig. 5.19.(c): the intra-elemental pores and intra-assemblage pores, e.g. Mic. 5.19.(b) and (c), associated with the very open matrix regions each appeared to form a considerable proportion of the pore space. Inter-assemblage pores, Mic. 5.19.(f), were observed forming a small proportion of the pore space.

(d) Composite microfabric: a typical view of the composite microfabric is presented in Mic. 5.19.(g), and the occurrence of a wavy trans-assemblage pore is clearly indicated.

(e) Anisotropy within composite microfabric - Fig. 5.19.(d): the microfabric appeared to be isotropic at each of the levels considered.

5.12.2.3. Afulah.

(a) Elementary particle arrangements - Fig. 5.20.(a): clay arrangements were observed to be the dominant arrangements present, with clothed grain-grain contacts also rarely observable. The former arrangements were partly discernible in character with some arrangements displaying relatively few edges and others displaying numerous edges. These edges where present, possessed crinkled forms generally. The detailed nature of the clay arrangements were found to be similar to those of the Holon deposit, Mics. 5.19.(a) and (b). The grain-grain contacts involved medium-fine silt size grains which were elongated and angular in shape. These arrangements appeared relatively loosely packed as indicated by Mic. 5.20.(a).

(b) Particle assemblages - Fig. 5.20.(b): a matrix appeared to be the only assemblage type present. Within this matrix, clay regions, very open in places, were found predominating over clay granular and granular regions which were occasionally and rarely present respectively. The clayey part of the matrix consisted of a partly discernible clay array and the embedded matrix grains were mainly coarse silt and fine sand sized with rounded shapes. Mic. 5.20.(b) serves to illustrate the typical character of the matrix and the variation in texture associated with the occurrence of the various differing matrix regions can be easily appreciated.

(c) Basic pore spaces - Fig. 5.20.(c): the pore space appeared to be dominated by the intra-elemental pores, and in particular those associated with the clay arrangements. The intra-assemblage pores, associated with the open clay regions appeared to account for an appreciable proportion of the pore space.

(d) Composite microfabric: Mic. 5.20.(c) serves to illustrate the typical character and texture of the composite microfabric, and once again a wavy trans-assemblage pore is in evidence.

(e) Anisotropy within composite microfabric - Fig. 5.20.(d): the microfabric appeared to be isotropic in character at each of the levels considered.

5.13. HURLFORD, U.K.

5.13.1. General Background.

A bulk sample of lacustrine soil from a site south west of Hurlford, Scotland is included. A detailed account of the geological history and geotechnical properties of this soil has been given by Gabr (1975). It is a typical example of the post-glacial freshwater lake deposits which occur in the Ayrshire region as patches amongst mainly lodgement till deposits and which were formed in the numerous post-glacial lakes which exist between existing glacial drumlins. The upper zone of the deposit from which the bulk sample for this study was taken is reported to be slightly over consolidated ($p'_c \approx 1.4\ p'_o \approx 54\ \mathrm{kN/m^2}$), and finely laminated in places. No layering effects were visible in the present bulk sample. It was a soft to very soft grey brown silty clay being classified as an inorganic medium sensitive ($S_t = 3$) soil of low plasticity.

5.13.2. Microfabric Characterisation.

(a) Elementary particle arrangements - Fig. 5.21.(a): clay arrangements appeared to be the only arrangements present and both parallel and random configurations were frequently observable. Their constituent particles appeared to be mainly coarse clay size and plate-shaped clay groups as demonstrated by Mic. 5.21.(a) which shows a haphazard arrangement of parallel clay arrangements around silt grains at high magnification.

(b) Particle assemblages - Fig. 5.21.(b): a clay-granular matrix appeared to be the only basic assemblage present. Within this matrix, no predominance of either random or parallel arrays was in evidence. Where present the parallel arrays displayed haphazard orientation as shown in Mics. 5.21.(a) and (b). The embedded matrix grains were haphazardly orientated silt sizes with flaky and elongated, but also irregular shapes. The distribution of grain sizes however, was found to be somewhat erratic with some regions containing only the medium and fine silt sizes, e.g. Mic. 5.21.(c) and others containing mainly coarse silt sizes, e.g. Mic. 5.21.(d). The clay-granular matrix was often disrupted by vein assemblages which consisted of parallel clay arrays and orientated silt as shown by Mic. 5.21.(e). Both branching and crossover systems were as illustrated by Mic. 5.21(f). Overall, the individual veins were fairly extensive relative to the specimen boundary and displayed either inclined or horizontal attitudes.

(c) Basic pore spaces - Fig.5.21.(c): the intra-elemental pores, particularly those associated with the random clay arrangements, were found dominating the pore space and only a small contribution from intra-assemblage pores was in evidence.

(d) Composite microfabric: the typical character of the composite microfabric is illustrated by Mic. 5.21.(g) and the rather patchy texture of the clay-granular matrix and the occurrence of the vein systems can be easily appreciated.

(e) Anisotropy within composite microfabric - Fig. 5.21.(d): the microfabric at the 500 μ level appeared to exhibit a low degree of anisotropy, the direction of preferred orientation being in the main towards the horizontal. At the 50 μ level the microfabric seemed to be predominantly isotropic. Approximately half of the microfabric at the 5 μ level displayed very high anisotropy with a range of directions of preferred orientation while the other half exhibited isotropy.

5.14. NEW LISKEARD, CANADA.

5.14.1. General Background.

A bulk sample of the well documented lacustrine varved clay deposits which occur in the vicinity of the town of New Liskeard in Northern Ontario, Canada has been included. Such deposits are believed to have been formed in late-glacial times from sediments transported from melting pleistocene glaciers by streams and deposited in cold fresh melt water, glacial lakes, Milligan et al (1962) and Eden and Bozozuk (1962). Typically, the varved deposit occurs as a thick stratum (33-49 metres) and the individual clay (dark) layers and silty (light) layers of the varves vary in thickness from about 1 mm to 3.8 cm. In bulk, the varved sample was soft in the undisturbed state and is classified as an inorganic soil of high plasticity. Both the dark and the light layers had water contents more or less equal to their liquid limits, and are classified as inorganic soils, but as might be expected the dark (clay) layer is highly plastic, whereas the light (silty) layer exhibits low plasticity. The mechanical properties of compressibility, shear strength and permeability of the varved clay deposits have been investigated by Lo and Stermac (1965), Quigley and Ogunbadijo (1972), Chan and Kenney (1973) and others. They are, geologically speaking normally consolidated but cementing has induced apparent preconsolidation pressures of ($p'_c \approx 2.5\ p'_o \approx 300\ \mathrm{kN/m^2}$) and ($p'_c \approx 2.3\ p'_o \approx 280\ \mathrm{kN/m^2}$) for the dark clayey layer and light silty layers respectively. Cementation has also been held primarily responsible for the medium quickness ($S_t \rightarrow 20$) displayed by this varved clay.

5.14.2. Microfabric Characterisation.

The dark clay layers within the bulk sample all appeared to have the same internal or composite fabric whereas in the case of light silty layers two types of internal organisation were identified, i.e., light type (1) and light type (2). Only macrolayers were identified.

(a) Elementary particle arrangements - Fig. 5.22.(a): within the dark layer random clay arrangements were the only arrangements observable while in both the light layers these predominated over clean grain-grain contacts which were occasionally present. The constituent clay particles of the various clay arrangements appeared to be platey and bulky shaped individuals with very fine-coarse clay sizes and clusters of very fine clay size, Mic. 5.22.(a). Within the dark layer a tendancy for the coarser clay individuals which were found separated by finer clay particle arrangements, to align themselves towards the horizontal, was detectable. The grain-grain contacts involved mainly angular and elongated shaped grains which in light layer (1) were the finer silt sizes, Mic. 5.22.(b), and in light layer (2) were fine-medium silt sizes, Mic. 5.22.(f).

(b) Particle assemblages - Fig. 5.22.(b): within the dark layer a region system was the only assemblage present. This system consisted of clay-regions comprising a random clay array, Mic. 5.22.(c).

Within light layer (1) a more complex basic assemblage network was observed wherein a region system and a connector system were both frequently abundant, Mic. 5.22.(d). The region system comprised mainly clay-granular regions and granular regions often honeycombed were frequently observed. Micro lenses of clay were to be found non-uniformly embedded in this basic assemblage network and these varied in extent with the maximum and minimum thickness being of the order of 200 μ and 10 μ respectively, Mic. 5.22.(e). As shown the long axis of the lenses were orientated towards the horizontal.

Light layer (2) comprised entirely of a region system wherein clay-granular regions predominated over granular and clay regions which were both occasionally abundant, Mic. 5.22.(f).

(c) Basic pore spaces - Fig. 5.22.(c): within the dark layer the intra-elemental pores of the random clay arrangements dominated the pore space and a very small contribution from intra-assemblage pores was in evidence. Within light layer (1) the inter-assemblage pores of the connector systems predominated over the intra-elemental pores of the clay and granular arrays within the matrix. A small contribution was noted from the intra-assemblage pores associated with the honeycombed granular regions. Within light layer (2) the pore space was accounted for entirely by the intra-elemental pores of the clay and granular arrays within the matrix.

(d) Composite microfabric: appreciation of the nature and texture of the composite microfabrics of the individual layers can be gained from the following: Mic. 5.22.(c) - dark layer; Mic. 5.22.(d) and (e) - light layer (1); and Mic. 5.22.(f) - light layer (2). The principal features of the composite layered system can be gained from Mic. 5.22.(g) which shows a thin light layer (2) sandwiched between two clay layers. It is clear that the interface between the clay layer and the overlying silty layer is sharp and irregular in character. In contrast it is difficult to identify an interface between the silty layer and the overlying clay layer, i.e. a diffuse interface is in evidence.

(e) Anisotropy within the microfabric of individual layers, Fig. 5.22.(d): the microfabric within the dark layer displayed a low degree of anisotropy at each of the 5 μ, 50 μ and 500 μ levels. Nil degrees of anisotropy were displayed by the microfabrics of the light layers at the 5 μ and 50 μ levels and by the light layer (2) at the 500 μ level. The microfabric of light layer (1) however, displayed a medium degree of anisotropy at the 500 μ level, in some areas.

SECTION 11 - WIND BORNE DEPOSITS.

5.15. FORD, U.K.

5.15.1. General Background.

A bulk sample of brick earth from a site at Ford in East Kent, England, is included. The Ford brickearth is dated Weichselian and is thought to be a true loess deposited under fairly cold arid conditions, Fookes and Best (1969). The deposit is calcarious at depth and shows in places a tendancy to maintain vertical faces on exposure and prismatic jointing is well seen. The sample selected for the present study was selected from this calcarious zone and possessed certain typical loessial properties. It was buff brown in colour; partly saturated ($<$ 40%) and hard in the undisturbed state; calcareous (20% $CaCo_3$), with no visible fabric apart from some rootlet holes; and had 50% of particles between 10 μ and 50 μ. It also exhibited typical index properties and is classified as an inorganic clayey silt of low plasticity. The sample however, also displayed the non-typical loessial properties of relatively low void ratio (approx. 0.75) and moderately high density, and this suggests possibly some previous collapse of the deposit. Despite this possibility, laboratory studies have shown that the Ford loess is still a potentially collapsible deposit, Fookes and Best (1969).

5.15.2. Microfabric Characterisation.

(a) Elementary particle arrangements - Fig. 5.23.(a): grain-grain contacts were observed to be the dominant arrangements present and clay arrangements were occasionally in evidence. The grain arrangements were mainly of the clothed type although clean arrangements were also frequently observable. As can be appreciated from Mics. 5.23.(a) and (b), the grains involved were silt sizes with mainly elongated and irregular shapes, and both closely and relatively loosely packed arrangements were apparent. The clay arrangements were predominantly partly discernible in character displaying few non-crinkled edges, and random clay arrangements were occasionally observable. The latter arrangements were apparently composed of coarse clay size individuals. The general nature of the clay arrangements can be appreciated from Mics. 5.23.(c) and (d).

(b) Particle assemblages - Fig. 5.23.(b): a granular matrix wherein haphazard orientation of the grains was in evidence, appeared to be the dominant assemblage present, although connectors were also frequently observable. The matrix was not entirely uniform and some areas were much finer than others as demonstrated by the contrasting textures of the granular regions shown in Mics. 5.23.(a) and (b). The connectors were predominantly of the buttress type although bridges were also frequently in evidence. The former were observed consisting usually of partly discernible clay arrangements, but also random clay arrangements, whereas the latter consisted usually of random clay arrangements. The occurrence and internal organisation of the various connector types can be appreciated from Mics. 5.23.(c) and (d). Regular silt size aggregations were rarely apparent, but where present were found to be composed generally of partly discernible particle arrays and observed interacting directly with both the matrix and the connected grains, as shown in Mic. 5.23.(d).

(c) Basic pore spaces - Fig. 5.23.(c): the intra-elemental pores particularly those associated with the grain-grain arrangements, Mic. 5.23.(a), appeared to dominate the pore space although the inter-assemblage pores present, e.g. Mic. 5.23.(d) were considered to account for a considerable proportion of the pore space. Overall, only a small contribution from intra-assemblage pores was apparent.

(d) Composite microfabric: the general nature and rather patchy texture of the composite microfabric are clearly illustrated by Mic. 5.23.(e). The occurrence of a very large irregular trans-assemblage pore is also illustrated.

(e) Anisotropy within composite microfabric - Fig. 5.23.(d): the microfabric appeared to be isotropic in character at each of the levels considered. The 50 µ level was inappropriate in many cases because of the particle sizes involved.

5.16. TONGRINNE, BELGIUM.

5.16.1. General Background.

A bulk sample of loess from a site at Tongrinne, is included. This soil is a typical example of the well known European loessial deposits and was formed during the maximum stage of Weichsel Glaciation in cold and dry conditions. The sample selected was yellow brown in colour, slightly carbonatious partly saturated and slightly mottled as a result of post-depositional weathering, Mellors (1971). Geotechnically, it is described as an inorganic clayey silt of low plasticity, and may be considered as potentially collapsible.

5.16.2. Microfabric Characterisation.

(a) Elementary particle arrangements - Fig. 5.24.(a): grain-grain contacts appeared to be the dominant arrangements present with clay arrangements also occasionally in evidence. The former were of both the clothed and the clean variety and the grains involved were silt sizes with mainly irregular and elongated, but also flaky shapes. Mic. 5.24.(d) serves to illustrate the general nature of these arrangements. Both closely and relatively loosely packed arrangements were apparent. The clay arrangements were parallel in character, and involved wavy groups of coarse clay size.

(b) Particle assemblages - Fig. 5.24.(b): a granular matrix wherein a haphazard orientation of grains was in evidence, and a connector system, were both frequently abundant and interacted to form a uniformly textured microfabric. The connectors were observed to be mainly of the bridge type, often extremely thin and tenuous and composed of parallel clay arrangements, as illustrated by Mic. 5.24.(a). Fine silt particles also interacted to form such assemblages in some cases as shown in Mic. 5.24.(b). A general view, illustrating the general nature of the connector system, is presented in Mic. 5.24.(c). In contrast to this Mic. 5.24.(d) shows a granular matrix region wherein relatively clean grain-grain contacts are in evidence.

(c) Basic pore spaces - Fig. 5.24.(c): the intra-elemental pores particularly those associated with the grain-grain arrangements, Mic. 5.24.(d), and the inter-assemblage pores within the connector systems, Mic. 5.24.(a), each appeared to form a considerable proportion of the pore space. Only a small contribution was evident from intra-assemblage pores.

(d) Composite microfabric: the highly uniform and fine texture of the composite microfabric can be easily appreciated from Mic. 5.24.(e).

(e) Anisotropy within composite microfabric - Fig. 5.24.(d): the microfabric appeared to be isotropic at both the 500 μ and the 50 μ levels although because of the grain sizes involved the 50 μ level was inappropriate in many cases. At the 5 μ level, high degrees of anisotropy were displayed.

5.17. TRANSVAAL, S.A.

5.17.1. General Background.

A bulk sample of the well known and extensive red aeolian collapsing sand deposits of the Transvaal has been included. These deposits were formed in pleistocene times in arid environments, and have a maximum depth of about 6 m, Jennings and Knight (1957). Insitu weathering under more humid conditions has resulted in the authigenic production of kaolinite and iron oxides. The latter are responsible for the red colouration of the sand. The selected sample was partly saturated ($<$ 40%), friable, had no visible fabric, a void ratio of about 0.85. and is classified as a clayey sand with slightly plastic fines.

5.17.2. Microfabric Characterisation.

(a) Elementary particle arrangements - Fig. 5.25.(a): thickly clothed grain-grain contacts were observed to be the dominant arrangements present, and these were to be found both closely and loosely packed. The grains involved were mainly medium-fine sand and coarse silt sizes. The coarsest grains were generally rounded in shape whereas the finer grains were rounded, irregular and elongated in shape. A very small amount of root material was often in evidence at grain-grain contact points. A detailed view of a grain-grain contact is given in Mic. 5.25.(a). Clay arrangements were occasionally observed being partly discernible in character, generally displaying a few non crinkled edges.

(b) Particle assemblages - Fig. 5.25.(b): a granular matrix appeared to be the dominant assemblage present. The degree of openness and the distribution of grain sizes within this matrix, were found to be non-uniform in character, and Mic. 5.25.(b) shows a coarse and rather open granular region. Regular fine sand and silt size aggregations were to be found interacting directly with each other and the matrix grains. The aggregations appeared generally to consist entirely of partly discernible clay arrays, although as suggested by Mic. 5.25.(c), some of the aggregations appeared to be composed of a mixture of finer aggregations and connected grains. Connectors were also occasionally found spanning sand and silt particles with the bridge and buttress types being equally abundant, and composed of partly discernible particle arrays. A typical buttress connector is illustrated by Mic. 5.25.(d).

(c) Basic pore spaces - Fig. 5.25.(c): the intra-elemental pores of the grain-grain arrangements, Mic. 5.25.(b), appeared to dominate the pore space while the various inter-assemblage pores, e.g. Mic. 5.25.(c) and (d) appeared to account for an appreciable proportion of the pore space. Overall, only a small contribution was apparent from intra-assemblage pores.

(d) Composite microfabric: the coarse and rather patchy texture of the composite microfabric is clearly illustrated by Mic. 5.25.(e). Although not shown in this view, irregular trans-assemblage pores were in evidence in places.

(e) Anisotropy within composite microfabric - Fig. 5.25.(d): the microfabric was apparently isotropic at each of the levels considered. Because of the grain sizes involved the 50 μ and 5 μ levels were generally inappropriate.

SECTION 111 - GLACIAL DEPOSITS.

5.18. HURLFORD, U.K.

5.18.1. General Background.

Samples of glacial till are included from the Barleith drumlin which is situated in the Hurlford region, Ayrshire, some 30 Km. south west of Glasgow, Scotland. The Barleith drumlin is composed of unstratified glacial basal lodgement till which was deposited as a result of successive glaciations during the last (or Weichselian) glaciation of Northern Europe, George (1958). The drumlin axis is aligned in a W.15.S. direction and was probably shaped by easterly flowing ice, McGown et al (1974).

The drumlin till is known to have been derived from nearby Barren Red Measure Sandstone, bedrock, Mitchell and Jarvis (1956). The soil character and profile at the Barleith drumlin site have been discussed and described by McGown et al (1974). They reported the profile as consisting of a weathered till zone some 3 m. thick which had overlays a deep unweathered deposit of red-brown lodgement till. The till was shown to be fissured throughout this profile and a very definite fissure pattern was identified.

Two samples were selected for the present study, the first from within the weathered zone at a depth of 2 m. and the second from within the unweathered zone at a depth of 12 m. Both samples were very stiff and fissured in the undisturbed state and had low water contents. They were essentially fully saturated with the weathered sample being the wetter of the two. As might be expected, the deeper unweathered sample was the denser of the two. As regards grading characteristics, both samples were found containing a range of particle sizes from boulder down to clay, thus the commonly used term 'boulder clay' with the weathered sample being the finer of the two. According to McGown et al (1975), the tills of West Central Scotland display multi-modal grading characteristics with the dominant mode occurring in the fine or medium sand class and subsidiary ones occurring in the gravel and medium silt fractions. According to the U.S.C.S. both the weathered and unweathered till samples are poorly graded gravel, sand clay mixtures having low plasticity fines with the weathered sample being the more plastic of the two.

5.18.2. Microfabric Characterisation.

5.18.2.1. Weathered Zone.

(a) Elementary particle arrangements - Fig. 5.26.(a): clay arrangements were observed predominating over grain-grain contacts which were occasionally in evidence. The former arrangements were predominantly parallel in character and random arrangements were only rarely observable. Their constituent particles appeared to be mainly plate shaped clay groups but also bulky and platey shaped individuals with fine and coarse clay sizes, as indicated in Mic. 5.26.(a) which shows parallel clay arrangements at high magnification. The grains involved in the grain-grain contacts were silt sized and generally clean and angular in shape, as shown by Mic. 5.26.(e).

(b) Particle assemblages - Fig. 5.26.(b): a matrix, wherein clay-granular regions predominated over granular regions which were occasionally in evidence, was found to be the only assemblage present. The clay-granular portion of the matrix consisted overall, of a predominantly parallel clay array displaying haphazard orientation and the embedded matrix grains, which were also haphazardly arranged, were silt and fine sand sizes with irregular elongated and flaky shapes. Fine sand particles in certain cases appeared to be in a state of decomposition, e.g. Mic. 5.26.(f) Mics. 5.26.(b) and (c) serve to demonstrate the extremes of organisation to be found within the clay-granular portion of the matrix. Furthermore, Mics. 5.26.(d) and (e) serve to illustrate the widely differing textures of the clay-granular and granular portions of the matrix respectively.

(c) Basic pore spaces - Fig. 5.26.(c): the pore space appeared to be wholly accounted for by the intra-elemental pores associated with both the clay and grain arrangements.

(d) Composite microfabric: the typical nature and texture of the composite microfabric are illustrated by Mic. 5.26.(f).

(e) Anisotropy within composite microfabric - Fig. 5.26.(d): the microfabric appeared to be isotropic at the 500 μ level. At the 50 μ level roughly half the microfabric displayed high anisotropy while the remainder displayed nil anisotropy. The vast proportion of the microfabric at the 5 μ level displayed a very high degree of anisotropy.

5.18.2.2. Unweathered Zone.

(a) Elementary particle arrangements - Fig. 5.27.(a): parallel clay arrangements appeared to be the only arrangements present and were observed consisting mainly of plate shaped clay groups but also bulky and platey shaped individuals with fine and coarse clay sizes, Mic. 5.27.(a).

(b) Particle assemblages - Fig. 5.27.(b): a clay-granular matrix appeared to be the only assemblage present. Overall, a parallel clay array displaying moderate preferred orientation towards the horizontal, was in evidence, and the embedded matrix grains were silt and fine sand sizes with mainly elongated and irregular shapes. The elongated grains displayed moderate preferred orientation overall, Mic. 5.27.(a) and (b) show a portion of the matrix wherein a parallel clay array and silt grains display strong preferred orientation towards the horizontal. In other regions the direction of preferred orientation was away from the horizontal, similar to that shown by Mic. 5.26.(c) and in other cases haphazard parallel arrays similar to that shown in Mic. 5.26.(b) were in evidence.

(c) Basic pore spaces - Fig. 5.27.(c): the pore space appeared to be wholly accounted for by the intra-elemental pores of the parallel clay arrangements.

(d) Composite microfabric: the typical nature and texture of the composite microfabric are illustrated by Mic. 5.27.(c).

(e) Anisotropy within composite microfabric - Fig. 5.27.(d): at the 500µ level roughly half the microfabric displayed high anisotropy while the remainder displayed nil anisotropy. Similarly, the major portion of the microfabric at the 50µ level possessed high anisotropy with the remainder displaying nil anisotropy. The microfabric at the 5µ level displayed very high anisotropy throughout.

5.19. GLEN ORCHY AND LAGLINGARTEN, U.K.

5.19.1. General Background.

Bulk samples of two basal melt out tills from sites at Glen Orchy and Laglingarten within the Cowal district of Argyll, have been included. These deposits were laid down by one of the readvancing pleistocene glaciers in late-glacial times and are the direct product of ice comminution, McGown (1975). They are known to be normally consolidated and to display a tendancy towards collapse or flow under certain conditions of topography, applied stress or wetting. Both samples selected were very loose and had no visible fabric and low water contents. The Glen Orchy sample is classified as a poorly graded gravel-sand-silt mixture and the Laglingarten sample classified as a poorly graded sand-silt mixture. In fact, they were both found to have multi-modal grading characteristics with the split occurring in the sand size fraction, McGown (1975).

5.19.2. Microfabric Characterisation.

5.19.2.1. Glen Orchy.

(a) Elementary particle arrangements - Fig. 5.28.(a): grain-grain contacts were the only arrangements observed and these were predominantly clean in character with clothed arrangements also occasionally in evidence. The grains involved were mainly medium-fine sand with some silt sizes, and generally were irregular, angular and elongated in shape. Some very thin and apparently transparent flaky particles were observed in the finer silt size range. Both closely and relatively loosely packed arrangements were apparent. Mic. 5.28.(a) serves to illustrate the general nature and constituent grains of the grain-grain arrangements.

(b) Particle assemblages - Fig. 5.28.(b): A granular matrix very open in places, appeared to be the dominant assemblage present. As demonstrated by Mic. 5.28.(a), the distribution of grain sizes within this matrix was found to be non-uniform in character and no preferred orientation of the grains was apparent. Both connector and aggregation assemblages were also occasionally in evidence. The connectors were found bridging and buttressing sand particles and consisting of haphazardly orientated silt particles, with some composed of coarser silt sizes and others composed of finer silt sizes, Mic. 5.28.(b) shows a buttress type connector consisting of coarse silt size grains. The aggregations, which were of both the regular and irregular type, were of silt and very fine sand size and were found interacting directly with the matrix grains, as indicated by Mic. 5.28.(c). Mic. 5.28.(d) serves to illustrate more clearly the occurrence of the connector and aggregation assemblages within the composite microfabric.

(c) Basic pore spaces - Fig. 5.28.(c): the intra-elemental pores of the grain-grain arrangements, e.g. Mic. 5.28.(a), were found to dominate the pore space with appreciable contributions coming from both the intra-assemblage, Mic. 5.28(a) and inter-assemblage pores, e.g. Mic. 5.28.(b).

(d) Composite microfabric: a typical view of the composite microfabric is presented in Mic. 5.28.(c) and an extremely patchy texture is quite apparent.

(e) Anisotropy within composite microfabric - Fig. 5.28.(d): the microfabric appeared to be isotropic at the 500 μ level. Because of the grain sizes involved the 50 μ level was generally inappropriate and since no clay arrangements were in evidence, the 5 μ level was also inappropriate.

5.19.2.2. Laglingarten.

(a) Elementary particle arrangements - Fig. 5.29.(a): grain-grain contacts were the only arrangements observed and these were predominantly relatively clean in character with clothed arrangements also occasionally in evidence. The grains involved were mainly silt sizes with mainly flaky and elongated, but also irregular shapes. The flaky micaceous particles in the finer size range were very thin and appeared to be almost transparent, as demonstrated by Mic. 5.29.(a). Mainly closely packed, but also some relatively loosely packed arrangements were apparent and in some cases face-face association of the grains was in evidence, e.g. Mic. 5.29.(b). Mic. 5.29.(c) serves to illustrate better the range of grain sizes, shapes and textures involved in the grain-grain arrangements.

(b) Particle assemblages - Fig. 5.29.(b): a granular matrix appeared to be the only basic assemblage present. A detailed view of this matrix is presented in Mic. 5.29.(c), which shows fine sand size matrix grains generally clothed and irregular in shape floating in a finer grain array which appears to be fairly uniform in texture, and rather open in places. A more general view of this matrix region is given in Mic. 5.29.(d). Overall, there appeared to be a tendancy for the flaky and elongated matrix silt grains to be preferentially orientated in a crosswise pattern, and this is also detectable in Mic. 5.29.(c). The matrix was disrupted in places by individual vein assemblages, rather short in length, which displayed overall, a similar crosswise orientation pattern, and were observed consisting of parallel orientated grains. A typical portion of such a vein is shown in Mic. 5.29.(b).

(c) Basic pore spaces - Fig. 5.29.(c): the intra-elemental pores of the grain-grain arrangements were observed dominating the pore space and only a small proportion of the pore space appeared to be accounted for by intra-assemblage pores, e.g. Mic. 5.29.(c).

(d) Composite microfabric: a general view of the composite microfabric is presented in Mic. 5.29.(e) and relatively uniform texture is apparent. The presence of an individual vein feature on the diagonal of the micrograph can just be detected.

(e) Anisotropy within composite microfabric - Fig. 5.29.(d): the microfabric at the 500 µ level appeared to display a low degree of anisotropy. The 50 u and 5 u levels were essentially inappropriate.

5.20. BREIDAMERKURJOKULL, ICELAND.

5.20.1. General Background.

A bulk sample of glacial till from the pro-glacial area of the Breidamerkurjokull glacier at central Breida is included. The geology and glaciology of the glacier and its associated till deposits have been discussed in detail by Price (1969). The pro-glacial till surface is in fact, characterised by widespread flutings rarely standing more than 0.5.m. above general ground level. Analysis of grading curves has confirmed that these deposits are admixtures of glacio-fluvial gravels, melt out tills and lodgement tills and that they are not the direct products of ice comminution, McGown (1975). The sample selected had a low water content and displayed an orthogonal system of joints in the undisturbed dry state. It is classified as a poorly graded sand silt mixture, and is known to exhibit collapsing behaviour.

5.20.2. Microfabric Characterisation.

(a) Elementary particle arrangements - Fig. 5.30.(a): grain-grain contacts were observed to be the dominant arrangements present although clay arrangements were also occasionally observable. The former arrangements were of the clothed type and the grains involved were mainly medium-fine silt sizes with irregular and angular shapes as indicated on Mic. 5.30.(b). Both relatively loosely and closely packed arrangements were observable. The clay arrangements were random in character and appeared to involve bulky shaped individuals of coarse clay size as illustrated by Mic. 5.30.(a).

(b) Particle assemblages - Fig. 5.30.(b): matrix and aggregation assemblages were both frequently observable and interacted to form a fairly uniform and fine textured microfabric. Irregularly shaped medium sized sand grains were observed floating in this assemblage network. Within the matrix, granular regions predominated with some being finer than others and clay-granular regions were occasionally in evidence. The rather heterogeneous texture of the matrix, arising from the interaction of the various regions, can be appreciated from the view presented in Mic. 5.30.(b). The aggregations were more or less regular in shape and silt sized. They appeared to consist generally of a mixture of random clay arrangements, and grain-grain contacts, and were observed interacting directly with each other and the matrix grains. Mic. 5.30.(c) serves to illustrate their general nature and occurrence.

(c) Basic pore spaces - Fig. 5.30.(c): the intra-elemental pores, particularly those associated with the grain arrangements, Mic. 5.30.(b), and the inter-assemblage pores of the aggregation system, Mic. 5.30.(c), each appeared to form a considerable proportion of the pore space. Only a small contribution from intra-assemblage pores was apparent.

(d) Composite microfabric: Mic. 5.30.(d) serves to illustrate the fairly uniform and fine textured assemblage network and the occurrence of several irregular trans-assemblage pores within the composite microfabric.

(e) Anisotropy within composite microfabric - Fig. 5.30.(d): the microfabric appeared to be isotropic at each of the levels considered.

5.21. STOCKHOLM, SWEDEN.

5.21.2. General Background.

A bulk sample of a basal melt out till from a site at Karrdal, Stockholm is included. This deposit was formed in the pleistocene age and is typical of the tills on the Archean bedrock in Sweden. Mollar and Stulhos (1965). Analysis of grading curves has confirmed that this till is the direct product of ice comminution, McGown (1973). It has also been known to exhibit collapsing behaviour. The selected sample had a very low water content, and possessed multi modal grading characteristics with the split occurring in the fine gravel fraction, McGown (1973). It is classified as a poorly graded sand-silt mixture.

5.21.3. Microfabric Characterisation.

(a) Elementary particle arrangements - Fig. 5.31.(a): grain-grain contacts were the only arrangements observed and these were predominantly clean in character with clothed arrangements rarely in evidence. The grains involved ranged from fine silt size, e.g. Mic. 5.31.(a), up to very fine sand size, e.g. Mic. 5.31.(b), and were irregular, elongated, flaky and angular in shape. Both closely and relatively loosely packed arrangements were apparent.

(b) Particle assemblages - Fig. 5.31.(b): a granular matrix, very open in places, appeared to be the only assemblage present. As clearly illustrated by Mic. 5.31(b), the distribution of grain sizes within the matrix was found to be non-uniform in character. Overall, the coarse matrix silt grains appeared to be preferentially orientated in a crosswise pattern with a dominant mode being apparent, as indicated by Mic. 5.31.(b). The finer silt grains however, were haphazardly orientated as indicated in Mic. 5.31.(a).

(c) Basic pore spaces - Fig. 5.31.(c): the intra-elemental pores of the grain-grain arrangements were observed dominating the pore space with an appreciable contribution coming from intra-assemblage pores associated with the open areas within the matrix, e.g. Mic. 5.31.(b).

(d) Composite microfabric: a typical view of the rather coarse textured microfabric is presented in Mic. 5.31.(c). As shown numerous sand grains are embedded in the finer textured grain matrix and these display preferred orientation in a crosswise direction. A dominant mode is apparent and coincides in direction with that of the coarse matrix silt pattern.

(e) Anisotropy within composite microfabric - Fig. 5.31.(d): the microfabric appeared to possess a low and nil degrees of anisotropy at the 500μ and 50μ levels respectively. Because of the grain sizes involved, both the 500μ and 50μ levels were found to be inappropriate to many parts of the microfabric. The 5μ level was inappropriate throughout.

5.22. TAYLOR VALLEY, ANTARCTICA.

5.22.1. General Background.

A bulk sample of glacial melt out till from the pro-glacial area of the Lacroix Glacier in the Taylor Valley is included. With the pro-glacial area basal melt out tills occur in the form of non-fluted hummocky tills. Despite their proximity to the glacier, these tills are thought to be thousands of years old. They have bi-modal grading characteristics and therefore the direct products of comminution, McGown (1975). They have also been known to exhibit collapsing behaviour. The sample selected showed a well developed macro-fissility which dropped down slope at 13° approximately, in accordance with the dip of the basal surface of the glacier. It is classified as a clayey sand and contains low plasticity fines. The very fine fraction is thought to be composed of rock flour.

5.22.2. Microfabric Characterisation.

(a) Elementary particle arrangements - Fig. 5.32.(a): grain-grain contacts were observed to be the dominant arrangements present and clay arrangements were also occasionally observable. The former arrangements were mainly of the clothed type although clean arrangements were occasionally in evidence. The grains involved were mainly of silt size with irregular, elongated and flaky shapes and generally relatively closely packed. The clay arrangements were predominantly partly discernible in character although random arrangements were also frequently observable. The former arrangements generally displayed relatively few non-crinkled edges as illustrated by Mic. 5.32.(a), while the latter appeared to be composed of bulky coarse clay size individuals, Mic. 5.32.(b).

(b) Particle assemblages - Fig. 5.32.(b): matrix and aggregation assemblages were both frequently observable while connector assemblages were only rarely present. Within the matrix, granular regions, wherein haphazard orientation of grains was in evidence, were found predominating over clay-granular regions which were occasionally observable. Mic. 5.32.(c) serves to illustrate the nature and occurrence of matrix regions. The aggregations were regular in shape and silt size, appeared to consist of a mixture of the various clay arrangements, and were observed interacting directly with each other and the matrix grains, as clearly illustrated by Mic. 5.32.(d). Connectors were of the bridge variety and had a similar internal organisation.

(c) Basic pore spaces - Fig. 5.32.(c): the intra-elemental pores particularly those associated with the grain arrangements and the inter-assemblage pores, e.g. Mic. 5.32.(d) of the aggregation system each appeared to form a considerable proportion of the pore space. Only a small contribution was in evidence from intra-assemblage pores.

(d) Composite microfabric: a general view of the composite microfabric is presented in Mic. 5.32.(e). Fine sand size particles, irregular and elongated in shape, can be clearly seen embedded in the fine and uniformly textured assemblage network.

(e) Anisotropy within composite microfabric - Fig. 5.32.(d): the microfabric appeared to be isotropic in character at each of the levels considered.

SECTION IV - GENERAL BACKGROUND AND MICROFABRIC OF RESIDUAL DEPOSITS STUDIED

5.23. CASENGA, ANGOLA.

5.23.1. General Background.

A bulk sample of a black or dark grey residual soils from a site at Casenga within the Casenga region is included. Such deposits have been referred to as Vertisols, Black Cotton and Black Tropical soils. They were derived during the Holocene period from the weathering of underlying calcareous Miocenic sedimentary rocks and extend over a relatively small flat and slightly depressed area and have a thickness varying between 0.5.m. and 4.m., Horta da Silva (1971a). In the present arid climate, a deep water table exists and the deposits are hard and fissured (at both macro and micro levels), with slickensides and desiccated. The Casenga deposit is classified as an inorganic clay of high plasticity and is known to exhibit both expansive and collapsing behaviour. In terms of composition, the clay fraction, which is dominated by its $\leq$ 0.2 μ fraction, is known to contain mainly montmorillonite. The sample selected contains equal amounts of both clay and sand sizes with only a very small amount of silt.

5.23.2. Microfabric Characterisation.

(a) Elementary particle arrangements - Fig. 5.33.(a): clay arrangements were observed to be the dominant arrangements present with clothed grain-grain contacts rarely observable. The clay arrangements were partly discernible in character, with some arrangements displaying relatively few crinkled edges, e.g. Mic. 5.33.(a) and others displaying numerous edges, e.g. Mic. 5.33.(b). The grains involved in the granular arrangements were of mainly fine sand size, with irregular shapes, as shown by Mic. 5.33.(e). The arrangements appeared generally to be fairly loosely packed.

(b) Particle assemblages - Fig. 5.33.(b): a complex assemblage network was apparent which was dominated by a matrix and within which both connectors and aggregations were also occasionally observable. Within the matrix, clay-granular regions predominated over grain regions which were occasionally present. The former consisted of partly discernible clay arrays with the embedded matrix grains being of fine sand size, with rounded and irregular shapes, as shown by Mic. 5.33.(c). The connectors were found bridging and buttressing sand grains and consisting mainly of partly discernible particle arrays. The aggregations were mainly regular in shape and ranged in size from coarse silt to medium sand. They appeared to be composed mainly of partly discernible particle arrays and were found interacting directly with each other and also the surrounding matrix. Mic. 5.33.(d) serves to demonstrate the occurrence and interaction of clay-granular matrix regions and also connectors and aggregations.

(c) Basic pore spaces - Fig. 5.33.(c): the intra-elemental and inter-assemblage pores present were each considered to account for a considerable proportion of the pore space. The intra-assemblage pores appeared to form an appreciable proportion of the pore space.

(d) Composite microfabric: Mic. 5.33.(e) serves to illustrate the typical character of the composite microfabric. The extremely coarse and heterogeneous texture and the prominence of wavy shaped trans-assemblage pores can be clearly appreciated.

(e) Anisotropy within composite microfabric - Fig. 5.33.(d): the microfabric appeared to be isotropic in character at each of the levels considered.

5.24. ONDERSTEPOORT, S.A.

5.24.1. General Background.

A bulk sample of residual soil from a site at Onderstepoort, north west of Pretoria in the Transvaal, is included. The soil is a stiff black clay which extends from a depth of 0.6.m. to about 3.4.m., and is a typical example of the 'Black Turf' soils of the Central Transvaal and has been developed from the insitu weathering of morite (gabbro) a very basic igneous rock of the Bushveld Igneous Complex. Although the deposits are referred to as being residual, they should perhaps be regarded as completely reworked in nature because of their very active characteristics, de Bruyn (1963). No permanent water table exists above about the 3.4.m. depth and in the present sub-humid climate the deposit is partly saturated and slickensided and contains the occasional lime nodule. Onderstepoort is classified as an inorganic silt of high plasticity despite its very high clay content. The clay fraction consists mainly of material which has been found to be unidentifiable by x-ray diffraction and so referred to as being amorphous in character. A significant amount of montmorillonite has also been recorded. The black clay from Onderstepoort has been found to show both a very large moisture affinity and potential expansiveness de Bruyn (1963).

5.24.2. Microfabric Characterisation.

(a) Elementary particle arrangements - Fig. 5.34.(a): clay arrangements appeared to be the only arrangements present and these were found to be partly discernible in character. Crinkled edges were generally prominent, as shown by Mics. 5.34.(a) and (b).

(b) Particle assemblages - Fig. 5.34.(b): a particle matrix appeared to be the only assemblage type present. Within this matrix clay regions were to be found predominating over clay-granular regions which were rarely abundant. The clayey parts of the matrix were composed of partly discernible particle arrays which were often very open in character. Mics. 5.34.(a) and (b) show dense and very open clay arrays respectively. The occurrence and interaction of such arrays within the clayey matrix can be appreciated from the detailed view of the clayey matrix presented in Mic. 5.34.(c). The few matrix grains present were of mainly fine sand size and were irregular in shape.

(c) Basic pore spaces - Fig. 5.34.(c): the pore space appeared to be dominated by the intra-assemblage pores associated with the very open clay arrays within the matrix, e.g. Mic. 5.34.(b). The intra-elemental pores were considered to account for a considerable proportion of it also.

(d) Composite microfabric: Mic. 5.34.(d) serves to illustrate the fine and uniform texture of the composite microfabric. The occurrence in places of wavy planar trans-assemblage pores is also apparent.

(e) Anisotropy within composite microfabric - Fig. 5.34.(d): the microfabric appeared to be isotropic in character at each of the levels considered.

SECTION V - SUMMARY

5.25. GENERAL REMARKS.

The foregoing sections have presented the results of the scanning electron microscopy investigation of the microfabric of a wide range of natural soil types. The observed microfabric of each soil was characterised using the system developed for this study and a high degree of success appeared to be achieved in every case, at least from an engineering standpoint. It must be emphasised and recognised however, that because of the very nature of the techniques of microfabric assessment adopted, namely the application of the scanning electron microscope to air-dried samples, microfabric observations or interpretations must be considered with a certain degree of caution. That is to say, the characterisation scheme is independant of the method of investigation, but the observations and interpretations are not. Nonetheless, considering the wide range of soil types and textures included in the study, the scanning electron microscope proved to be a very useful and meritable tool and as stated in Chapter 4, the major problem of sample shrinkage during preparation, was only really encountered in a relatively small number of cases. Furthermore, the preliminary critical point drying investigation also outlined in Chapter 4, suggests that air-drying of even wet soils does not alter significantly the general character of the composite microfabric.

The other major problem encountered was the fact that the various aspects of the characterisation scheme, and in particular those of relative abundance and anisotropy, could only be assessed on a purely qualitative basis in the scanning electron microscope. However, even with this approach, a reasonably realistic and acceptable representation of the actual situation is considered to have been attained in each case.

Regarding presentation of the microfabric characterisation data, the approach adopted herein has proved to be fairly satisfactory from the point of view of degree of detail and conciseness. Certain improvements however, could undoubtedly be made in this area.

5.26. SUMMARY OF MICROFABRIC OBSERVATIONS.

1.(a) Nature of constituent particles of random or parallel clay arrangements occurring within 'total clay array', Figs. 5.35. and 5.36.: in 30 per cent of those cases wherein random or parallel clay arrangements occurred, it was observed that these arrangements comprised entirely of single type arrangements, i.e. either groups only and clusters only (~ 10% of total) or individuals only (~ 20% of total). In the vast majority of cases however, (~ 70% of total) both groups (or clusters) and individuals were to be found interacting to form these clay arrangements with the former on the whole either predominant over, or equally as abundant as the latter, Fig. 5.35. In the vast majority of cases the clay individuals were mainly or only of coarse clay size and only a minority of cases (~ 32% of total) had fine-coarse clay sizes. In the few remaining cases individuals were of fine clay size, Fig. 5.36.

(b) Composition of 'total clay array' - Fig. 5.37.: in the majority of the cases, the total clay array was heterogeneous, i.e. it was composed of more than one type of clay arrangement. In a very substantial proportion of cases however, (~ 44% of total) homogeneity was in evidence. Homogeneous arrays of random clay were more frequently observed than homogeneous arrays of partly discernible clay which in turn were more often encountered than homogeneous arrays of parallel clay. In the heterogeneous arrays combinations involving random and parallel clay were more frequent than those involving random and partly discernible clay. None were recognised involving parallel and partly discernible. All three types of clay arrangement were observed only in approximately 3 per cent of the cases.

(c) Composition of 'total granular arrays' - Fig. 5.38.: in the great majority of cases the 'total granular array' was homogeneous although in approximately 40 per cent of cases, heterogeneity was in evidence, i.e. both clean and clothed grain-grain contacts were present. Homogeneous arrays of clean grain-grain contacts were more abundant than homogeneous arrays of clothed grain-grain contacts. Within the heterogeneous arrays clean grain-grain contacts generally either shared dominance with, or predominated over clothed grain-grain contacts.

(d) Composition of 'total elementary particle arrays' - Figs. 5.39. and 5.40.: the total elementary particle array was in many cases heterogeneous, i.e. it comprised both clay and granular arrays (the former predominated in 28% of cases and the latter predominated in 23% of cases), Fig. 5.39. However, in almost the same number of cases homogeneity was in evidence with the total elementary particle array being comprised entirely either of clay arrays (~ 38% of total) or granular arrays (~ 10% of total). Moreover of those cases where both clay and granular were observed, approximately 62 per cent were heterogeneous due to the fact that one or other or both of the constituent array types were themselves heterogeneous, Fig. 5.40.

2.(a) Dominant particle assemblage(s) - Fig. 5.41.: in the vast majority of cases (~ 80% of total) the basic order assemblage network was either composed entirely of or was dominated by a particle matrix. In the remainder of cases, except for two cases where a connector system dominated, a particle matrix (or region system) shared dominance with either connector or aggregations or both.

(b) Relative abundance of individual basic order particle assemblages, Fig. 5.42. - 5.45.: a particle matrix (or layer region system) was observed in all but one case, Fig. 5.42. These assemblages generally dominated the basic order assemblage network and in the other cases were at least occasionally or frequently to be seen and often shared dominance with connectors or aggregations or both. Aggregations were observed in a minority of cases (~ 42% of total). They never dominated the basic order assemblage network and their occurrence appeared to be evenly spread over the middle band, i.e. the 'rarely' to 'frequently' band, Fig. 5.43. Connectors were also only observed in a minority of cases, (~ 42% of total). When present they were mainly occasionally but also rarely and frequently abundant, Fig. 5.44. They dominated the basic order assemblage network in two cases only. Interweaving bunches proved to be extremely uncommon features and in fact were only rarely observed in one case, and occasionally abundant in another, Fig. 5.45.

(c) <u>Composition of individual basic order assemblage systems, Figs. 5.46. - 5.48.</u>:

i) Homogeneous matrix or layer region systems were observed in just under half of the cases, i.e. they singly comprised a region. In just over half the cases however, some degree of heterogeneity was in evidence due usually to the presence of two types of region, Fig. 5.46. Matrix or layer region systems comprised entirely of clay regions were infrequently seen (~ 8% of total) whilst in contrast the solitary presence of either granular or clay-granular regions was in evidence in a significant number of cases (~ 23% and ~ 18% of total respectively). Overall, clay-granular regions were perhaps the most widespread system acting either singly or in connection with clay or granular regions and in a small number of cases, with both. Combinations involving clay and granular regions were infrequently observed.

ii) The majority of connector systems (~ 58% of total) were heterogeneous in character being comprised of both bridge and buttress type connectors with the same order of abundance, Fig. 5.47. The remainder were mainly homogeneous and comprised entirely of bridges. Buttresses were never seen either totally comprising or dominating a connector system.

iii) The vast majority of aggregation systems (~ 88% of total) were found to be homogeneous, comprising either regular aggregations only or irregular aggregations only. In fact regular aggregations were by far the most abundant of the two overall, Fig. 5.48.

(d) Higher order particle assemblages:

i) Vein assemblages proved to be unusual features and in fact were observed in three individual composite microfabrics only. In two of these cases veins were of the clay variety and were found displaying rather complex patterns which were more extensive (relative to the specimen boundary), in one of the cases than in the other. Inclinations of individual clay veins were, in the main, towards the horizontal and otherwise were approximately 45°. Individual silt veins of rather short length were observed forming in a crosswise pattern in one case.

ii) Microlenses of clay proved to be extremely unusual features being observed in one individual composite microfabric only. They were non-uniformly distributed, variable in thickness and extent and orientated towards the horizontal.

iii) Microlayers both granular and clayey in texture were identified in two of the three layered samples investigated.

iv) Layer interfaces were observed being sharp and straight, sharp and wavy and ill-defined in character.

3.(a) Basic pore spaces - Fig. 5.49.: in the vast majority of individual composite microfabrics intra-elemental pores dominated the basic pore space. In most of the remaining cases these intra-elemental pores shared dominance with inter-assemblage pores.

(b) Trans-assemblage pore spaces: the occurrence of trans-assemblage pores was identified in a significant number of cases (~ 25%) and the irregular and wavy shaped varieties seemed overall to be more or less as common.

4. Composite microfabric anisotropy - Fig. 5.50: in just over half the cases the individual composite microfabric appeared to be essentially isotropic no matter the level considered, i.e. 500 μ, 50 μ or 5 μ. Moreover, overall, very high or high degrees of anisotropy were rarely seen at the 500 μ level. In the vast majority of the cases where some anisotropy was identified the degree of anisotropy was seen to vary with the level of fabric considered. This variation seemed to be associated, essentially with the presence of parallel clay arrays within which there was less than complete preferred orientation and the presence at the 500 μ and 50 μ levels of veins and clay microlenses and also the overall preferred orientation of silt or sand grains. Complex situations were encountered in several cases where two directions of preferred orientation were exhibited essentially at the 500 μ level, e.g. the crosswise pattern of individual silt veins and the crossover system of clay veins.

5.27. THE CHARACTER OF NATURAL SOIL MICROFABRIC - A GLOBAL VIEW.

An attempt is made at this stage to present a 'global view' of the likely character of the individual composite microfabrics which make up the total composite microfabric of the transported inorganic soil group. This view is based on the comprehensive and detailed microfabric observations just given in the 'catalogue of natural soil microfabric', section 5.2. - 5.26. Confirmation or otherwise of the previous concepts of microfabric as reviewed in Chapter 2, will be made where possible.

(a) Elementary particle arrangements: the total elementary particle array within the individual composite microfabric is probably as likely to be homogeneous as it is to be heterogeneous.

The total clay array in most of the individual composite microfabrics in which it occurs might be expected to display some degree of heterogeneity whereas the total granular array would tend to be fairly homogeneous in character probably being comprised in the main of clean grain-grain contacts. Nevertheless, clothed grain-grain contacts like those reported on in Chapter 2, Section 2.2.1.3., will be found.

No one type of clay arrangement would have either a universal occurrence, or a clear dominance over the other types throughout the total composite microfabrics. On the contrary, the emphasis, or the dominance, is likely to shift from one arrangement type or combination of types to another as passage is made from one individual composite microfabric to another within the total composite microfabric.

Random or parallel clay arrangements would in most of the individual composite microfabrics within which they occur be comprised of both clay groups (or clusters) and clay individuals. Individuals would in fact be seen to some extent in the vast majority of cases and would be mainly of coarse clay size. Thus it would seem that the various clay arrangements reported in Chapter 2, Section 2.2.1.2, including those involving individual clay particles, are realistic, in general concept at least. As stated in Chapter 3, Section 3.2.2.1.(a) no account was made in this study of the occurrence of specific types of random clay group arrangements, e.g. salt-flocculated, bookhouse or the models of Van Olphen (1963), and therefore no statement as to their likely occurrence or otherwise can be made here.

It should be pointed out that the so called partly discernible clay arrangements have been highlighted for the first time by this study. Discussion of their likely make-up and internal organisation will be made in Chapter 6.

(b) Particle assemblages:

i) Composition of the basic order assemblage network: it is likely that in the main the basic order assemblage network will either be composed entirely of a particle matrix (or layer region system as the case may be) or will be dominated by such an assemblage. Moreover, it seems equally as likely that the network will be composed entirely of a particle matrix, i.e. homogeneous, as it is that it will be composed of more than one type of basic order particle assemblage, i.e. heterogeneous. Matrices or layer region systems will be homogeneous in some cases and in others, heterogeneous. Not all the homogeneous matrices will be either clay or granular and in fact a significant proportion will be of the intermediate type, i.e. clay-granular. Within the heterogeneous matrices, in the main, extreme combinations of clay and granular types or combinations of all three types will not be in evidence. Combinations either of clay and clay-granular regions or clay-granular and granular regions are by far the most likely. On balance then, it would seem that there is some level of support for the notion outlined in Chapter 2, that granular particles do not touch within a clay-silt sand mixture but rather float in a clay background. The likely prominence of the so called clay-granular regions is evidence of this. Nevertheless, it must be recognised that (1) clay-granular regions may by definition, and will in many cases, still contain isolated grain-grain contacts and (2) granular regions will be observed in a significant number of cases involving clay-silt sand mixtures. Therefore, grain-grain contact within clay-silt sand mixtures is by no means as unlikely as the previous notion suggests.

Aggregations will be encountered in many but not the majority of the basic order assemblage networks, probably occurring in the rarely to frequently observed range of abundances. Aggregation systems in the vast majority of basic order assemblage networks are likely to be homogeneous and composed of regular type aggregations.

Connectors will be encountered in many but not the majority of basic order assemblage networks occurring mainly in the rarely to frequently observed range of abundance. On the whole, connector systems will be heterogeneous and comprised more or less of equal numbers of bridges and buttresses. Homogeneous (bridge) connector systems may be present to some extent in a significant number of networks.

Interweaving bunches are likely to be present in an extremely small number of basic assemblage networks only.

It would appear therefore, that the occurrence of multilevel forms (Chapter 2, Section 2.2.1.4. III), like the so called aggregations, connectors and interweaving bunches has been confirmed. Their relative abundance however, has been put perhaps into clearer perspective, i.e. they often will not be present at all (this will be particularly true in the case of the bunches) and where they do occur, they will not in the majority of cases dominate or even share domination of the network with the matrix or region systems.

ii) Occurrence of higher order particle assemblages: clay or granular microvein systems, and even less so clay microlenses, are likely to be infrequently seen disrupting the basic order assemblage network. Occurrence of clay veins (Chapter 2, Section 2.2.1.4.(iii)) has thus been confirmed but rather like the bunches their occurrence will be by no means widespread. It is likely in the main, that microlayers will be present to some degree where layered systems are encountered.

(c) Pore spaces: the basic pore spaces in the vast majority of individual composite microfabrics are likely to be either wholly or predominantly of the intra-elemental variety.

Trans-assemblage pores, of either irregular or wavy planar form, are likely to be encountered in a significant number of cases.

(d) Anisotropy and heterogeneity within the individual composite microfabric: in most cases the individual composite microfabric will be essentially isotropic at the 500 μ, 50 μ and 5 μ levels. Nevertheless, in many cases the microfabric will exhibit a degree of anisotropy, although very rarely will this be very high at the 500 μ level. Moreover, anisotropy where exhibited will tend to vary in degree as the level of fabric considered changes from 500 μ to 5 μ, due largely to the presence of parallel clay arrays with less than complete preferred orientation. This view is in agreement with those presented earlier in Chapter 2, Section 2.2.1.4.(ii). In a number of cases it is possible that a complex situation will occur wherein more than one direction of preferred orientation is observed, and associated with crosswise patterns displayed by for example, vein features or preferentially orientated grains within a granular matrix.

On balance it would appear that the individual composite microfabric will be heterogeneous to at least some degree in the vast majority of cases. This will be due to one or a number of aspects of fabric such as the following:

i) A heterogeneous total clay array, i.e. the presence of more than one type of clay arrangement.
ii) A heterogeneous total granular array, i.e. the presence of more than one type of granular arrangement.
iii) A heterogeneous total elementary particle array, i.e. the presence of both clay and granular arrangements.

iv) A heterogeneous matrix or layer region system, i.e. the presence of more than one type of region or a variation in pattern displayed by, e.g. parallel clay arrays within clayey regions.

v) A heterogeneous connector system, i.e. the presence of both bridges and buttresses.

vi) A heterogeneous basic order assemblage network, i.e. the presence of more than one type of basic order assemblage.

vii) A non-uniform distribution of higher order pores, i.e. trans-assemblage pores.

viii) A non-uniform distribution of higher order clay microlenses or groups of clay microlenses.

ix) A variation in the pattern displayed within, and non-uniform distribution of the higher order vein systems.

Therefore probably the most important aspect of the natural individual composite microfabric to have been highlighted by the present investigation is that generally speaking, this will be comprised at either the elementary particle or particle assemblage level, or both, of more than one type of feature or form. The relative abundance of the various forms will vary from one individual composite microfabric to another. This 'multiple form' situation of course, will be much more pronounced in some 'individual composite microfabrics' than in others. Furthermore, the idea has been introduced that layered soils whether they be laminated or varved, are not simply comprised of silty or sandy layers of one type which are combined with clayey layers of another type. On the contrary, it would appear that a number of different types of silty or sandy layer are likely to combine with a number of different types of clayey layer to form the composite microfabric of the layered system. It is suggested that layered soils should be considered as being 'multi-fabric' soils.

These important findings also tend to highlight perhaps the major deficiency of the majority of previous concepts of the character of soil microfabric. That is to say, the previous concepts, while being perhaps realistic in the sense of the specific forms or configurations they portray, do in most cases largely imply uniformity or homogeneity of configuration whether at elementary particle or particle assemblage level.

In this context, it is worth drawing attention to the fact that laboratory prepared pure clay materials tend to be fairly homogeneous in configuration, and it is therefore suggested that their microfabrics will, on the whole, be unrepresentative of even the simplest of natural soil microfabrics. The question of whether or not such unrepresentative systems when compressed and deformed can yield useful results, relating to the genesis or mechanical behaviour of soils, requires serious consideration. Perhaps more emphasis should be placed on testing natural systems or alternatively on attempts to derive more realistic artificial systems.

The opinions or views expressed above, and the 'catalogue of natural soil microfabric', upon which they are based, it is believed, allow for a detailed and realistic appreciation of the 'global' character of the fabric of natural transported engineering soils, at the micro-level. They have also allowed an appraisal to be made of the validity of many of the previous microfabric concepts.

PART 11

THE GEOLOGICAL AND GEOTECHNICAL SIGNIFICANCE OF THE MICROFABRIC OBSERVATIONS.

CHAPTER 6

THE GENESIS OF NATURAL SOIL MICROFABRIC

6.1. INTRODUCTION.

The factors influencing the development of soil microfabric in the natural environment are varied and numerous. In the case of sedimentary soils, they are known to operate both during and after deposition, and in the case of residual soils, throughout the weathering process. This chapter, first reviews briefly the previous concepts of microfabric genesis and then goes on where possible, to examine the validity or otherwise of these concepts and to introduce some new ones in the light of the observations made in the present study and detailed previously in Chapter 5. Many of the microfabric models described in Chapter 2, will again be referred to.

6.2. PREVIOUS CONCEPTS.

The factors which are thought to influence microfabric development are considered under two headings (1) Depositional Factors, and (2) Post-depositional Factors.

6.2.1. Depositional Factors.

The factors which are considered to influence particle arrangement at deposition include grain size, shape and gradation; the clay fraction and its mineralogy; electrolyte concentration; exchange cations, particularly their valency; acidity; organic constituents; depositional agent and environment; concentration of sediment; state of agitation of water; direction of water, ice or air flow; temperature and pressure. In the case of residual soils, the 'early stage' of weathering is perhaps a more appropriate term than 'depositional factors' but again chemistry of the environment, presence of water, temperature, pressure, as well as parent material, leaching, drying, wetting, are all important.

Electrolyte Concentration Mineralogy and Cation Type.

Most attention has however, been given to the influence of the electrolyte concentration during deposition on the microfabric of sedimentary clays. For example, Casagrande (1932) postulated that 'honeycomb' clay arrangements, Fig. 2.14. are associated with deposition in a salt water environment. Schofield and Samson (1954) and Lambe (1958) by considering the double layer theory and behaviour of clay platelets in dilute colloidal suspensions suggested that sedimentation in a very low electrolyte concentration leads to 'edge-face' flocculation or 'non-salt' flocculation, i.e. the cardhouse arrangement, Fig. 2.2. As mentioned previously in Chapter 2, Section 2.2.1.2. apart from evidence presented by a few workers, e.g. Rosenqvist (1959), there appears little to suggest that such individual clay mineral platelet interaction of the cardhouse and non-salt flocculated types, is common in nature, Smart (1971, 1975) Barden (1972b).

Schofield and Samson (1954) and Lambe (1958) also argued that sedimentation in a high electrolyte concentration leads to a suggestion of parallelism of the clay platelets in the form of a stepped arrangement of edge-edge, face-face and edge-face contacts, the so called 'salt-flocculated' model, Fig. 2.3. Schofield and Samson further suggested that edge-face flocculation is exhibited most readily when monovalent counterions are involved and salt-flocculation most readily obtained when di- or trivalent ions exist. Moreover, Lambe postulated that the relation between electrolyte concentration and degree of randomness is not a simple one and in fact at electrolyte concentrations between that of Low and High, 'dispersion' is induced, involving essentially face-face association of platelets, Fig. 2.4. Meade (1964), after an extensive review, concluded that a direct relationship does exist between electrolyte concentration and degree of randomness for kaolinitic and illitic clays with higher concentrations of electrolyte, tending to produce a configuration of the salt-flocculated variety. He concluded however, that for montmorillonitic clays such a relationship cannot be clearly identified and the cation type involved has a marked influence.

A rather different view of the influence on fabric of electrolyte concentration has been presented by Pusch (1973), who based on electron (transmission) microscope investigations, suggested that clay arrangements in very fine grained natural freshwater illitic clays consist of small relatively porous clay size aggregates and small voids, Fig. 2.10.(a), whereas clay arrangements in salt water illitic clays are comprised of larger but denser clay size aggregations separated by larger voids, Fig. 2.10.(b). Sides and Barden (1971), studying the microfabric of laboratory dispersed and flocculated samples of kaolinite, illite and montmorillonite, indicated that surface activity had an important influence on the resulting fabric, and attention has been drawn by Smalley et al (1973) and Hammond et al (1973) to the role which clay size and mainly plate shaped quartz particles ('rock flour') play in forming open cardhouse particle arrangements.

Concentration of Sediment, Organic Matter and Gradation.

Concentration of clay in the sediment also appears to be a vitally important factor where kaolinitic and illitic clays are concerned. Generally speaking, assumming all other factors to be equal, the higher the clay concentration the more likely it would seem that a random particle configuration will be attained for any specific electrolyte concentration, Meade (1964), O'Brien (1970). The findings of O'Brien (1971) are also of wider interest. He in fact, found little difference between the arrangement of kaolinite flocculated in distilled water with a high clay concentration and the arrangement in salt water with a lower clay concentration. In both cases a 'stair-stepped cardhouse' configuration, Fig. 2.7.(a) was in evidence.

Although the presence at deposition of organic matter is thought to have some physico-chemical influence on clay particle arrangement, few direct indications have been made. Exceptions, are Ingram (1953), Odom (1967) and O'Brien (1970) each of whom identified a direct correlation between degree of preferred orientation of clay minerals and the co-existence of organic matter.

It would also appear from the evidence provided by Mitchell (1956), Lafeber (1963) and Fookes and Best (1969), that a small to moderate amount by weight of clay size material in the sediment is sufficient to allow there to be a uniform distribution of grains within the skeleton and thus few grain-grain contacts. Mitchell (1956), also suggests that high percentages of silt and sand particles tend to prevent the development of preferred orientation of clay over large areas. Additionally, the degree of openness of flocculated microfabrics has been reported as being influenced directly by the degree of angularity of silt grains, Barden (1972)[b].

Gravity, Direction of Water, Wind, or Ice Flow, and Glacial Environment.

The preferred orientation of the long axes of skeleton grains has been shown to be influenced at the time of deposition by gravity (the 'Brownian Structure' of Smart (1969), Fig.2.15) and by the pattern of water flow, Lafeber and Willoughby (1971) and Feda (1975).

In other depositional environments the orientation of the grains has been shown to be influenced by the direction of prevailing wind, Matalucci et al (1969); and by the direction of ice flow, Korina and Faustova (1964). Korina and Faustova also offer a rather interesting concept of the origin of the 'perpendicular fibrous' pattern, Fig. 2.18., found in glacigenic clays. They suggest that such patterns, like the skeleton grain configurations, are inhereted from the ice fabric and more specifically are formed as a result of the melting of ice crystals, on whose basal surfaces are distributed aggregates of clay particles. It is assumed that the melt water was removed without causing significant particle reorientation. Some later work by Derbyshire et al (1976), and McGown and Derbyshire (1977), confirms and extends this general concept but with greater emphasis placed on the variation of glacigenic environments.

Variation in Depositional Factors.

Layering has been associated with changes in depositional conditions by Odom (1967). Moreover, the nature of the textural change which occurs between the fine and coarse-grained layers in a varved glacio lacustrine clay, has been shown to be related to the nature of the changes in deposition conditions, Kenney and Chan (1972) and Harrison (1975). In the light of this and the above discussion, it is perhaps obvious but necessary to state that it is now known that variation in one or more of the depositional factors from point to point in a depositional medium, or overall changes with time of one or more factors, will tend to result in fabric heterogeneity or layering unless of course changes in certain factors counter balance or nullify changes in other factors so as to produce a uniform configuration. It was Odom (1967) who said "I feel that fabric and structure variations in sediments subjected to essentially equal overburden load, which have not been significantly disturbed by organisms, fluid or plastic flow or deformation, reflect physico-chemical conditions in depositional environments".

6.2.2. Post Depositional Factors.

The factors which are operative and which influence particle arrangement after deposition include (1) burial and subsequent consolidation, (primary and secondary), (2) shear deformation, (3) drying and wetting, (4) swelling and shrinking, (5) freezing and thawing, (6) stress relief, (7) chemical weathering, (8) seepage, (9) precipitation and cementation, and (10) organic activity. Although the term 'post-depositional' is inappropriate with regard to residual soils, all the above factors with the exception of possibly consolidation can be considered relevant to their case.

One Dimensional Consolidation.

Perhaps greatest attention has been paid to the influence of burial or overburden pressure on fabric development and more specifically on the extent to which one dimensional consolidation or compression induces preferred orientation of clay particles or aggregates normal to pressure.

Certain workers have postulated what may occur when pressure is applied to 'depositional arrangements'. Transmission of stress through silt grains embedded in honeycombed clay resulting in local densification of clay honeycombs, was postulated by Casagrande (1932), Fig. 2.14. whilst the breakdown of random arrangements into more parallel ones was suggested by Quigley and Thomson (1966), Moon (1972) and Yong and Warkentin (1975). Breakdown and preferred re-orientation of clay aggregates was also put forward by Engelhardt and Gaida (1963) and Yong and Warkentin (1975), respectively.

A number of investigations involving laboratory consolidated kaolin, have suggested that one-dimensional consolidation does indeed produce increased parallelism. For example, increased parallelism was reported due to a consolidation pressure of 400 kN/m^2 by Smart (1966b), and due to an increase in consolidation pressure from 200 to 2000 kN/m^2 by Tovey (1970) In contrast, Morgernstern and Tchalenko (1967b) and McConnachie (1974) both found that considerable parallelism was induced by consolidation pressures of around 10-15 kN/m^2 and that at higher pressures, up to 100000 kN/m^2, no significant increase in parallelism was induced. In this context Meade (1966) reviewed certain experiments on kaolinitic and illitic slurries and pastes and concluded that given enough water most of the preferred orientation might be expected to develop at pressures of around 100 kN/m^2.

Mitchell (1956) measured increased parallelism in a laboratory prepared illitic clay consolidated to 400 kN/m^2. Bowles et al (1969) tentatively suggested that for undisturbed clay sediments with high void ratios (3 - 4) normal compressive stresses in excess of 400 kN/m^2 are required before any increase in parallelism can develop. Engelhardt and Gaida (1963) found preferred orientation in a montmorillonitic clay after it had been laboratory consolidated to pressures in the range 8000 - 80000 kN/m^2.

Meade (1964, 1966), and Odom (1967) carried out exhaustive reviews of a number of other studies, in particular those involving the study of fabric variations displayed with depth of burial within natural soils which have been heavily compressed. They concluded that the relation between pressure and parallelism is by no means as clear as the results of laboratory studies, such as those mentioned previously, might indicate. It would seem in fact, that compression for a variety of reasons does not always induce preferred orientation in the natural environment. Odom (1967) said, "variations in the degree of preferred clay mineral orientation from good to very poor may occur within several inches stratigraphically in mineralogically similar sediments. Such variations indicate that clay fabric cannot be entirely due to the effects of overburden load". The upward passage of pore water as it was squeezed out from a sea bottom sediment during diagenesis has been held responsible for the reorientation of particles and aggregates into inclinations of 45° - 90° to the horizontal, Koff et al (1973). Furthermore it is known that fine-grained (colloidal) clays, e.g. very fine-grained illite and montmorillonite are not as readily affected by physical compression forces as are the coarser less active clays, e.g. kaolinite. Meade (1966) postulated that natural compression in calcium montmorillonites may result in a random domain type arrangement. This opinion was later reinforced by the observations of Pusch (1971). He also observed however, a highly orientated arrangement in a heavily compressed sodium montmorillonite. It would seem, Pusch suggests that cation valency is important in determining whether preferred orientation develops in montmorillonitic clays. Also, a significant bulky granular fraction tends to encourage disorder, Burnham (1970). Moreover, certain of the other factors important at deposition, namely electrolyte concentration, acidity, organic content and particularly water content plus natural cementation and rate of loading also appear to play a significant role in determining whether or not post-depositional compression results in parallelism perpendicular to the axis of loading.

Delayed compression subsequent to intense salt leaching has been held responsible for the degree of preferred orientation displayed by the microfabric of two Norwegian quick clays, Kazi and Moum (1973).

Shear Deformation.

Post-depositional shear strains may be induced in soil masses as a result of for example, tectonic activity, freezing and thawing, swelling and shrinking, stress relief, solifluction and chemical activity. A number of stress or shear induced microfabric features have been specifically identified. For example, optical microscope studies of 'undisturbed' natural soils have reported the occurrence of narrow features comprising parallel clay arrangements orientated in a different direction from that of the remainder of the material, Mitchell (1956), Brewer (1964) and Lafeber (1966), and Greene-kelly and Mackney (1970). Lafeber (1964) also put forward the notion of cutan tails resulting from stress-induced rotational movement of skeleton grains, Fig. 2.20. Examination of laboratory prepared and sheared kaolinite has yielded evidence of the occurrence of highly complex shear induced features such as major or primary shear discontinuities, branch or secondary shear discontinuity and kink bands, Smart (1966b), Morgernstern and Tchalenko (1967c), Foster and De (1971). A feature common to all these fabrics is the high degree of preferred orientation of clay particles within their boundaries. Burnham (1970) inferred that features such as the perpendicular fibrous features found in glacial tills and described by Korina and Faustova (1964) may be associated with moderate but not severe shearing. Deformation mechanisms have been discussed in terms of detailed changes in microfabric by a number of workers, e.g. Pusch (1970) Barden (1972a),Feda (1975), Smart (1975) Andrawes et al (1975a).

In general terms, cyclic processes of wetting and drying, swelling and shrinking and freezing and thawing are disruptive and can induce a variety of effects including collapse of both open clay and granular fabrics, the formation of grain contact features, e.g. clay bridges and the formation of cracks or fissures, Fookes and Best (1969) and Mitchell (1976). The notion of essentially irreversible edge-edge intergrowth, due to drying, in divalent montmorillonites has been discussed by Stocker (1969). The intense microfissuring which has been observed by Horta da Silva (1971a) in the highly desiccated montmorillonitic clay from Casenga included in the present study, is a particularly good example of the disruptive effects of desiccation. Greene-kelly and Mackney (1970) demonstrated that a remoulded clay soil, while drying produced considerable shrinkage it did not significantly increase visible clay orientation (at x 100 magnification).

Chandler (1972) demonstrated that the process of solifluction can be responsible for disturbing and remoulding a preferentially orientated fabric to produce overall randomness.

Chemical Weathering.

Chemical weathering processes, including leaching, are time dependant and responsible for a complex variety and chain of events leading to a breakdown of some minerals, and the arrangements which they comprise, with the growth of others, possibly with some preferred orientation. Indeed the removal of soluble and colloidal matter by leaching has been reported to have completely changed the character of some microfabrics, e.g. Brink and Kantey (1971). Changes in the electrochemical environment may also be induced which may then leave the fabric susceptible to collapse. Kazi and Moum (1973) have indicated, on the basis of an experimental study of non quick and quick Norwegian clays, that salt leaching may induce densification but not necessarily preferred orientation. The 'in place' decomposition of large particles can result in the formation of orientated clay textures, e.g. Korina and Faustova (1964).

Precipitation and Cementation.

Precipitation of materials such as iron oxide and calcium carbonate onto particle surfaces and at particle contacts can produce diffuse particle arrangements, Mitchell (1976), and grain contact features or bridges, e.g. Horta da Silva (1971b). By virtue of a cementing action, open clay or granular fabrics will tend to be maintained against the forces of compression and deformation. The resistance to compression offered by natural cementation has been well demonstrated by the investigations of Quigley and Thomson (1966), Jarret (1972) and Quigley and Ogunbadejo (1972). Their results indicated that measurable densification and parallelism occurred only when the cementation bonds had been ruptured. Pressures in excess of the apparent precompression pressure were required, i.e. 200, 500 and 300 kN/m^2 respectively. It would seem to follow therefore, that had the fabrics not been cemented, then reorientation would have occurred at pressures below those required for rupture.

6.2.3. Discussion.

The above discussion has given of necessity a brief account of the main concepts of microfabric genesis.

One cautionary point arises, and that is that many of the contributions cited in the above discussion have been derived from (i) pure hypothesis or (ii) from the study of laboratory prepared and tested clayey materials. Moreover the prepared materials in many cases were monomineralic clays, fractionated so as to remove colloidal and coarse clay fractions, and prepared and tested under controlled conditions of, e.g. electrochemical environment, pressure application, etc. In other words, because of the complexity of the real problem, recourse to an idealised situation has been made where the 'depositional' and 'post-depositional' factors involved have been reduced to a small number either in the mind or in the laboratory.

The comments of Meade (1964) are still valid: 'In most experiments, furthermore, a single factor has been so isolated for study that one cannot tell whether the factor might be significant or inconsequential when it operates in concert with other factors in nature. The experiments however, to indicate what the effects of some of the factors might be .... ', so while such contributions are of value they must be looked at within the overall scheme of things.

6.3. FINDINGS OF THE PRESENT INVESTIGATION.

6.3.1. Preamble.

It has been demonstrated in the previous section that the number and the complexity of factors influencing microfabric development are great and the results from studies of idealised situations may therefore be misleading. A better approach would be one involving the study of natural situations, however, in order to assess the influence of one factor or a combination of factors it would in most cases be necessary to study and compare the microfabrics of a large number of carefully selected natural undisturbed soils so that the critical variables or combinations of variables could be isolated. The number of soils required so that the role played by each of the genetic factors may be examined is so enormous that in practical terms it is not only difficult but perhaps impossible to undertake such a task, indeed this is why in past studies, recourse has been made to idealised models. Therefore, this study does not attempt to carry out such a detailed analysis due to the time involved and the fact that few soils are available which have an extensively documented geological history, mineralogy and chemical composition.

It is only the intention of this section then, to attempt to identify where possible trends on the basis of the broad microfabric observations made of the various geological soil types presented in Chapter 5. To facilitate this the occurrence and distribution of certain of the observed microfabric features within certain genetic soil groups will be examined. Two main groups are in fact identified; namely the lightly compressed and heavily compressed deposits, Table 6.1. Compression is taken to be associated either with pressure from overburden or from desiccation. Each of the main groups therefore, is further sub-divided into essentially one-dimensionally compressed, i.e. as a result of consolidation and essentially three-dimensionally compressed, i.e. as a result of desiccation.

6.3.2. Summary of Microfabric Observations.

The following sections represent a summary of the main microfabric characteristics of the soils studied. Soils are grouped for the purposes of analysis according to precompression history and depositional or formational environment. Certain summary diagrams are also presented and referred to, but reference should also be made to the microfabric characterisation data given in the microfabric catalogue presented in Chapter 5.

6.3.2.1. Lightly Compressed Deposits.

A. Essentially One-dimensionally Compressed Deposits.

(i) Marine Deposits.

The total clay array in all but the Grangemouth clayey silt was essentially random throughout, Fig. 6.1. Within Grangemouth randomness predominated but parallel clay did form in interweaving bunches. The constituent clay particles were apparently both groups and individuals in each case, Fig. 6.2. Of the five deposits, three, namely Drammen Town, Sundland and Solbergelva contained a total granular array which was essentially clean in character, Fig. 6.3. In all but one soil, the flaky and elongated grains present exhibited haphazard orientation. The exception, Ellingsgrud displayed a moderate preferred orientation of silt grains, Fig. 6.5.

Matrices dominated in all but the Sundland clayey silt wherein connectors dominated. Connectors were apparently absent in the Grangemouth soil while being evident in the remaining three soils up to the occasional level of abundance, Fig. 6.6. Aggregations, while never dominating and being rather less abundant overall, did display a similar trend. Bunches were seen only in the Grangemouth deposit at the occasional level of abundance and haphazardly orientated. It follows that the basic order assemblage network was heterogeneous to some degree in each of the marine soils, Fig. 6.6.

It also follows to an extent that inter-assemblage pores played a significant role generally, although apart from the Sundland deposit they were dominated over by intra-elemental pores, Fig. 6.9. Intra-assemblage pores were essentially insignificant in all but the Drammen plastic clay and no trans-assemblage pores were in evidence. Overall, the composite microfabric displayed isotropy in all but the Ellingsgrud deposit wherein, by virtue of the preferred orientation of silt grains, a low degree of anisotropy was in evidence, Fig. 6.10.

(ii) Estuarine Deposits.

A total clay array was observed in all but the Laurieston, Layer III. A wide variety and fairly even distribution of array compositions were identified ranging from essentially random to essentially parallel, Fig. 6.1. As indicated partly discernible forms combined with random clay in the Shannon A soil. The constituent clay particles appeared to be mainly groups (or clusters) in most cases, although individuals were apparently as prevalent in the Shannon, Saint Jean Vianney and Boston deposits. In the Saint Alban deposits individuals were more prevalent, Fig. 6.2. Regarding the internal organisation of the parallel clay arrays, Fig. 6.4. shows that haphazard orientation was in evidence in the Gallowgate and Shannon B deposits and the Renfrew Layer II, while in stark contrast, strong preferred orientation was displayed in the Laurieston Layers I and II, Renfrew Layer I and Boston deposits. Indeed Laurieston Layer I exhibited an essentially complete preferred orientation. A total granular array was apparently absent in six of the soils, but where present it was in the main, essentially clean in character, Fig. 6.3., the exceptions being Renfrew Layer III and Shannon A, wherein clothed contacts were also prevalent. The flaky and elongated grains were haphazardly orientated in Gallowgate, Renfrew Layer II, Shannon A and B and Saint Alban; weakly orientated and moderately orientated in the Saint Jean Vianney and Laurieston Layer III respectively and strongly orientated in the Laurieston Layer II, Renfrew Layers I and III and Boston, Fig. 6.5.

Matrices or layer region systems dominated in all but the Renfrew Layer III wherein connectors dominated. On the whole, connectors and aggregations were absent and where occurring were generally rarely to occasionally abundant. Interweaving bunches were identified in only one soil, Renfrew Layer II, being strongly orientated towards the horizontal. In the majority of cases therefore, homogeneity was in evidence, within the basic assemblage network, Fig. 6.6.

Layer interfaces varied in nature in the Renfrew and Laurieston soils being sharp in some cases and ill-defined in others. A rough trend was identified generally, with the sharp interfaces occurring between the fine-grained and the overlying coarse-grained layers and the ill-defined interfaces occurring between the coarse-grained and the overlying fine-grained layers. Higher order vein systems were observed in the Gallowgate soil.

Intra-elemental pores dominated the basic pore space in all but the Renfrew Layer III and Shannon A microfabrics wherein these pores were dominated over by, and shared dominance with inter-assemblage pores respectively, Fig. 6.9. Inter-assemblage pores were absent and intra-assemblage pores played an insignificant role in most cases. Trans-assemblage pores were totally absent.

Overall, as shown by Fig. 6.10. the composite microfabric displayed nil degrees of anisotropy in the Gallowgate, Shannon A and B, Renfrew Layer II, Saint Alban and Saint Jean Vianney materials. Renfrew Layer III showed a less than medium degree of anisotropy while Laurieston Layer III, Renfrew Layer I and Boston displayed moderate anisotropy. High and very high degrees of anisotropy were exhibited by Laurieston Layers II and I respectively.

(iii) Lacustrine Deposits.

The total clay array in all but the Hurlford deposit was essentially random throughout. Within Hurlford, random arrangements combined with parallel arrangements to make up the array and overall the parallel clay array displayed haphazard orientation, Figs. 6.1., and 6.4. respectively. Constituent clay particles appeared to be both clusters and individuals in the New Liskeard Layers. Within the Hurlford deposit however, groups seemed to dominate, Fig. 6.2. A total granular array comprised essentially of clean contacts was in evidence in New Liskeard light layers I and II, Fig. 6.3. Flaky and elongated grains within the Hurlford and New Liskeard light layers I and II showed haphazard orientation, Fig. 6.5.

A matrix comprised the entire basic assemblage network in the Hurlford deposit and in the New Liskeard dark layer and light layer II. Within the New Liskeard light layer I, the matrix shared dominance with a connector system. It follows that homogeneity of the basic assemblage network was prevalent, Fig. 6.6. Higher order vein systems were observed in the Hurlford deposit. Layer interfaces in the New Liskeard varved clay were sharp in some cases and ill-defined in others. A definite trend was identified with the sharp interfaces occurring between the dark (fine-grained)and the overlying light (coarse-grained) layers and the ill-defined interfaces occurring between the light (coarse-grained) and the overlying dark (fine-grained) layers. Preferentially orientated clay micro-lenses were observed in the New Liskeard light layer I.

Intra-elemental pores dominated the basic pore space, except in the case of New Liskeard light layer I, wherein inter-assemblage pores dominated, Fig. 6.9. Intra-assemblage pores were essentially absent in the New Liskeard microfabrics, but were seen providing an appreciable contribution in the Hurlford microfabric. No trans-assemblage pores were in evidence. Overall, the composite microfabric was essentially isotropic in the New Liskeard light layers I and II and exhibited low degrees of anisotropy in the Hurlford deposit and New Liskeard dark layer, Fig. 6.10.

B. Essentially Three-dimensionally Compressed Soils.

A total clay array was present in the melt-out till from Breidamerkurjokull and Taylor Valley and the three wind-blown soils, Fig. 6.1. This array was essentially random and essentially parallel in the Breidamerkurjokull till and the Tongrinne loess respectively, while in the remaining soils, it was essentially or predominantly partly discernible with a few edges of non crinkled forms. A total granular array was in evidence in each of the soils and a wide variety and fairly even distribution of array compositions were identified, Fig. 6.3., varying from essentially clean in the Stockholm till to essentially clothed in the Transvaal sand and Breidamerkurjokull till. Predominantly clean arrays were observed in the Scottish tills, while predominantly clothed arrays were in evidence in the Ford loess and Taylor Valley tills. A balanced composition was apparent in the Tongrinne loess. Flaky and elongated grains were in evidence in all but the Breidamerkurjokull till and as indicated by Fig. 6.5., were haphazardly arranged, exceptions were the Laglingarten and Stockholm tills wherein such grains were strongly orientated in a cross-wise pattern.

The basic assemblage network was dominated by a matrix in all but the Tongrinne loess and the Breidamerkurjokull and Taylor Valley tills. In the loessial soil a matrix shared dominance with a connector system while in the two tills a matrix shared dominance with aggregations. In actual fact connectors were, overall, more prevalent in the wind-blown soils while aggregations were more prevalent in the melt-out tills. The basic assemblage network was heterogeneous in the wind-blown and most of the melt-out deposits, Fig. 6.6. Higher order granular veins were observed in the Laglingarten till and these displayed a cross-wise pattern.

Intra-elemental pores dominated the basic pore space totally in the Ford and Transvaal sand deposits as well as the Scottish and Stockholm tills, and shared dominance with inter-assemblage pores in the remaining cases. Intra-assemblage pores were rarely seen except in the Glen Orchy and Stockholm tills where they provided an appreciable contribution, Fig. 6.9. Irregular trans-assemblage pores were identified in the Ford, loess and Transvaal sand and the Breidamerkurjokull till.

The composite microfabric displayed anisotropy in only two of the soils, namely the Laglingarten and Stockholm tills. In their cases a low degree of anisotropy was in evidence overall due to cross-wise grain patterns, Fig. 6.10.

6.3.2.2. Heavily Compressed Deposits.

A. Essentially One-dimensionally Compressed Deposits.

Parallelism was seen to be highly prevalent, indeed essentially the only configuration within the total clay array in three out of the four soils. In the fourth soil, namely the Jackson clay, parallelism predominated over randomness, Fig. 6.1. Regarding the internal organisation of the parallel clay array, strong preferred and haphazard orientation patterns were evident in the Jackson marine clay and Hurlford (weathered) till respectively, Fig. 6.4. As indicated in Fig. 6.4. moderate preferred orientation was evident in the Luanda marine clay, and the Hurlford (fresh) till. A granular array was observed in only the Hurlford (weathered) till and this comprised essentially clean grain-grain contacts, Fig. 6.3. Flaky and elongated matrix grains were haphazardly orientated in both the Luanda marine clay and the Hurlford (weathered) till, while in contrast medium and strong preferred orientation of such grains was evident in the Hurlford (fresh) till and the Jackson marine clay respectively, Fig. 6.5.

A matrix comprised the entire microfabric in each case, Fig. 6.6. Intra-elemental pores accounted almost entirely for the basic pore space, Fig. 6.9. and no trans-assemblage pores were in evidence.

The composite microfabric displayed significant anisotropy in every case except the Hurlford (weathered) till wherein a nil degree of anisotropy was exhibited, Fig. 6.10. Overall, the composite microfabric displayed a moderate degree of anisotropy in the case of the Hurlford (fresh) till and Luanda marine clay, and a high degree of anisotropy in the case of the Jackson marine clay.

B. Essentially Three-dimensionally Compressed Deposits.

The total clay array was essentially or predominantly partly discernible in character in every case. In the main a prominence of crinkled forms was in evidence. Random individual arrangements were also in evidence in the floodplain deposits from Tucson, Maricopa and Holon. A total granular array in the Tucson, Maricopa, Lydda, Afulah and Casenga deposits, being essentially clothed in character in every case except for Maricopa, wherein a balanced array was apparent, Fig. 6.3. Where present, flaky and elongated grains were haphazardly arranged, Fig. 6.5.

In all but one case, the basic assemblage network was dominated by a matrix, Fig. 6.6. The exception, namely the Tucson deposit comprised approximately equal proportions of matrix, connector and aggregation systems. Overall, connectors were less prevalent than aggregations. The basic assemblage network was heterogeneous in five of the seven soils, the two exceptions being the Afulah and Onderstepoort clays, Fig. 6.6.

Intra-elemental pores feature prominently in all cases and in fact, dominated totally in the Maricopa, Lydda and Afulah deposits, Fig. 6.9. They also dominated in concert with intra-assemblage pores in the Holon clay, and with inter-assemblage pores in the residual clay from Casenga. The basic pore space was dominated by intra-assemblage pores in the case of the residual clay from Onderstepoort and inter-assemblage pores in the case of the floodplain deposit from Tucson, Fig. 6.9. Overall however, intra-assemblage pores were more prevalent than inter-assemblage pores. Irregular trans-assemblage pores were evident in the Tucson and Lydda deposits and wavy planar trans-assemblage pores were apparent in the Holon, Afulah, Casenga and Onderstepoort deposits.

The composite microfabric appeared to be totally isotropic in each case, Fig. 6.10.

6.3.3. Discussion.

The finding that overall, randomness prevailed in the lightly one-dimensionally compressed soils studied, appears to provide little support for the suggestions of Morgernstern and Tchalenko (1967 b), and McConnachie (1974) that intense preferred orientation occurs at pressures of around 10 - 15 kN/m^2. As far as is known the lightly one-dimensionally compressed soils have suffered compression under pressures of between 50 - 120 kN/m^2 and (perhaps larger in the case of Boston and Saint Jean Vianney clays), Table 6.1. Also, it would seem that the opinion of Meade (1966), that given sufficient water preferred orientation is induced by pressures of around 100 kN/m^2, requires to be challenged. Using Meade's own reasoning (p1094), sufficient water is likely to have been available at the time of deposition of the marine, estuarine and lacustrine soils presently studied. It seems probable that cementing agents have assisted in preserving an open random arrangement in the case of the New Liskeard layers, and the Champlain Sea deposits. The works of Mitchell (1956), Smart (1966b), Bowles et al (1969) and Tovey (1970), and others which tend to indicate that pressures of the order of 200 - 400 kN/m^2 are required to initiate or induce significant preferred orientation in kaolinitic and illitic materials, remain unchallenged. The delayed compression subsequent to intense salt leaching which is known to have operated in the Ellingsgrud clay, has not apparently induced any preferred orientation. This appears to be in direct conflict with the findings of Kazi and Moum (1973).

Nevertheless, parallel clay arrays were to be found in the light one-dimensionally compressed soils and while this observation at first glance gives a measure of support for the findings of Meade (1966), Morgernstern and Tchalenko (1967b), McConnachie (1974), a closer examination reveals that parallel clay arrays occur almost totally in the estuarine soil group wherein they vary from prominent in some cases to highly prevalent in others and wherein they formed in matrices or region systems displaying in all but two cases, strong preferred orientation. This lends strong support to the postulation of Lambe (1958) that at intermediate electrolyte concentrations between that of low and high, dispersion at deposition is likely. It would appear therefore, that the parallel clay arrays displaying strong preferred orientation observed in the lightly compressed soils are not pressure induced features, but are associated with certain depositional conditions principal among which is a brackish water environment. This is not to say however, that a brackish water environment will tend to produce within clay and clay-grain regions, an essentially parallel clay array with a strong preferred orientation. In fact as the present observations show, randomness is still likely to be prevalent, perhaps even the dominant feature for many lightly, one-dimensionally compressed, estuarine or brackish water deposits.

It would seem to be the case however, that an estuarine flow regime strongly encourages the preferred orientation of flaky and elongated grains towards the horizontal. The observations also suggest that the presence of irregular and angular shaped silt prevents complete preferred orientation and tends to discourage overall preferred orientation of parallel clay arrays and elongated and flaky silt at deposition, albeit that all other factors may be conducive to the development of such configurations. This confirms the findings and opinions of Mitchell (1956) and Burnham (1970) and is well demonstrated by the fact that the only parallel clay array to display complete preferred orientation occurred in the case of Laurieston Layer I, which was comprised entirely of clay regions. Also it would seem no mere coincidence that two of the lightly compressed brackish water materials which contained haphazard parallel clay arrays, and displayed haphazard orientation of flaky and elongated matrix grains, namely the Renfrew Layer II, and the Shannon B deposit, also contained a significant proportion of bulky grains. Of course where flaky and elongated grains are preferentially orientated, the degree of disorder imparted to a surrounding parallel clay array is considerably reduced as demonstrated by the microfabrics of the Laurieston Layer II, Renfrew Layer I and Boston deposits.

There is also a possible explanation for the presence of the haphazard grain and essentially parallel clay arrays in the Gallowgate deposit. This is based on the observation that clay microvein systems were observed throughout the microfabric of these samples. Since the overwhelming weight of evidence suggests that such features are shear or stress induced, it follows that perhaps the deposit at

Gallowgate has suffered post-depositional deformation and shearing which have resulted in a disordered matrix, disrupted by clay veins. The microfabric of the lightly compressed Lacustrine clay from Hurlford also seems to bear witness to such events. Its fabric is also intensely veined and its matrix contains haphazard grain and parallel clay arrays. This of course is a matter of some conjecture.

It would seem, from the rough estimates made of the nature of the constituent clay particles comprising the various random and parallel clay arrangements present within the microfabrics of the lightly one-dimensionally compressed soils, that there is a tendancy for arrangements to comprise both clay groups* or clusters and clay individuals. This tendancy was more pronounced in the lightly compressed marine and lacustrine soil groups than in the estuarine soil group. It is suggested however, that the clay individuals are not in the main clay minerals, but in fact are particles of inactive non-clay mineral material, e.g. quartz feldspars. This notion is based partly on the observation that the clay individuals were of mostly coarse clay size, Section 5.26.(a) and on the knowledge of the mineralogical data which is available, Table 5.1. as well as on the observed overall morphology of these units. This view reinforces the findings of Hammond et al (1973) and Smalley et al (1973). The findings, therefore, of Smart (1971, 1975), Barden (1972b) and others would also seem to have been confirmed in that it appears that despite perhaps favourable electrolyte conditions, the complex interaction of all the factors at deposition is more likely to result in some sort of clay mineral group or cluster configuration, than (single clay) mineral platelet interaction.

It is tentatively suggested that for the case of lightly one-dimensionally compressed soils which are strongly illitic in character, a marine environment is more conducive to the formation of a heterogeneous basic order assemblage network than is either a

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* it must not be overlooked that results of the preliminary critical point drying investigation (Section 4.3.8.) indicate that air-drying may have induced some clay group formation and extension.

brackish or freshwater environment. It follows that inter-assemblage pores are more likely to feature in marine deposits. Furthermore, it appears that irregular aggregations as opposed to regular ones, prefer to form under marine conditions, and that interweaving bunches might possibly be expected to display haphazard orientation when forming in marine soils and to exhibit preferential orientation under brackish water conditions.

It largely follows from what has been said, that significant anisotropy of the composite microfabric of soils or layers, is more likely to be associated with lightly one-dimensionally compressed estuarine and brackish water deposits, than with lightly compressed marine or freshwater deposits.

Observations made of the nature of the layer interfaces in the New Liskeard varved clay suggest that a definite pattern does tend to exist in glacial lacustrine deposits due to the detailed nature of the sedimentation process as explained by Kenney and Chan (1972) and Harrison (1975). Furthermore the present microfabric observations of the layered estuarine deposits from Laurieston and Renfrew indicate that similar mechanisms of deposition may also in certain cases operate in estuarine environments.

The three individual layer types within the Laurieston and Renfrew deposits displayed dissimilar composite microfabrics, and this tends to reflect differing sets of factors at deposition, Odom (1967).

The finding, that parallelism was highly prevalent at the elementary particle arrangement level in the heavily one-dimensionally compressed marine and lodgement till deposits suggests that very high pressures do tend to induce parallelism. It is possible of course that parallelism was induced at deposition in the two marine clays, but while direct comparisons are not strictly valid because of differing structural and environmental characteristics, it would seem reasonable to suggest that since the lightly one-dimensionally compressed marine soils displayed no such tendancies, parallelism in the Jackson and Luanda clays is probably a pressure induced feature.

It is rather interesting to note that parallelism prevails in those marine clays which are known to be strongly montmorillonitic in character. Their parallel clay arrangements are in fact very similar to those reported by Pusch (1971), in the heavily one-dimensionally compressed Na montmorillonitic London clay.

While parallel clays displayed significant preferred orientation overall in most cases, the influence of factors other than pressure, namely bulky grain content and weathering also appear to have exerted their influence. For example, the high proportion of irregular shaped silt grains in the clay-granular matrix of the Luanda marine clay, would seem to be responsible for the lack of strong preferred orientation of parallel clay arrays and elongated grains*. Indeed regions which were essentially of the clay variety did display strong preferred orientation, but these were predominated over by clay-granular regions wherein, by virtue of the bulky grain content, a tendancy towards haphazardness was in evidence. In the Hurlford (fresh) till irregular shaped silt and sand grains although subordinate to elongated grains, would still seem to have had a disrupting influence on the preferred orientation under pressure, of the parallel clay arrays and elongated silt and sand grains within the clay-granular matrix.

In contrast, the predominantly parallel clay array within the essentially grain free matrix of the Jackson clay, displayed strong preferred orientation.

The haphazard parallel clay array and the haphazardly arranged elongated and flaky silt and sand grains within the clay-granular regions which form the bulk of the matrix of the Hurlford (weathered) till would seem to be the result of disrupting influences from both a bulky granular content and possibly the effects of some type of weathering.

Weathering as a disruptive element, has already been identified by

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* the Luanda clay has also suffered intense desiccation and this may also have induced some disorder, see later.

Chandler (1972) and it would appear that similar mechanisms to the ones described by Chandler may have been operative in the case of the Hurlford lodgement till. Moreover, evidence of the 'in place' decomposition of fine sand grains appears to have been found and this in fact may explain for example, some of the orientated clay textures as suggested by Korina and Faustova (1964), as well as the occasional occurrence of the clean granular regions within the matrix of the Hurlford (weathered) till. The notion that these may be the fragmented remains of large sand grains is consistent with the fact that the grading of the weathered till is finer than that of the fresh till at Hurlford as explained in Chapter 5, Section 5.18.1.

It would seem reasonable to state, on the basis of the microfabric observations of the heavily one-dimensionally compressed marine and till deposits that extreme compression promotes homogeneity within the basic assemblage network, i.e. assemblages such as connectors, aggregations and bunches do not survive high degrees of one-dimensional compression. This statement in general terms reinforces the postulations of Engelhardt and Gaida (1963) and Yong and Warkentin (1975). It follows of course, from this statement that inter-assemblage pores will tend to be absent in heavily one-dimensionally compressed soils. It also follows from what has been said, that it is likely that a significant degree of anisotropy will be displayed by a heavily one-dimensionally compressed material providing disruptive elements have not been at work. Moreover, high degrees of anisotropy are more likely to be associated with heavily one-dimensionally compressed deposits with a low bulky grain content.

Clay arrays wherein interaction of constituent clay particles was not clearly discernible no matter the direction of viewing in the S.E.M., i.e. the partly discernible clay arrays, were highly prevalent and dominant in the highly three-dimensionally compressed deposits and were prominent in certain of the lightly three-dimensionally compressed deposits. These are undoubtedly highly complex features. A simple arguement is offered to explain their possible origin and overall character and this will now be discussed.

It is suggested that a partly discernible clay array is either a confused mixture of clay mineral particles and amorphous material, or a haphazard parallel clay array, or a combination of both.

The first of these requires little or no explanation and is based on the knowledge that many of the soils in question, namely the Tucson deposit, the three Israeli floodplain deposits and the Ford loess, contain free calcium carbonates. Free iron oxides are known to be present in significant quantities in the Transvaal sand and 'amorphous' materials have been reported as being abundant in the Onderstepoort clay. The indistinguishable clay-cement phase model already cited in Chapter 3., Fig. 3.3., seems particularly appropriate to this type of situation.

The second of these however, requires some explanation and the following discussion is centred around the conceptual model presented in Fig. 6.11. Fig. 6.11.(a) shows a portion of a clayey matrix which is partly discernible in character when viewed in the S.E.M. and which is honeycombed in places and disrupted by two wavy, planar trans-assemblage pores. Fig. 6.11.(b) represents the internal organisation of an aggregation and a connector which, externally, display a partly discernible character in the S.E.M.

According to these simple models, these so called partly discernible configurations are in fact extremely perturbed three-dimensional parallel clay arrays wherein crinkled forms prevail and very strong edge-edge intergrowth is intense.

Several embedded grains are shown in Fig. 6.11.(a) and as indicated the parallel arrangements in the immediate vicinity of the grain surfaces are sympathetically orientated with the surfaces. Elongated and flaky grains are shown displaying haphazard orientation. The trans-assemblage pores, which may tend to follow grain surfaces, are also shown having parallel clay arrangements aligned along their boundaries.

The configuration in Fig. 6.11.(a) is appropriate to the case of the three Israeli deposits and the two residual clays, and to a lesser extent the Maricopa deposit. Fig. 6.11.(b) is appropriate to the Tucson, Lydda, Holon and Casenga deposits. It is considered that the various clay arrangements and pore features represented in Fig. 6.11. have formed as a result of the desiccation of the highly active clay mineral phase.

Although the above concept is a matter of some conjecture, a number of points do seem to support it:

1. All the materials in question are strongly montmorillonitic in character and have suffered large essentially three-dimensional compression due to desiccation. Edge-edge intergrowth, crinkled edges, the randomly arranged wavy-planar trans-assemblage pores, the sympathetic orientation of arrangements with grain and pore boundaries, and an essentially isotropic pattern can each be taken to be consistent with the above aspects.

2. Such a configuration offers a possible explanation as to why no matter the direction of the fracture plane, the same type of pattern was observed in the microscope.

   By way of demonstration, several modes of fracture are suggested in Fig. 6.11.(a). In each case the fracture plane will tend to follow the route offering the least resistance, i.e.:

   (a) Fracture mode (1) and (2): here the fracture plane will tend to travel along, rather than cut across the planes of preferred orientation the result being a surface of very rough topography at the microlevel which displays a partly discernible character due to the fact that the plane of edge-edge intergrowth is being viewed*. The prominence of crinkled edges

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* This aspect was discussed in Chapter 3, Section 3.2.2.1. and the model of Smart (1969), Fig. 2.12. is particularly appropriate.

which was observed is probably due to the disruption of some of the weaker edge-edge bonds during fracture.

(b) Fracture mode (3): here the fracture plane will tend to travel along the existing trans-assemblage pore. The result is a topography which is probably not as rough as those in (a) above and which displays fabric which is partly discernible in character and which displays a lack of edges.

3. Similar clay configurations have previously been associated with montmorillonitic clays and more specifically with calcium montmorillonites*, e.g. Meade (1966), Pusch (1971). Meade pointed out that such arrangements are not detectable by conventional optical or x-ray methods. These would simply indicate that randomness was prevalent overall.

This may explain optical and scanning electron microscope observations made by Horta da Silva(1974a) on the Casenga clay which indicated randomness of the microfissures and the clay aggregate as a whole.

Much work remains to be done in order to confirm or otherwise the above concepts and to reveal the true nature of these complex features. Improved techniques for the preparation of a surface for viewing plus particle orientation and scanning electron microprobe studies may assist in this matter.

It would seem to follow from the above, that the clothing on the grains involved in the grain-grain contacts, which has the same partly discernible appearance as the arrays described above, is also associated either with the presence of amorphous material or the edge-edge intergrowth of clay particles which are associated with grain surfaces. It would appear to be no mere coincidence that the prominence or prevalence of partly discernible clay arrays almost coincides with that of the clothed grain-grain contacts.

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* The three Israeli floodplain deposits are known to contain calcium as the predominant adsorbed cation.

The above discussion has considered the occurrence and distribution of certain of the observed microfabric features within various geological soil groups. This has allowed the influence of some of the genetic factors to be examined in broad terms and thus the possible origin of these microfabric features to be assessed. It has been demonstrated that electrolyte concentration, clay fraction mineralogy and chemistry, depositional environment, deformation, high pressures - both one and three dimensional, and weathering - both mechanical and chemical, all appear to play a highly significant role in the genesis of soil microfabric.

It requires to be emphasised and must not be overlooked, however, that there are a large number of factors which were not, and could not be investigated specifically, due to lack of data and the difficulties involved in assessing the extent to which they had been operative. These include concentration and gradation of sediment, acidity, organic constituents and activity, temperature, state of agitation of water, cementation, leaching, seepage, stress relief, rate of loading, etc.

Finally, it is worth while to reflect at this stage on the global view expressed in Chapter 5, and to examine broadly its validity with respect to the transported soil sub-groups identified in the general plots shown in Figs. 6.1. - 6.10. These are, the lightly compressed marine, estuarine and lacustrine groups, the wind-blown and melt-out till groups, the heavily compressed marine and lodgement till groups and the over consolidated and desiccated floodplain group. The global view gave an idea of the likely character of the individual composite microfabrics which make up the total composite microfabric of the transported soil group. It would appear from the relevant microfabric plots given in Figs. 6.1. - 6.10. that this view is in essence, applicable to each of the geological sub-groups mentioned. Exceptions are by no means clear or firm, but it is tentatively suggested, in the light of the previous discussion that:

(a) Heterogeneity within the total clay array is more likely to be pronounced in the estuarine soil group.

(b) Random arrangements will tend to dominate the total clay array in the lightly compressed marine and lacustrine groups. Parallel clay arrangements are likely to be distributed mainly in the lightly compressed estuarine group, and the heavily one-dimensionally compressed marine and lodgement till groups. Partly discernible clay arrangements are likely to be distributed within the wind-blown and heavily over consolidated and desiccated floodplain groups.

(c) Clothed grain-grain contacts are more likely to prevail in the wind-blown and heavily over consolidated and desiccated floodplain groups.

(d) The lightly compressed marine, wind-blown, and heavily over consolidated and desiccated floodplain groups are likely to display heterogeneous basic assemblage networks whereas the heavily compressed marine and lodgement till groups are likely to display homogeneity within the basic assemblage network. This implies in fact, that connectors and aggregations and therefore inter-assemblage pores are more likely to be found in the former and that these assemblages and pores are less likely to be encountered in the latter. Moreover, while connectors and aggregations are likely to be more or less equally as prominent in the lightly compressed marine group, connectors are likely to be more prevalent than aggregates in the wind-blown group, and aggregations are likely to be more prevalent than connectors in the heavily over consolidated desiccated floodplain groups. Interweaving bunches seem likely to be confined to the lightly compressed water laid groups.

(e) The individual composite microfabric is more likely to display some degree of anisotropy overall, within the lightly compressed estuarine and heavily compressed marine and lodgement till groups.

CHAPTER 7

MECHANISMS OF STRUCTURAL INSTABILITY FROM THE MICROFABRIC VIEWPOINT

7.1. INTRODUCTION.

It is the aim of this chapter to examine certain of the mechanisms of structural instability from the microfabric point of view, in the light of the observations made in this study.

Attention will be focussed on the mechanisms of sensitivity, collapse and expansion which are examples of structural instability as discussed for example, by Sultan (1969) and Aitchison (1973). Sensitivity will be considered first and collapse and expansion will then be considered together, since (i) they occur in essentially the same geographical areas and in the same climates, (ii) they are in the main both triggered by the imbibation or ingress of water, and (iii) certain soils can display both mechanisms, i.e. dual behaviour.

7.2. SENSITIVITY.

7.2.1. The Mechanism.

Sensitivity (S_t) is defined as the ratio of undisturbed to remoulded undrained shear strength. Soils may be classified according to their measured (S_t) values and the scheme suggested by Rosenqvist (1953), Table 7.1. is used here. As shown, the broad categories are insensitive ($S_t \approx 1.0.$), sensitive ($S_t \approx 1-8$), and quick ($S_t > 8$). A quick clay is one which turns to a viscous liquid on remoulding, i.e. its remoulded strength is extremely low. Such deposits occur in many parts of Scandinavia and Eastern Canada.

The causes of sensitivity are by no means clear but as discussed by Skempton and Northey (1952), Mitchell and Houston (1969), Smalley et al (1973) and Mitchell (1976), a metastable fabric, inactive non clay mineral clay size particles, cementation, delayed compression, weathering, thixotropy, salt leaching, ion exchange and selective leaching (change in the monovalent, divalent cation ratio) and the formation or addition of dispersion agents all may contribute to the development of sensitivity.

To elaborate a little on the fabric contribution, this has been associated with the breakdown on remoulding of open random (flocculated) clay particle networks of various types, e.g. Casagrande (1932), Fig. 2.14., Rosenqvist (1959), Fig. 2.2., Pusch (1966, 1970), Fig. 2.10., Mitchell and Houston (1969), Fig. 2.6., Hammond et al (1973), Moon (1975) and Mitchell (1976). It requires to be emphasised that while some sort of open fabric is necessary for the development of sensitivity it alone is not sufficient to cause quickness and indeed the microfabric of a quick clay and adjacent zones of much less sensitive clay may be the same, Mitchell (1976).

7.2.2. The Microfabric of the Sensitive Soils Studied.

Twelve of the soils investigated in this study are known to display sensitivity to some degree. These include, five medium sensitive water laid deposits from Scotland, U.K., four very sensitive and quick marine clays from Norway and three quick water laid deposits from Eastern Canada. The geological and geotechnical background as well as the microfabric character of these soils have previously been given in Chapter 5. The more general engineering properties are summarised in Table 7.1. This Table in addition, gives the undrained shear strength values for the soils. A broad summary of their microfabric character will now be given.

7.2.2.1. Elementary Particle Arrangements.

The total elementary particle array was dominated by a total clay array in all but one case, namely the medium quick Sundland clayey silt, Fig. 7.1. wherein a clay array shared dominance with a granular array.

Clay arrays were essentially random in the Norwegian and Canadian clays, but in the Scottish medium sensitive soils the clay array ranged from being predominantly random to essentially parallel in character, Fig. 7.2. Although by no means prominant features, partly discernible configurations were observable in the medium sensitive Grangemouth deposit, and the very sensitive and medium quick deposits from Drammen Town and Sundland, respectively.

The constituent clay particles were in the medium sensitive Scottish soils, mainly clay groups, while in the very sensitive and quick Norwegian deposits, clay groups and plate or bulky shaped individuals* of coarse clay size appeared to be equally prominent, Fig. 7.3. Clay clusters and clay individuals appeared to be equally abundant in the Canadian clays, although in the case of the Saint Alban deposit, platey individuals of mainly fine clay size and often very thin, predominated over clay groups and clusters, Fig. 7.3. It also seemed in the case of the Saint Alban deposit, that amorphous material was present at the contact points, and also in the case of the Saint Jean Vianney clay it appeared that coarse clay size individuals were coated with some type of amorphous material.

The granular arrays which were perhaps most prevalent in the group of Norwegian soils generally involved clean grain-grain contacts, Figs. 7.1. and 7.4. In the case of the Scottish medium sensitive soils, the grains were generally medium-fine silt sized with flaky and elongated or flaky and angular shapes, and were generally closely packed. In contrast grains involved in the grain-grain contacts within the Drammen Town, Solbergelva, Sundland and New Liskeard deposits were mainly fine silt sized with flaky and elongated or flaky and angular shapes and were loosely packed, Fig. 7.4.

7.2.2.2. Particle Assemblages.

Regarding the make-up of the basic order assemblage network, Fig. 7.5., matrices (or layer region systems where appropriate) totally

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* As discussed in Chapter 6, it is believed that these clay individuals are in fact particles of inactive quartz and feldspar derived from the process of glacial grinding.

dominated in all but the medium quick Sundland clayey silt. These assemblages were comprised in most cases either entirely or predominantly of clay-granular regions while in all but one of the remaining cases they comprised entirely of either granular or clay regions, Fig. 7.6. In the case of Sundland, connectors bridged and buttressed silt grains and also served to link silt sized and irregular shaped aggregations. Similar connector aggregate systems, although not as abundant, were observed in the extra quick Ellingsgrud deposit. Also silt sized and irregular shaped aggregations were linked to the surrounding matrix via bridge connectors in the very sensitive Drammen Town deposit while connectors were occasionally seen bridging and buttressing silt grains in the very sensitive Solbergelva deposit.

As may be appreciated from Fig. 7.5., connectors, aggregations and bunches were not on the whole, readily observed in the Scottish medium sensitive deposits, and the Canadian quick clays. Possible exceptions were, the Grangemouth clayey silt wherein aggregations and haphazardly arranged bunches were occasionally abundant; the Renfrew clay, wherein connectors, aggregations and bunches were observable, and the New Liskeard varved clay wherein connectors were in evidence.

7.2.2.3. Pore Spaces.

It largely follows from what has been said above, that intra-elemental pores associated with the clay particle arrangements, dominated the basic pore space in all but one case, i.e. the Sundland clayey silt wherein these pores were predominated over by inter-assemblage pores of the connector aggregate system. Moreover, it seemed that inter-assemblage pores were more prevalent in the very sensitive and quick Norwegian clays, than in either the medium sensitive Scottish clays or the quick Canadian clays, Fig. 7.7. No trans-assemblage pores were observed.

7.2.3. Discussion.

The following sections deal with the mechanism of sensitivity, as displayed by the Scottish, Norwegian and Canadian deposits, primarily from the microfabric viewpoint.

(i) Scottish Medium Sensitive Deposits.

Sensitivity to disturbance as displayed by these soils would seem from the microfabric standpoint to be associated principally with the breakdown of random clay group networks which predominated over, or shared dominance with parallel group arrangements in the case of the Grangemouth, Renfrew and Hurlford deposits.

This view is consistent with the general concepts presented previously by e.g., Mitchell and Houston (1969). Also, in the case of the Grangemouth and Renfrew deposits the breakdown of aggregations and interweaving bunch networks may have contributed to the mechanism.

It seems unlikely however, that the parallel clay arrays and the granular arrays (comprising closely packed medium-silt grains) would have contributed significantly to sensitivity in the various clays, particularly in the case of the Laurieston and Gallowgate deposits wherein they were most prevalent.

Considering this last point and that the microfabrics of the five deposits differed significantly at the elementary particle array level, to some extent at the assemblage level and their measured sensitivities were essentially the same, Table 7.1., it becomes evident that other factors must also have been at work. For example, thixotropy or possibly a small degree of salt leaching in the case of the marine and estuarine deposits.

(ii) Norwegian Very Sensitive and Quick Deposits.

Sensitivity to disturbance displayed by these deposits would seem from the microfabric point of view, to be associated principally with the breakdown of the following:

(a) Open random clayey group arrangements. This again is consistent with the view of Mitchell and Houston (1969).

(b) Open random clay individual (quartz and feldspar) arrangements. This reinforces the opinions of Smalley et al (1973) and Hammond et al (1973).

(c) Loosely packed fine silt (quartz and feldspar) grain-grain contacts. This again confirms the findings of Hammond et al (1973).

(d) Bridge and buttress connectors which span silt grains.

(e) Open linked aggregate systems.

It has to be remembered that breakdown of these configurations takes place against a background of salt leaching Bjerrum (1967). Moderate leaching has occurred in the Drammen Town and Solbergelva deposits whereas strong leaching has occurred in the Sundland and Ellingsgrud deposits, Table 7.1. Leaching has the effect of reducing the plasticity of clay deposits. In the leached environment however, the water content remains close to the value which existed prior to leaching and hence it now tends to approach or exceed the liquid limit depending on the degree of leaching involved, Table 7.1.

This means that when the breakdown of the arrangements (a) to (e) occurs, the now less active clay minerals and the fine grained quartz and feldspars which form in the clay and granular arrangements, are pitched into a fluid phase, which is in excess of that with which they can become electrochemically balanced. Contact between particles is limited, and therefore the effective stresses and hence the remoulded strength is very low. This would seem to be the principal reason for the high sensitivity measured in the moderately leached clays and the quickness displayed by the intensely leached deposits.

Hence the breakdown of the microfabric features (a) - (e), mentioned previously, contributes to the sensitivity but it alone does not cause high sensitivity or quickness. This view serves to reinforce the statement made by Mitchell (1976). The notion is better demonstrated by the observation that while the microfabrics at the elementary particle array level, and to a large extent the assemblage level, are somewhat similar, the measured sensitivities cover a wide range.

(iii) Canadian Quick Clays.

Sensitivity to disturbance displayed by the two Champlain Sea deposits would seem from the microfabric point of view to be associated principally with the breakdown of open random clay cluster arrangements, and open clay individual (quartz and feldspar) arrangements. Again this is in general agreement with the findings of Smalley et al (1973), and Hammond et al (1973). This would also appear to be the case for the New Liskeard varved clay wherein it seems that the breakdown of fine silt size quartz and feldspar grain-grain contacts and connectors spanning silt grains, also contributes to the mechanism.

It has to be remembered that this fabric breakdown occurs against a background of leaching and cementation in the case of the Champlain Sea deposits, la Rochelle (1974), and cementation in the case of the New Liskeard varved clay, Quigley and Ogunbadejo (1972). The broad concept of the effect of leaching was discussed above. Cementation has the effect of preserving, against the forces of compression, a very open fabric and a correspondingly very high water content in relation to the liquid limit as indicated in Table 7.1. It also has the effect of imparting a higher shear strength to the soil structure than would normally be associated with such very wet clays. Compare for example, the strengths of the cemented Canadian and the non-cemented Norwegian deposits, Table 7.1.

This means that a dramatic decrease in strength occurs on rupture of the cementation bonds and moreover on the subsequent breakdown of the configurations mentioned above, the constituent clay clusters and the inactive clay individuals and fine silt grains are pitched into an excessive amount of pore fluid. The remoulded strength therefore, is very low. Hence the breakdown of the various microfabric features mentioned above contributes to the sensitivity, but it alone does not cause the quickness which is displayed by these Canadian deposits. Again, this reinforces the general statement of Mitchell (1976).

Finally, two points of general interest emerge from the observations made on the cemented Canadian quick clays.

(a) The observation that clay individuals in the Saint Jean Vianney clay were coated with some kind of material (probably carbonates), is in agreement with previous observations, Bjerrum (1973) and Hammond et al (1973). Bjerrum in fact, used his 'uniform smear model' to explain the fact that the strength of the cementation bonds in the Saint Jean Vianney clay appear to be dependant on the maximum past overburden pressure. Presumably, if cementation agents simply exist at the contact points, as for example would seem to be the case in the Saint Alban clay, no such relationship would tend to exist, i.e. the strength of the bonds is independant of overburden pressure.

(b) It is suggested that this uniform coating or smear of cementatious material may have been responsible for the formation of the clay clusters at deposition. To the author's knowledge, no previous investigations have reported the presence of clusters in the Champlain Sea (Leda) clay deposits. In contrast the observed morphology of the clay particles in the Saint Alban clay is more like previous reports, e.g. Gillot (1970), and Barden (1972b).

(iv) Summary.

On balance the mechanism of sensitivity appears, from the microfabric point of view, to be associated principally with the breakdown of one or a combination of the following:

(a) open random clay group arrangements,
(b) open random clay individual (quartz and feldspar) arrangements,
(c) open random clay cluster arrangements,
(d) loosely packed fine silt grain-grain contacts,
(e) open silt grain connector (bridges and buttresses) systems,
(f) open linked aggregate systems.

These opinions serve to both confirm and extend previous concepts of the part played by microfabric in the mechanism of sensitivity. For example, those regarding the random group arrangements confirm the views of Mitchell and Houston (1969) while those relating to the involvement of inactive quartz and feldspars in the clay and fine silt fractions, reinforce the concepts put forward by Smalley et al (1973), and Hammond et al (1973).

On the other hand, the present study has suggested for the first time, that clay cluster arrangements may be involved in the mechanism, specifically in the Canadian quick clays. It has also pointed out that the mechanism of sensitivity not only operates at the elementary particle array level, but also involves the breakdown of higher level fabric features, i.e. the connector and aggregation assemblages.

This study has also demonstrated that cementation agents can occur either as coatings to clay particles, confirming previous findings for example of Bjerrum (1973), or as particle contact features. Moreover, it has been suggested that the former may be responsible for the development of the clay clusters which were discussed above.

The observation that clay-granular regions play a prominent role in the particle matrix features also poses the question, is the 'bond clay' concept of Casagrande (1932) perhaps a reasonable one?

Finally, the findings of this investigation have demonstrated that factors such as leaching and cementation do play a more dramatic role than microfabric does in the development of very sensitive and quick deposits.

7.3. COLLAPSE AND EXPANSION

7.3.1. The Mechanisms

7.3.1.1. Collapse

Collapse is generally the term used to describe the mechanism whereby a desiccated* soil deposit undergoes rapid settlement under load when moisture becomes available. Fookes and Best (1969) define collapse as a settlement on flooding occurring very rapidly with 95% of the settlement being completed within 10 minutes.

The nature of the collapse mechanism can perhaps be more easily appreciated by referring to the e-log p curve given in Fig. 7.14. As can be seen, the soil to which these curves refer in the natural desiccated state has a low compressibility. At an applied vertical pressure of around 100, 800 and 2800 kN/m^2, soil samples were flooded and consequently suffered a dramatic settlement at these pressures, i.e. they collapsed.

The fundamental causes of the collapse mechanism have been the subject of a large number of investigations principal among which are Jennings and Knight (1957), Sultan (1969), Dudley (1970), Horta da Silva (1971b), Aitchison (1973) and Barden et al (1973). It would seem, according to these studies, that the collapse mechanism is associated essentially with an open desiccated structure of a bulky granular nature where the structural elements are held together by some sort of force or material which has temporary strength

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* A desiccated condition is defined as a moisture state, such that if free water is brought into contact with the soil, a portion of this water will be absorbed by the soil, Jennings (1973).

from electrochemical or cementatious bonding or from surface tension forces. Collapse involves the elimination, through the introduction of moisture, of these sources of strength, and the consequent breakdown under shear stress, of an open fabric which may be comprised of (a) clothed grain-grain contacts, (b) grain bridges or buttresses comprised of either clay or silt plus possibly cementatious material such as iron oxides or carbonates, and (c) clay aggregates.

It has to be emphasised that while some type of open fabric is a prerequisite for collapse it is not the only factor involved. The amount of collapse or fabric breakdown is in fact, a function of a large number of factors, including initial structure*, degree of water imbibation and stress level. This last point is well demonstrated by Fig. 7.14. As shown, wetting under 2800 kN/m^2 caused more collapse settlement than did wetting under 800 kN/m^2, which in turn caused more settlement than 100 kN/m^2. It is also seen that the post flooding curves are above the remould curve, which Fookes and Best (1969) suggested indicates that wetting particularly under the lower stresses did not completely destroy the pre-wetted fabric.

It was considered at first that collapse behaviour contradicted the principal of effective stress, since with the reduction in effective stress which occurs upon water imbibation the result should, according to this principal be one of expansion, not settlement. However, as pointed out by Horta da Silva (1971b),Barden et al (1973), and later by Mitchell (1976), collapse is a micro-shear problem and in fact while the effective stress principal is violated at the continuum level, it is not violated at the inter particle level.

7.3.1.2. Expansion.

Expansion is usually the term used to describe the mechanism whereby a desiccated soil deposit displays either an increase in volume or, if the deposit is partially or fully restrained, swelling pressures when moisture becomes available.

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* structure as defined in Chapter 1.

The nature of the expansion mechanism can perhaps be best appreciated by referring to the e-log p curves given in Fig. 7.15. As can be seen, the soil to which these curves refer, is practically incompressible in the natural desiccated state. When however, water is made available to a sample under an applied total stress of 200 kN/m^2, it undergoes an increase in volume. Expansion would be greater under lesser loads and smaller under higher loads.

The fundamental causes of this type of expansion are extremely complex and can be considered as being associated with physical, mineralogical and physico-chemical effects, Mitchell (1976).

Physical effects include microfabric and the elastic rebound of flaky particles and platey clay groups upon the reduction in effective or capillary stresses. Mineralogically speaking, expansion is normally associated with the expanding lattice minerals such as montmorillonite and vermiculite. Physico-chemical influences involve particle surface adsorption forces and osmotic repulsion. Unfortunately the individual effects cannot be expressed quantitatively and in order to overcome this problem the expansion mechanism is considered from the effective stress (continuum) viewpoint, Jennings and Kerrich (1962) and Aitchison (1973).

Aitchison presented the effective stress equation given below.

$$\sigma' = \sigma + X_m p''_m + X_s p''_s$$

where P''_m = matrix suction, which may be taken as being associated with capillary, adsorptive and micro osmosis effects.

P''_s = solute suction, which has been largely ignored and which may be associated with concentration of dissolved solutes in the pore fluid, essentially at the continuum level.

X_m and X_s - empirical factors which are normally within the range 0 - 1 and which are dependant upon stress paths.

A decrease in either the matrix or solute suction thus results in a decrease in effective stress and thus overall expansion.

From the microfabric viewpoint, the expansion mechanism has been discussed generally in terms of the stability of random (flocculated) or parallel, clay particle or group configurations, e.g. Seed and Chan (1959), Seed et al (1962), Burland (1965), Gillot (1968), Quirk (1968) and Yong and Warkentin (1975) and others.

Depending on the cation type involved, expansion will tend to occur between clay groups or quasi-crystals (Ca illites and montmorillonites) or within and between groups or quasi-crystals (Na illites and montmorillonites).

Tovey et al (1973) appear to have been the only workers to actually observe the changes in fabric which occurred during the expansion process. They used the scanning electron microscope and the technique of freeze-drying to facilitate this. Their observations will be dealt with later in Section 7.3.3.

The emphasis has been laid, and it is easy to understand why, on clay particle arrangements. However, bulky granular arrangements have been linked with expansiveness by De Bruyn et al (1957), who stated that potential expansiveness may be expected if the grains are surrounded by a uniform colloidal coating. They also concluded that if the grains are bare no expansion need occur.

7.3.1.3. Dual Behaviour.

Certain soils exhibit the dual behaviour of expansion (under light loads) and collapse (under heavier loads). This rather complex situation is most easily demonstrated by reference to the e-log p curves given in Fig. 7.16. This shows, that for the particular soil in question, wetting at pressures less than 800 kN/m^2 results in expansion, whereas wetting at pressures in excess of this critical pressure results in collapse of the structure or fabric.

Dudley (1970) remarks that the clay content appears to be critical in this regard. No direct indication however, has been made as to the likely character of the microfabric of soils which exhibit such dual behaviour.

7.3.2. The Microfabric of the Collapsing and Expansive Soils Studies.

The collapsing, expansive and dual behaviour soils included in this study, Table 7.2. possess a wide variety of origins and properties and serve to exemplify the widespread occurrence of such soils. The broad geological and geotechnical background as well as the microfabric character of the various soils have previously been given in Chapter 5. Details of their collapsing and expansive behaviours are given in Table 7.2. A broad summary of their microfabric character is given below.

7.3.2.1. Elementary Particle Arrays.

(a) Collapsing Soils.

The total elementary particle array was either predominantly or entirely of a granular nature. Clay arrangements were occasionally abundant in the three windblown deposits and in the Breidamerkurjokull and Taylor Valley tills, Fig. 7.8. The total granular array was essentially or predominantly clothed in character in some cases while being essentially or predominantly clean in character in others, Fig. 7.10. Where present clay arrays were generally essentially partly discernible in character, Fig. 7.9. On the basis of the discussion in Section 6.3.3., these are likely to be confused mixtures of clay mineral particles and amorphous material, probably either carbonates or iron oxides.

(b) Expansive Soils.

The total elementary particle array was generally entirely of a clayey nature, Fig. 7.8. Essentially clothed granular arrays were occasionally and rarely abundant in the Lydda and Afulah deposits respectively. The total clay array was essentially and predominantly parallel in the Luanda and Jackson marine clays respectively whereas it was essentially partly discernible in character in the other expansive soils,

Fig. 7.9. On the basis of the discussion in Section 6.3.3. it is likely that these partly discernible forms are extremely perturbed parallel clay arrays. Some cementatious carbonates may also be present.

(c) Dual Behaviour Soils.

The total elementary particle array was predominantly granular in nature in the Tucson and Maricopa deposits, wherein clay arrays were also occasionally abundant, but was predominantly clayey in character in the case of the Casenga clay, wherein a granular array was also rarely abundant. Granular arrangements were essentially clothed in character in the Tucson and Casenga deposits whereas a balanced granular array was apparent in the case of the Maricopa deposit, Fig. 7.10. Clay arrangements were essentially or predominantly partly discernible in character, Fig. 7.9., possibly involving both confused mixtures and parallel clay arrays.

7.3.2.2. Particle Assemblages.

(a) Collapsing Soils.

Broadly speaking, granular matrices dominated over or shared dominance with either regular aggregations or connectors, in the basic order assemblage network, Fig. 7.11., and 7.12. Clay regions were occasionally abundant within the matrices of the Breidamerkurjokull and Taylor Valley tills. Connectors were more prevalent in the collapsing wind blown soils, while aggregations were more prevalent in the meltout tills.

(b) Expansive Soils.

A matrix formed either the entire or the major portion of the basic assemblage network in each case. Broadly speaking connectors and aggregations were generally absent, and indeed were only occasionally abundant in the Lydda and Holon clays respectively, Fig. 7.11. Matrices comprised essentially either of clay or clay-granular regions or both, in most cases, Fig. 7.12. Granular regions were evident at the occasional and rare levels of abundance in the Lydda and Afulah soils respectively.

(c) Dual Behaviour Soils.

A matrix dominated the scene in the Maricopa and Casenga deposits, while this type of assemblage shared dominance with connectors and regular aggregations in the Tucson soil, Fig. 7.11. As shown, aggregations were in fact frequently to occasionally abundant in each of the three soils. The matrix was comprised essentially of granular regions in the Tucson and Maricopa deposits whereas clay-granular regions predominated over occasionally abundant granular regions in the Casenga clay, Fig. 7.12.

7.3.2.3. Pore Spaces.

The following statements largely follow from what has been said above.

(a) Collapsing Soils.

Intra elemental pores associated principally with the grain-grain contacts either dominated or shared dominance with the inter assemblage pores of the connector and aggregate systems, Fig. 7.13. The latter therefore, generally provided a sizable contribution to the basic pore space, while the intra-assemblage (honeycomb) pores were not prevalent overall.

Irregular trans-assemblage pores were in evidence in the Ford loess, Transvaal sand and the Breidamerkurjokull till.

(b) Expansive Soils.

Intra-elemental pores associated principally with the parallel clay arrangements dominated the pore space in each case. Intra-assemblage (honeycomb) pores overall contributed a significant amount, but were most prevalent indeed dominant, in the Onderstepoort clay, Fig. 7.13. As shown inter-assemblage pores were in overall terms, essentially insignificant.

Wavy planar pores were in evidence in the Holon, Afulah and Onderstepoort deposits. Irregular trans-assemblage pores were apparent in the Lydda clay.

(c) Dual Behaviour Soils.

In overall terms, intra-elemental and inter-assemblage pores each made significant contributions to the basic pore space, Fig. 7.13. The former were associated principally with the granular arrangements in the case of the Tucson and Maricopa deposits, but were associated principally with the clay arrangements in the Casenga clay. Intra-assemblage (honeycomb) pores were generally insignificant although such pores made an appreciable contribution in the Casenga clay.

Irregular shaped trans-assemblage pores were in evidence in the Tucson deposit while wavy planar pores were apparent in the Casenga clay.

7.3.3. Discussion.

The following sections deal with the mechanisms of collapse, expansion and dual behaviour, primarily from the microfabric viewpoint.

i) Collapse.

Collapse appears to be associated principally with the following microfabric features.

a) Granular matrices comprising clothed grain-grain contacts or clean grain-grain contacts or both. The clothing layers may be formed by either iron oxides and carbonates or low swelling minerals, e.g. kaolinite.

b) Open networks formed by bridge and buttress connectors. The connectors may have a variety of internal organisations, e.g. grain-grain contacts, random or parallel (tenuous bridge) clay (low swelling), and confused clay (low swelling) and iron oxide or carbonate (partly discernible) arrangements.

c) Open networks formed by direct interaction of regular aggregations with each other or the granular matrix. These are likely to comprise grain-grain contacts or confused clay (low swelling) and iron oxide or carbonate arrangements.

Of these, the granular matrix appears overall, to play the major role, the connectors and aggregations however, are both likely to play a significant role, although connectors may be more involved than aggregations in certain cases, and vice versa.

Hence introduction of water to a desiccated collapse prone structure (1) reduces surface tension or meniscus forces at grain-grain and aggregation contact points, (2) may cause dispersion or softening of low swelling clay arrangements either on grain surfaces (critical at contact points), or within connectors and aggregations and (3) causes dissolution of cementing agents. These events in combination with shear load, result in a rapid breakdown of arrangements a), b) and c) above, i.e. collapse. In terms of pore spaces, it was emphasised previously that an open fabric is an essential requirement for collapse to occur. It follows from what has been said above, that collapse involves the reduction in size of intra-elemental pores and the elimination of inter-assemblage pores. Moreover, the presence of irregular trans-assemblage pores prior to water imbibation, enhances collapse.

In summary, for collapse to occur two main structural characteristics are usually required, (1) an open fabric with partially saturated pores, and (2) an inactive clay fraction and possibly the presence of cementing agents. It requires to be stated that the above views are, broadly speaking, not new ones and only serve to reinforce existing concepts.

ii) Expansion.

Expansion appeared to be associated with matrices which are comprised mainly of clay and clay-granular regions which may be honeycombed. Connector and aggregation assemblages and granular matrix regions appear to play little or no role in the case of purely expansive behaviour.

In the particular expansive soils studied parallel clay arrays with overall, either some preferred orientation or no preferred orientation were in evidence. They are known to involve mainly montmorillonitic minerals, probably in the form of wavy clay groups (quasi-crystals). Expansion is likely to be between these groups and therefore, in the case of preferentially orientated arrays is likely to be mainly in the direction perpendicular to the direction of overall preferred orientation. In the case of haphazard and parallel clay arrays, expansion is likely therefore, to be essentially the same in all directions. These observations seem to be consistent with the results from mechanical tests. For example, a parallel clay array with a moderate degree of preferred orientation towards the horizontal was observed in the Luanda clay which under test displayed a degree of anisotropic behaviour with the greatest expansion occurring in the vertical direction, Table 7.2. Also, isotropic parallel clay arrays, (i.e. the partly discernible configurations, Fig. 6.11.), have been associated with the Israeli deposits which are known to exhibit essentially isotropic expansiveness, Table 7.2.

Regarding the actual mechanism of fabric change during expansion, the observations of Tovey et al (1973) are drawn on. They studied samples of the Lydda clay included in this study using scanning electron microscopy and freeze drying techniques. In broad terms, they reported for the undisturbed desiccated state a rather dense arrangement of particle domains between which large pores (1 μ and greater) existed. This study described a comparible microfabric for the Lydda clay in the air dried state, i.e. a haphazard parallel clay array which was honeycombed in places. In stark contrast the free swell sample showed an extremely random and open array of discrete elements.

It is postulated that from the desiccated state, wherein a dense packing of wavy clay groups, or quasi-crystals with edge-edge intergrowth is in evidence, due to the introduction of moisture, expansion has occurred perpendicular to the planes of the quasi-crystals and edge-edge bonds have been disrupted*. This leads to an open arrangement of discrete clay groups. The suggested mechanism is represented by the schematic sketches given in Fig. 7.17.

It is further suggested that microfabric studies of this nature may prove helpful in prediction of expansive potential. The analogy of the density index of sands seems to be valid, i.e. the densest parallel clay configuration corresponds to the air dried state and the 'discrete' random or parallel clay configurations as the case may be, corresponds to the free swell state, Fig. 7.17. Intermediate arrangements correspond to intermediate stages of the swelling mechanism. Further study is required in this regard.

In summary, expansion from the microfabric viewpoint, has been shown to be associated essentially with clay and clay-granular

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* This may be a time-dependant process particularly if cementation agents are involved.

matrices which may comprise of parallel clay (wavy group) honeycomb arrays which display a full range of degrees of anisotropy. Expansion has been considered as occurring in the direction perpendicular to the basal plane of the clay groups and therefore, will tend overall, to be isotropic for the case of a haphazard parallel clay array and will tend to be anisotropic for the case of preferentially orientated parallel clay arrays. Expansion has also been associated with the breakdown of edge-edge bonds.

iii) Dual Behaviour.

The dual behaviour of expansion under light loads and collapse under heavier loads appears to be highly dependant upon microfabric.

Both collapse and expansion require there to be a desiccated structure. Moreover in the light of the above discussion, it appears that expansion requires that there be a significant proportion of swelling clay minerals forming within a clayey matrix. Any essentially non-swelling clay minerals or cementatious material will tend to reduce expansion. Collapse requires that there be a microfabric which is open by virtue of the presence of granular arrangements, connectors and aggregations in various proportions. It seems logical therefore to suggest that a structure which exhibits both behaviours will require to be (1) desiccated (2) rich in swelling clay minerals, and (3) have a fabric which at least in part is comprised of open collapse prone arrangements.

Microfabric therefore, appears to play a major role in the dual mechanism. If the fabric comprises (1) granular matrix regions which consist essentially of predominantly grain-grain contacts clothed with swelling minerals and other materials, and (2) large numbers of either connectors, aggregations or both, which are each comprised of swelling clay mineral arrangements (this is the case in the Tucson and

Maricopa deposits), then expansion will only occur over a limited range of applied stresses. This indeed has been found to be the case in the Tucson and Maricopa deposits, Table 7.2.

On the other hand, if the fabric comprises (1) a matrix within which clayey regions predominate over clothed granular matrix regions, (with both the clayey regions and the clothing layers comprising swelling clay minerals), and (2) significant numbers of either connectors, aggregations or both, which comprise swelling clay arrangements (this is the case for the Casenga clay), then expansion will occur over a larger range of applied stresses. This indeed appears to be the case in the Casenga deposit, Table 7.2.

In summary, dual behaviour appears to be governed principally by microfabric which to some extent, reflects the amount, Dudley (1970), and distribution of clay material, and by composition, which serves to reflect the type of clay material. Broadly speaking, for a given swelling clay fraction and providing all other factors are equal, the more open and granular the microfabric, the lower will be the critical pressure*. Conversely, the less open and granular the fabric, the higher is likely to be the critical pressure. Hence, assumming all other factors to be equal, the critical pressure in a dual behaviour soil is a function of the relative proportions, by volume, of (1) granular matrix regions, connectors, aggregations and (2) clayey matrix regions.

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* Critical pressure is the pressure below which expansion occurs on wetting, and above which collapse occurs on wetting. It is sometimes referred to as the swelling pressure.

CHAPTER 8

DISCUSSION AND CONCLUSIONS

1. To date no suitable microfabric characterisation scheme has been available for use in the disciplines of engineering geology or soil mechanics. The schemes which are available have been devised for purposes other than engineering ones and primarily for use in the disciplines of soil pedology or soil science. They are too complex and detailed for engineering purposes and are therefore of little value in geotechnical engineering.

Thus a characterisation scheme has been developed in this study which is suitable for engineering purposes. Its suitability may be substantiated from a number of general points of view.

(i) It is relatively simple to apply.
(ii) Its terminology is limited and easy to remember.
(iii) It accounts for all levels of microfabric.
(iv) It is consistent throughout all levels, up to and including the macrolevel, and will serve to link very well with macrofabric study.
(v) It is not too specific at any one level and keeps in mind the global picture.
(vi) It has been well tested on a wide and representative range of natural engineering soils, and is sufficiently comprehensive and so structured that it accounts very well for the previous microfabric concepts as well as the variety and combinations of microfabric forms likely to be encountered in natural engineering soils.
(vii) It is flexible and open enough to allow for any additions and extensions that may have to be introduced as a result of future microfabric study.
(viii) Apart from form or morphology, it is based on both genesis and mechanical function and is therefore in broad terms, truly geotechnical in character.
(ix) It is independant of the technique of observation used.

In developing the scheme, the present study has considered four important aspects of soil microfabric.

(a) The nature of individual microfabric forms.
(b) The composite microfabric.
(c) The relative abundance of individual microfabric forms within the composite microfabric.
(d) Anisotropy within the composite microfabric.

Considering these one by one.

(a) The nature of individual microfabric forms.

Three main types of form are identified, namely, the Elementary Particle Arrangements, the Particle Assemblages, and the Pore Spaces. This approach is a totally new and simple one.

Elementary Particle Arrangements involve essentially interaction between a small number of like constituent particles. Sub-forms and sub-divisions of sub-forms are identified on the basis of size, nature and mutual organisation of the constituent particles. These are as follows: (i) the random or parallel clay group and clay individual arrangements, (ii) the random clay cluster arrangements, (iii) the partly discernible clay configurations, (iv) the clean and clothed grain-grain contacts and (v) the organic arrangements. This is a rather novel, and broad approach, and while further sub-division is possible, particularly in the case of the random clay group and organic configurations, this would seem from the engineering viewpoint, to be rather pointless in the majority of cases.

Particle assemblages are units of particle organisation which have definable physical boundaries and consist of arrays of one or more forms of elementary particle arrangements or smaller particle assemblages. Sub-forms and sub-divisions are identified on the basis of origin, mechanical function or morphology. The so called basic order particle assemblages include; the connectors (bridge and buttress); the aggregations (regular and irregular); the interweaving bunches; and the particle matrices or layer region systems (clay, granular and clay-granular). The so called higher order particle assemblages include; the microlenses; the microveins; and the microlayers. Again this is a novel and by design a broad view.

Pore spaces are formed by or occur within and between the elementary particle arrangements, and the particle assemblages. The so called basic pores are those which have a specific relationship to the occurrence of the elementary particle arrangements, and particle assemblages and include the intra-elemental, the intra-assemblage (honeycomb), and the inter-assemblage pores. Higher order (trans-assemblage pores) are those which occur without any specific relationship to the occurrence of particular microfabric forms. This is not a totally new concept and is in fact in sympathy with, and an adaption of existing ones.

(b) The Composite Microfabric.

The term composite microfabric described and accounts for the spatial organisation and interaction of the various particle assemblages and any trans-assemblage pores or large embedded grains which are present. In non-layered soils it refers to the organisation and interaction of the various features to form the complete microfabric within the limits of the soil deposit boundaries. In the case of layered soils, the term composite microfabric is applied in two senses. Firstly, it is applied in the sense of the composite microfabric of individual layers, whether they be macro or micro layers and secondly, it is applied in the sense of the composite microfabric of the layered system.

The term total composite microfabric refers to the summation of all the individual composite microfabrics of either individual soil masses or individual layers to form the composite microfabric of the total engineering soil regime. Sub-divisions such as the total composite microfabric of the transported inorganic soil group are identified. These are of course, simplifying and novel concepts introduced specifically for the purposes of discussion.

The general notion that soil microfabric may have a composite character involving the synthesis of a variety of different types and levels of form, is not of course a totally new one in as much as this is one of the principal features of the existing pedological fabric characterisation schemes. This study however, serves to emphasise that such an approach must also be embodied in any engineering fabric characterisation scheme.

(c) The Relative Abundance of Individual Microfabric Forms.

The relative abundance of certain of the microfabric forms within the individual composite microfabric of non-layered soils and of individual layers within layered soils, is considered using a two stage approach. Firstly, the relative abundance of the various subforms of elementary particle arrangement, basic order particle assemblage and basic pore space are assessed to give the so called primary relative abundances. Secondly, the relative abundance of the various elementary arrangements and basic order assemblage subdivisions, is assessed to give the so called secondary relative abundances. This is a novel approach. It provides, for the first time, a way of expressing, using a consistent language, the relative extent to which microfabric forms are involved within the composite microfabric.

(d) Anisotropy Within the Composite Microfabric.

Anisotropy within the composite microfabric of both non-layered soils and individual macro or micro layers within layered soils is assessed. The basic approach involves a consideration of the composite microfabric at three levels, namely, 5 μ, 50 μ and 500 μ. Aspects of anisotropy, including degree of anisotropy, direction of preferred orientation and principal feature or features inducing anisotropy are assessed at each of these three levels. This is not a totally new approach in the sense that it is generally recognised in engineering studies that anisotropy does tend to vary with the level of fabric considered. However, this study strongly emphasises the need for such an approach, and the point of view that causal features are also extremely important. The particular levels were chosen after some thought and it is believed that these will be sufficient in the majority of cases.

The prime deficiency of the scheme is that it does not lend itself to complete quantification. However, neither this nor any other acceptable microfabric characterisation scheme will ever be fully quantifiable due to the complex nature of soils. If any quantitative data does ever become available relating either to degree and direction of preferred orientation or pore size distribution, then this would serve as a valuable supplement.

2. The scanning electron microscope has been applied fairly successfully to a large range of engineering soil types. It has proved to be highly versatile and, for the first time, this study has applied the scanning electron microscope over a full range of magnifications (x 20 to x 50,000) in a systematic manner. Previous scanning electron microscopy studies have

tended rather to concentrate on the higher ranges of magnification. By virtue of the wide application of the scanning electron microscope in this study, it becomes clear that the scanning electron microscope could be used in conjunction with, and to overlap with, visual and optical techniques at lower magnification and transmission electron microscopy study at higher magnifications. Thus a complete microfabric appreciation could be obtained.

Difficulties were encountered in relation to assessment in the scanning electron microscope of the various aspects of the characterisation scheme devised in this study, such as the morphology and relative abundance of microfabric forms, along the degree and direction of preferred orientation. The main problem is that natural soil fabric tends to be highly complex at all levels and highly variable. Moreover, scanning electron microscopy is essentially a qualitative tool, and the quantitative techniques which are being developed have still to be evaluated for use with natural soil materials. Anyway, they only provide information relating to degree and direction of preferred orientation. It follows then, that scanning electron microscopy of natural soil fabric is highly subjective in nature. The need for a consistent and systematic approach which is painstakingly and meticulously applied to the study of fabric, was realised early in the project. This philosophy of thoroughness must be applied to the selection of specimens as well as to fabric examination of specimens.

The approach adopted and recommended herein involved selection of a minimum of six specimens, four of which provide roughly vertical surfaces, and two of which give roughly horizontal surfaces. These should be selected such that, as far as possible, representative portions of the overall texture are included. The fabric examination procedure involves essentially scanning each fracture surface at low magnifications, for representative areas which are subsequently searched through at a full range of magnifications up to x 50,000 for representative microfabric forms and features. In order to achieve as far as possible a realistic assessment, the techniques of overlapping and stereophotography were utilised. Overlapping photography is particularly valuable for assessing the organisation of the various basic and higher order assemblages etc., within the composite microfabric. Sequential stereopairs are also useful in this context, but perhaps their greatest attribute is in being able to assist in guarding against misinterpretation of microfabric morphology. The techniques of overlapping and stereo-photography, used in this study, are by no means new, however, they have never before been applied in such a systematic and extensive manner to the study of natural soil microfabric.

Regarding specimen preparation and more specifically, the method of specimen dehydration for microscopy, the simple air drying technique has been employed. This method can, and has been easily applied to any type of soil texture. A preliminary critical point drying investigation to evaluate the detrimental effects of air drying when applied to wet kaolinite and illite clays was undertaken. The results of this investigation suggest that air drying induces densification, but does not alter the overall character of the microfabric of such soils. It has been confirmed that critical point drying does indeed tend to reduce the degree of overall shrinkage, and it would seem that a more realistic view of the character of the overall microfabric is obtained using this approach, than is obtained using air-drying. However, certain artefacts may be introduced by this technique, i.e. cracking, excessive grain plucking and some clay particle break-up. Thus, keeping in mind that it is the overall character of soil microfabric which is of prime interest in soil engineering, it is the recommendation of this study, that (1) air-drying be used in the case of essentially non-shrinkable soils, or soils where the shrinkage on drying is liable to be small, and (2) both air drying and critical point drying methods be used in the case of wet kaolinitic and illitic clays.

On balance then, the variety of microscopy procedures employed in this study, it is believed, have enabled a realistic appreciation of the character of the microfabrics of the soils examined, to be obtained. It cannot be over-stressed that above all, such procedures have been and require to be applied thoroughly and meticulously.

Thus scanning electron microscopy study of natural engineering soil is an extremely time consuming, but highly rewarding operation, if it is carried out properly.

3. This study has for the first time, provided an extensive catalogue of natural engineering soil microfabric, which serves to demonstrate the enormous microfabric spectrum which exists in nature. The soils included represent a diverse range of transported soil types, although the black soils from South Africa and Angola also serve to represent very well, the black residual clays of the world. A wide range of engineering soil types is also a feature of the catalogue. The mode of presentation of characterisation data was a subject which was given a great deal of attention. The method adopted for this study involves firstly giving a brief account of the geological and geotechnical background of the soil in question. This is followed by the microfabric characterisation data which is presented in written text under five headings (1) elementary particle arrangements, (2) particle assemblages, (3) basic pore spaces, (4) composite microfabric, and (5) anisotropy within composite microfabric. Certain summary figures are also provided together with a number of selected micrographs which illustrate the main features in vertical section. This approach would seem to be a reasonable and concise one.

On the basis of the large number of observations made, a global view of the likely character of the individual composite microfabric of either non-layered soils or individual layers from within layered soils, which make up the total composite microfabric of the transported inorganic soil group as a whole, has been presented.

The principal conclusions drawn are:-

(a) The total clay array in most of the individual composite microfabrics in which it occurs may be expected to display some degree of heterogeneity, albeit small in some cases. No single clay arrangement type is likely to display either universal occurrence or clear dominance over the other types, in every individual composite microfabric. That is to say, the emphasis will tend to shift from random to parallel to partly discernible clay arrangements as passage is made from one individual composite microfabric to another. It seems probable that random and parallel clay arrangements will generally involve both clay groups (or clusters) and clay individuals. The clay individuals are likely to be of coarse clay size.

(b) The total granular array, in most cases, is likely to be fairly homogeneous in character, probably being comprised in the main of clean rather than clothed grain-grain contacts.

(c) It seems equally as likely that the basic order assemblage network will be either homogeneous and comprised entirely of a particle matrix, (or layer region systems where appropriate), or heterogeneous and comprised in the main predominantly of a particle matrix. Aggregations and connector systems are both likely to be encountered, often together, in many but not the majority of the basic assemblage networks, probably occurring in the 'rarely to frequently' range of abundance. Interweaving bunches are likely to be present in an extremely small number of cases only.

(d) Regarding the make up of the individual basic order assemblages; the matrix or layer region systems are likely to be homogeneous in some cases and heterogeneous in others, with the clay-granular regions likely to be prominent; the aggregation systems are in the main likely to be homogeneous in character, and composed of regular aggregations and the connector systems are likely on the whole, to be heterogeneous and comprised more or less of both bridges and buttresses in equal proportions.

(e) Higher order clay or granular microvein assemblages, and even less so, clay microlenses, are likely to be infrequently seen disrupting the basic assemblage network. It seems probable that in the main, microlayers will be present to some degree where layered systems are encountered.

(f) The basic pore space in the vast majority of individual composite microfabrics is likely to be either wholly or predominantly of the intra-elemental variety. Trans-assemblage pores, of either irregular or wavy planar forms, are likely to be encountered in a significant number of cases.

(g) It would seem that, in most cases, the individual composite microfabric will be essentially isotropic at the 500μ, 50μ and 5μ levels. Nevertheless, in many cases the microfabric will exhibit a degree of anisotropy, which will vary as the level of fabric considered varies from 500μ to 5μ, but which will rarely be very high at the 500μ level.

(h) On balance, it would appear that the individual composite microfabric will be heterogeneous to at least some degree in the vast majority of cases, due to heterogeneity at either the elementary particle arrangement, or particle assemblage level, or both.

Therefore, probably the most important aspect of the natural individual composite microfabric to have been highlighted by the present micromorphology study is that generally speaking this will be comprised at either the elementary particle arrangement, or particle assemblage level, or both, of more than one type of feature or form. The relative abundance of the various forms will vary from one individual composite microfabric to another. This multiple form situation will of course, be more pronounced in some cases than in others. Furthermore, the notion that layered soils are likely to be comprised of a number of different types of granular and clayey layers has been emphasised. Also it is suggested that layered soils should in fact be considered as being multi-fabric in character.

These important conclusions also serve to highlight perhaps the major deficiency of the majority of previous microfabric concepts. That is to say, the previous concepts while being perhaps realistic in the sense of the specific forms or configurations they portray, do in most cases largely imply uniformity of configuration throughout all levels.

Finally, it is strongly suggested that the question of whether or not the testing of laboratory prepared pure clay materials, which tend to have fairly homogeneous microfabrics and which are therefore, on the whole, unrepresentative of even the simplest of natural soil microfabrics, yields useful results should now be given serious consideration. It is the conclusion of this study that the time has come for efforts to be directed more towards the study of natural soil systems or alternatively towards the derivation of more realistic artificial systems.

4. The large number and range of microfabric observations made in this study have afforded the opportunity to examine the role played by some of the genetic factors in the development of engineering soil microfabric.

The main findings are summarised briefly as follows:

(a) Although it has been suggested previously by laboratory studies that significant preferred orientation of kaolin particles occurs under low pressures (≤ 100 kN/m^2), (Section 6.2.2.), there appears to be little or no support for the idea that this is the case for naturally compressed illitic or kaolinitic clayey soils.

(b) The long standing concept that dispersion or parallelism of clay particles at deposition is associated with electrolyte conditions between that of low and high would seem to have been reinforced to some extent. There is however, no evidence to suggest that a totally unique relationship exists between clay arrangement type and electrochemical environment.

(c) It has been confirmed and demonstrated that the presence of irregular and angular shaped silt grains, promotes disorder at deposition, and tends to discourage overall preferred orientation of parallel clay arrays and elongated and flaky silt grains.

(d) It is possible that a haphazard grain and parallel clay array may in certain cases be the result of post-depositional deformation.

(e) It would appear that the clay individuals, comprising clay arrangements, which have been widely and frequently observed in this study, are not in the main clay minerals, but are in fact particles of inactive non-clay mineral material, e.g. quartz and feldspar. This view is not in conflict with, and in fact serves to support, the general opinion that clay mineral particles are more likely, despite perhaps favourable electrolyte conditions, to form into some sort of clay mineral group or cluster configuration.

(f) It is tentatively suggested that for one-dimensionally compressed illitic clays a marine environment is more conducive to the formation of a heterogeneous basic order assemblage network and the associated inter-assemblage pores, than is either a brackish or freshwater environment.

(g) Significant anisotropy of the composite microfabric of soils or layers seems more likely to be significant in thecase of lightly one-dimensionally compressed estuarine and brackishwater deposits than in lightly compressed marine or freshwater deposits.

(h) It would seem that very high one-dimensional compression does indeed tend to induce a parallel association of clay particles. This view would appear to be equally as valid for montmorillonitic clays as for kaolinitic clays. A tendancy for the overall preferred orientation of parallel clay arrays and flaky and elongated silt and sand is also probable.

(i) The presence of irregular and angular shaped silt and sand grains will prevent overall preferred orientation (under one-dimensional compression), of parallel clay arrays and elongated and flaky silt and sand grains. In fact very high one-dimensional pressures coupled with a high bulky grain contact could conceivably lead to an isotropic configuration overall.

(j) It would seem that weathering processes may in certain cases help to disrupt and transform a parallel clay array with a tendancy for overall preferred orientation into one which displays haphazard orientation. Moreover, it is possible that the in place disintegration of sand grains may result in the formation of clean grain-grain contact arrays.

(k) It would seem reasonable to suggest that heavy one-dimensional compression tends to break down and eliminate connector, aggregation and bunch assemblages, and their associated inter-assemblage pores, with the result being the growth of matrix assemblages and the increase in prominence of inter-elemental porosity.

(l) A significant degree of anisotropy is likely to be displayed by heavily one-dimensionally compressed soils, providing disruption from weathering processes has not operated and the bulky grain content is low.

(m) The involvement in clay arrangements of amorphous materials such as iron oxides and calcium carbonates may lead to the development of partly discernible configurations.

(n) Desiccation of highly active montmorillonitic clays may lead to very strong edge-edge intergrowth of wavy clay groups or quasi-crystals. Moreover, heavy three-dimensional compression resulting from desiccation of such clays is likely to lead to the formation of randomly orientated planar trans-assemblage pores, (i.e. microfissures), which tend to follow grain surfaces, and to the development of haphazard and parallel clay arrays. The occurrence of edge-edge intergrowing within haphazard parallel clay arrays would seem to offer a reasonable explanation of the fact that in certain cases no matter the direction of the fracture plane, the same partly discernible pattern was observed in the scanning electron microscope.

It must be emphasised that the views given above represent only rough trends which have been identified on the basis of the microfabric observations of the broad geological soil groups included. The factors which may influence microfabric development in the natural environment, of course, are numerous and interact in a complex manner and the difficulties and dangers involved in trying to isolate variables for study has been recognised and highlighted. This study recommends that (1) results from investigations of laboratory prepared materials should serve merely as a guide and not as a basis for discussion of microfabric genesis and (2) efforts should be directed towards the much more valid but difficult task of studying groups of selected natural soils for the purposes of isolating a particular factor or set of factors.

5. This study has examined the mechanisms of sensitivity, collapse and expansiveness from the microfabric viewpoint. This type of approach has proved to be extremely useful and has been shown to be essential to the understanding of these mechanisms of structural instability.

The principal findings are summarised as follows:

(a) <u>Sensitivity</u>

It would appear that the mechanism of sensitivity involves the breakdown of a variety of open random clay particle configurations, particularly those involving clay groups and particles of inactive quartz and feldspar. This view serves to confirm and reinforce previous concepts. Clay clusters may also be involved in certain cases. Furthermore it is emphasised that the mechanism may operate at the assemblage level as well as the elementary particle arrangement level, i.e. sensitivity may also be associated with the breakdown of open connector and connector-aggregate systems.

It has also been well demonstrated and confirmed that while some type of open fabric may be considered to be a prerequisite for sensitive behaviour, it is only one of the factors involved and the processes of leaching and cementation, or both, must also be operative in order to produce high degrees of sensitivity.

(b) <u>Collapse and Expansion</u>

It has been confirmed that from the microfabric viewpoint, purely collapsing behaviour appears to be associated principally with open granular matrices comprising clothed and clean grain-grain contacts. Open connector or regular aggregation networks are also likely to play a significant role in certain cases. It is necessary that these arrangements be comprised of essentially non-swelling clay minerals or iron oxides and carbonates, and that the structure be moisture deficient. Moreover, the presence of irregular shaped trans-assemblage pores is likely to enhance collapse.

Expansion from the microfabric viewpoint appears to be associated with desiccated swelling clay and clay-granular matrices. In many cases the clay arrays will involve parallel clay group arrangements. The mechanism of expansion in such cases, appears to occur perpendicular to the basal planes of clay groups and to involve the breakdown of edge-edge bonds. This tends to lead to an open arrangement of discrete clay groups (perhaps unit layers). In the case of preferentially orientated parallel clay arrays, expansion thus tends to be anisotropic, whereas in the case of haphazard parallel clay arrays, expansion tends to be essentially isotropic.

The dual behaviour of expansion under light loads and collapse under heavier loads appears, from the microfabric point of view to be associated with the presence to some degree, of open clothed granular matrix regions, and connector or regular aggregation systems in combination with clay and clay-granular matrix regions. Again it is necessary that these arrangements be comprised of swelling clay minerals and that the structure be moisture deficient. The critical or swelling pressure for dual behaviour soils, appears to be inversely proportional to the degree to which clothed grain-grain contacts, connectors and aggregations are involved in the microfabric.

Therefore, the role of microfabric in the structural instability mechanisms of sensitivity, collapse and expansiveness, has perhaps been placed into a clearer perspective. It has been emphasised that while a particular type of microfabric is a prerequisite for a particular type of behaviour, it is only one of the factors involved.

6. Two features of general engineering significance emerge from the discussions of the previous sections, these are:

   (a) It would seem that any model of the general mechanisms of engineering behaviour such as compressibility, shearing or water conductivity must take account of the idea that natural soil microfabric is likely to be heterogeneous to some degree in the vast majority of cases and is seldom likely to display very high degrees of anisotropy. Any model which does not in some way incorporate the appropriate variety, relative abundance and levels of microfabric form, cannot account successfully for natural soil behaviour. On the same theme, when sampling in layered soils, consideration has to be given to the variety of layer types (classified according to composite microfabric) present in order to ensure that good representation is achieved.

   (b) Realistically speaking, it would seem to be generally impossible at this stage in time, to link successfully and directly, geology with engineering behaviour on the basis of microfabric study, owing to (i) the difficulties involved in assessing the nature of natural microfabric, which is often complex, using the available study techniques which all have their limitations, (ii) the uncertainties which are associated with the geological history of particular soil deposits and the difficulties involved in trying to assess the role played by the various genetic factors in microfabric development, and (iii) the difficulties associated with trying to establish the role played by microfabric in engineering behaviour.

RECOMMENDATION FOR FUTURE RESEARCH

(i) Future studies should endeavour to link microfabric with the other levels of fabric so that a unified appraisal is achieved, e.g. the 'total fabric' approach suggested by Derbyshire et al (1976). This means that the various techniques of fabric observation including the scanning electron microscope will have to be employed in a co-ordinated manner.

(ii) Further investigations are required to establish the value of the techniques of air-drying and critical point drying when applied to natural kaolinitic and illitic clays. Dehydration of wet and highly active natural clays remains a serious problem, and apart from the technique of freeze-drying, the carbowax - chloroform technique developed by Jalili (1976) could be useful in this regard. Developments in scanning electron microscopy, in the direction of 'cold stage' techniques and in the application of qualitative x-ray analysis would seem to be desirable.

(iii) It is important that the catalogue of natural engineering soil microfabric initiated by the present study be extended to include not only more transported inorganic soils, but also soils from the residual and organic groups. It will be necessary to continually revise and define clearly the nature and range of natural soil microfabric. Presentation of microfabric data is another area for development, particularly from the point of view of routine fabric description, and any progress made will require to be consistent with the idea of total fabric description.

(iv) Efforts should be directed towards studying groups of selected natural engineering soils, and perhaps more realistic laboratory prepared materials for the purposes of isolating variables so that microfabric genesis and mechanisms of engineering behaviour can be better understood.

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APPENDIX A

List of soil materials examined in the scanning electron microscope but not included in this thesis.

(I) NATURAL SOILS

(a) Marine silty clay - Erskine, Scotland. - Barden & McGown (1973)

(b) Marine silty clay - Singapore. - Barden (1972)

(c) Marine clay - Waddesdon, England. - Barden (1972)

(d) Estuarine silty clay - Immingham, England. - Barden (1972)

(e) Estuarine silty clay - Govan, Scotland. - Gabr (1975)

(f) Estuarine sands and silts - Shannon, Eire. - (Soil Mechanics Ltd)

(g) Loess - Maidstone, England. - Mellors (1971)

(h) Melt out tills - Blaisen, Norway; Reeks, Eire. - McGown (1975)

(j) Residual soils - various grades of weathering - Curitaba and Itapevi, Brazil. - Clemency (1974)

(II) LABORATORY PREPARED AND RECONSTITUTED MATERIALS

(a) One-dimensionally compressed ($p'_c = 300\ kN/m^2$) and sheared (plane strain) kaolinite, illite and mica-kaolinite mixtures. - Andrawes et al (1975 a,b)

(b) Bentonite / sand mixture - slurried and air-dried. - Dudley (1973)

(c) Marine clay - Luanda, Angola - reconstituted and compacted samples (wet and dry of optimum). - Horta da Silva (1974b)

APPENDIX (B)

CRITICAL POINT DRYING INVESTIGATION

B.1. APPARATUS.

B.1.1. Apparatus for Trimming and Containing Specimens.

The trimming apparatus is shown clearly in Fig. B.1. and consists essentially of a perspex base upon which is mounted two sets of perspex spacer blocks spaced 40 mm apart. The blocks are arranged as shown such that a gap exists between them which is just sufficient to allow a fine diameter cheese wire cutter and thin specimen support plates to be inserted. The arrangement thus facilitates the trimming of specimens down to approximately 10 mm square cross section. The specimen containers are also shown in Fig. B.1. and can be seen to consist of a cage with a good fitting lid both of which are made from a perforated mesh of light, but fairly rigid metal alloy. The inside dimensions of the assembled containers are just over 30 x 10 x 10 mm.

B.1.2. Apparatus for Methanol Substitution.

The apparatus set up for the substitution stage of the critical point drying procedure is illustrated schematically in Fig. B.2. and in essence is the same as that employed by Smart (1966b). As shown this consists basically of the following components:

1. Crystaline container (150 mm diameter 100 mm deep). Fitted at its base with a drainage / filler tap.
2. Glass cover for container.
3. Crystaline dishes approximately 20 x 25 x 75 mm.
4. Rubber tubing fitted to funnel and stand.

B.1.3. Apparatus for Critical Point Drying.

The critical point drying apparatus, shown in Figs. B.3. and B.4., was supplied by Polaron Equipment Limited, Watford, Hertfordshire. It consists of the following component parts.

1. Pressure vessel with integral water jacket for heating and cooling and pressure chamber plus supporting stand. The normal operating range of the pressure chamber is 0 - 14 MN/m^2 and 10 - 50°C.
2. Four pressure control valves (i) over pressure safety valve set at 14 MN/m^2, (ii) manual inlet valve at the top rear of the vessel body for admitting liquid Co_2 to the chamber. A transfer pipe with couplings connects the apparatus to the Co_2 high pressure cylinder, (iii) manual drain valve at bottom rear of the vessel body for draining methanol, (iv) manual vent valve situated at top front of the body for venting gas from chamber.
3. Pressure guage (0-14 MN/m^2) at top front of vessel body.
4. Thermometers, at top front for measuring the temperature of pressure vessel body and to rear at the water inlet for measuring water temperature.
5. Detachable viewing window at front end of pressure vessel.
6. Removable access door to pressure chamber.
7. Boat shaped specimen holder inside dimensions 12 x 12 x 75 mm. and integral automatic drain valve in bottom.

B.2. PROCEDURE.

The steps performed in the critical point drying investigation are detailed as follows:

1. Nine specimens of each soil were trimmed to 10 x 10 x 30 mm. approx. from wet bulk samples, using the trimmer device and placed in the perforated specimen containers.
2. Three contained specimens were then taken and air-dried in the manner described in Section 4.3.1. In the case of the Lake Portchartrain clay three specimens were also oven dried at 105°C.
3. The remaining six specimens (three in the case of Lake Portchartrain clay) were then subjected to impregnation by methanol using a substitution apparatus. Two methods were employed, one involving the direct immersion of specimens in

a solution of 100% methanol and the other involving immersion of specimens in successive aqueous solutions of increasing concentrations. Methanol / water mixtures of 25%, 50%, 75% and 100% were used. In both methods, specimens were placed in the crystaline dishes in order to ensure that specimens were not exposed to the atmosphere during drainage of the crystaline container. Specimens were kept in the 25%, 50%, and 75% solutions for a minimum of 24 hours. Drainage and filling were facilitated using the drainage / filler tap and rubber tube and funnel arrangement as indicated by Fig. B.2. Specimens were kept in the 100% methanol solutions for a minimum of 72 hours, after this time, drainage and refilling with 100% methanol carried out and a final immersion maintained for several hours.

4. The impregnated specimens were then taken for critical point drying. The basic procedure adopted for each specimen was as follows:

A quick transfer under methanol of the contained specimen from the impregnation container to the specimen boat, was first carried out. This was followed by a transfer of the specimen boat and submerged specimen to the pressure chamber. Cold water from the domestic water supply was then circulated through the water jacket. At this stage, with all vessel pressure valves closed, the valve of the Co_2 pressure cylinder was open to allow Co_2 liquid to travel up to the inlet pressure valve which was subsequently slowly opened to allow access of liquid Co_2 to the pressure chamber. The vent valve was also opened to allow expulsion of the trapped air. Once the chamber was full, the drain valve was slowly opened to flush away very gently, the displaced methanol. Care was taken to ensure that at no point did the level of liquid Co_2 fall below the top of the specimen boat. Opening the vent valve was sometimes necessary here. This flushing action was maintained for a minimum of 15 minutes. The chamber was then allowed to fully fill and all the pressure valves closed. A further 2 flushes were carried out over a period of 24 hours. At this stage the level of liquid Co_2 was brought down to just above the top of the specimen boat by opening the drain valve. The drain valve was then closed and the temperature of the circulating water gradually increased by mixing hot water from the tap with the circulating cold water. The rate of temperature increase was made such that the difference in temperature recorded by the chamber and water thermometers was never more than 2 - 3°C. The temperature was brought up to between 35 - 40°C at which the pressure in the chamber was around 9800 KN/m^2. At a temperature and pressure of 30°C and approximately 7700 KN/m^2 respectively the interface between the liquid Co_2 and the vapour in the chamber began to disappear. At a temperature and pressure of 32°C and 7900 kN/m^2 respectively, the interface had completely disappeared and the chamber was full of vapour. While maintaining the temperature in the chamber at around 40°C, the vent valve was opened to release the carbon dioxide gas. This was done very slowly over a period of around 20 minutes to prevent condensation in the chamber. Finally, the access door to the specimen chamber was opened and the specimen boat removed.

B.3. MACROSCOPIC OBSERVATIONS.

Observations made of the degree of overall shrinkage or swelling and the change in general character of specimens during the drying procedures described in the previous section are detailed in Tables B.2. - B.6.

A quantitative measure was made of overall shrinkage or swelling except for the specimens from Lake Portchartrain. A simple visual comparison was made in their case using the inside boundaries of the specimen containers as reference. Due to the number of specimens to be measured and the lack of available time measurement using a travelling microscope while being by far the best method would have been impractical so careful measurement using a finely graduated ruler in combination with a simple hand lens was employed instead.

A qualitative measure was made of the degree of distortion or disintegration experienced by the specimens during drying. Also in the case of the critical point dried specimens a visual estimate was made of the amount of swelling during impregnation and again the specimen container boundaries were used as reference.

The observations are broadly summarised as follows:

A. Shrinkage Measurements.

(i) The critical point drying methods induced considerably less shrinkage than air drying.

(ii) The critical point (graded methanol) method induced less shrinkage than the critical point (100% methanol) method in the case of the illite and varved clay specimens, whereas the converse was found in the case of the San Francisco Bay Mud and Ottawa clay specimens.

(iii) Oven drying appeared to induce greater shrinkage to specimens of Lake Portchartrain clay than air-drying did.

(iv) On the whole vertical and horizontal linear shrinkages were of the same order of magnitude.

B. General Characteristics.

(v) Distortion of specimens was apparently uncommon and was only noted in one air-dried specimen of varved clay and one air dried specimen of Leda clay.

(vi) Disintegration of specimens by surface flaking was observed after critical point drying in two specimens of Lake Portchartrain clay (100% methanol); two specimens of illite (graded methanol); three specimens of San Francisco Bay Mud (100% methanol) and one specimen of San Francisco Bay Mud (graded methanol). No flaking was apparent in the case of the Leda and varved clay specimens. Flaking was not induced by air-drying.

(vii) Cracking of specimens during methanol impregnation was fairly common. This was observed in two specimens of Lake Portchartrain clay (100% methanol); two specimens of illite (100% methanol); three specimens of laboratory prepared illite (graded methanol); one specimen of San Francisco Bay Mud (graded methanol); one specimen of Leda clay (100% methanol); two specimens of Leda clay (graded methanol); three specimens of varved clay (100% methanol). Cracking of specimens during air-drying appeared to be essentially non-existent.

(viii) Swelling of specimens was observed during methanol impregnation in two specimens of Lake Portchartrain clay (100% methanol); three specimens of illite (100% methanol); and three specimens of illite (graded methanol). Swelling however appeared to be completely absent in the case of the Bay Mud, Leda and varved clay specimens.

B.4. MICROSCOPIC OBSERVATIONS - LAKE PORTCHARTRAIN CLAY.

Microscopic observations made on the sets of critical point dried, air dried and oven dried specimens of the Lake Portchartrain clay are given below. The microfabrics were assessed using the routine detailed in Section 4.4. The approach to microfabric description followed here is similar to that adopted for the main part of the present microfabric investigation as detailed in Chapter 5. Summary diagrams and illustrative micrographs are similarly provided.

(a) Elementary Particle Arrangements - Fig. B.5.(a).

Clay arrangements were the only arrangements to be observed in each set of specimens.

In both the critical point dried and air dried specimens the clay arrangements were random in character throughout, Mics. B.1.(a), (b). As can be seen however, the random arrangements comprising the critical point dried specimens were much more open. The oven dried specimens appeared to consist predominently of parallel clay arrangements, the nature of which can be appreciated from Mics. B.1.(c), (f). Random clay arrangements were occasionally in evidence.

The constituent clay particles comprising the various clay arrangements varied in character. Clay groups and clay individuals with mainly fine clay sizes were to be seen in the critical point dried specimens, while in contrast coarse clay size groups and some individuals were observed in the air dried specimens and very coarse clay size groups were generally in evidence in the oven dried specimens.

(b) Particle Assemblages - Fig. B.5.(b).

A particle matrix was observed to be the only assemblage present in each of the three sets of specimens examined.

In each case clay-granular regions predominated over clayey regions which were variously abundant, from occasionally in the critical point dried specimens to rarely and extremely rarely in the air and oven dried specimens respectively. The regions of the critical point dried and air dried specimens were comprised throughout of random clay arrays, Mics. B.1.(d) and (e) respectively, while in contrast a predominantly parallel clay array displaying haphazard orientation was in evidence in the oven dried specimens, Mic. B.1. (f). In the case of the critical point dried specimens an extremely large number of grain cavities were to be observed within the regions.

(c) Basic Pore Spaces - Fig. B.5. (c).

The intra-elemental pores of the various clay arrangements appeared to account for the basic pore space in each case although a small contribution from intra-assemblage pores was in evidence in the critical point dried specimens.

(d) Composite Microfabric.

The typical character and texture of the composite microfabrics of the critical point dried, air dried and oven dried specimens are illustrated by Mics. B.1.(g), (h) and (j) respectively.

As shown by Mic. B.1.(g), the critical point dried specimens appeared to have a very porous looking fabric due to the presence of the large number of grain cavities within the particle matrix. As indicated, this matrix was disrupted in many places by what appeared to be fine curvi-planar trans-assemblage pores which displayed near horizontal to near vertical attitudes.

The rather dense and apparently granular matrix of the particle matrices comprising the composite microfabrics of the air dried and oven dried specimens are shown clearly by Mics. B.1.(h) and (j) respectively.

(e) Composite Microfabric Anisotropy - Fig. B.5. (d).

The microfabrics of the critical point dried, air dried and oven dried specimens appeared to be isotropic in character at both the 500 μ and 50 μ levels, with the isotropy being associated with the random clay arrays plus in the case of the oven dried specimens the haphazard parallel clay array.

The microfabric at the 5 μ level in both the critical point and air dried specimens was also found to be isotropic due to the presence of the random clay arrangements. In contrast however, the microfabric of the oven dried specimens due to the occurrence of the parallel clay arrangements, generally displayed high degrees of anisotropy and a full range of directions of preferred orientation.