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Micromorphometric techniques in engineering soil fabric analysis

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INTRODUCTION

A large amount of the effort displayed in soil micromorphology over the last few decades has been directed, necessarily, towards the recognition and qualitative classification of the various fabric elements occurring in natural soils [2, 9]. A more recent trend in the development, already suggested in the term micromorphometry, and explicitly stated in Altemüller's [1] definition of soil fabric, is the quantitative study of the three-dimensional arrangement *patterns* of the fabric elements in soils [10, 14]. Presently, the main effort of these studies, as far as pedology is concerned, seems to be concentrated on attempts to obtain as much *genetical* information as possible from the soil fabric pattern.

The purpose of engineering soil fabric analysis, on the other hand, is primarily the study of the relationships between soil fabric characteristics and soil mechanical properties. Another major difference between pedological and engineering soil fabric analysis is that the majority of soils containing more than a few percent of organic matter are unsatisfactory or cumbersome for engineering purposes. Consequently, where practicable, such soils (usually the upper horizons of the soil profile) are removed before construction commences. As a result, such soils are generally *not* included in engineering soil fabric analysis, and will not be discussed in the present paper.

For practical purposes it has frequently been *assumed* in soil mechanics that natural soils are essentially isotropic and homogeneous. The justification for this assumption has to be found largely in the resulting simplification of the mathematical operations required for conventional design procedures. A very strong tendency, however, has developed more recently in soil mechanics not only to doubt the validity of the previous assumption but to study the effect of soil anisotropy on soil mechanical behaviour not only for the sake of its theoretical significance but also for its practical value.

PATTERN PROPERTIES IN SOILS

Common to both the pedological as well as the engineering approach, there appears to be a need for an objective appraisal of a given natural soil fabric pattern, independent of the purpose of the investigation, and, therefore, *initially* independent of genetical or engineering interpretations. This evaluation has to be considered in the first instance as a purely geometrical problem attempting to recognize and formulate one or more appropriate and relevant *geometrical pattern properties.* These geometrical pattern properties must be features that can serve to distinguish various patterns from each other, and that, eventually, can provide a basis for classification. They must express *mutual relationships* between the individual elements in complex spatial arrangements. These relationships are *not* included in the simple summation of the characteristics of the single elements. The simplest and presumably most obvious pattern properties are the *spatial distribution* [13] or relative location, and the *spatial orientation* of the various individual elements in such a pattern. Both spatial distribution and orientation, however, are contributing independently to the well-known pattern properties of isotropy and anisotropy. The concepts of isotropy and anisotropy, however, need not be restricted any more to purely geometrical features, but may include physical features (such as strength, optical properties, permeability, etc.) as well. Frequently, isotropy and anisotropy are defined in the following simple manner.

(a) A material system is said to be *isotropic,* if the magnitude of one or more of its properties (geometrical, physical, or otherwise) remains the same in or is *independent of the direction* in which it is measured within the system.

(b) A material system is termed *anisotropic* if the magnitude of one or more of its properties is *dependent on the direction* in which it is measured within the system.

Both notions are well-known from their use in elementary morphological crystallography and crystal optics. Their application in the fabric analysis of real (even simple) materials, however, requires the introduction of statistical considerations, and particularly that of the concept of statistical symmetry [24, 32].

In the present paper recently developed micromorphometric techniques for the measurement of preferred *dimensional* orientation [12] of the major soil components, i.e. skeleton grains, platy clay mineral domains, and pores, will be briefly described as an approach to the determination of geometrical and physical anisotropy of natural soil fabric patterns. The particular techniques allow the measurement of the three-dimensional orientation of simple and compound linear and planar features in soil fabric patterns. In these procedures the compound features are considered to consist of continuous series of simple linear (straight line segments) or simple planar (plane strips) elements. Examples of such features are elongated skeleton grains, platy skeleton grains, planar pores (i.e. fissures or cracks), linear pores (plant root channels), and the basal plane (001) of platy clay minerals. As the three-dimensional orientation of a plane surface is also unambiguously determined by the spatial orientation of its normal, the problem of the description of the orientation of both linear and planar features can be reduced to the description, either analytical or graphical, of the orientation of linear elements. only. Orientation data in fabric analysis are of a stochastic nature, and their distribution patterns, therefore, are generally complex. Consequently, it is usually simpler to represent these data graphically rather than analytically. The appropriate techniques have been described elsewhere [14, 18, 32].

PREFERRED ORIENTATION OF SKELETON GRAINS IN NATURAL SOILS

Although the occurrence of preferred dimensional orientation of mineral grains and/or rock fragments in sandstones and similar sedimentary rocks, as well as in unconsolidated sedimentary deposits has been known for many years [25], little attention seems to have been paid to the occurrence of the same phenomenon as far as the skeleton grains in natural soils are concerned. This lack of interest is possibly due to the assumption, in both pedology and soil mechanics, that the clay fraction is by far the most important factor in the behaviour of a natural soil, and that the skeleton grains (and the skeleton domain) are virtually inert constituents as far as soil behaviour is concerned. There is no lack of information [15], however, to show that particularly stress-induced differential movements in natural soils may be expressed more clearly in the preferred dimensional orientation of skeleton grains than in preferred orientation of clay material.

The simplest way to determine preferred dimensional orientation of skeleton grains in natural soils is by means of direct measurement of the orientation (or, under certain conditions, orientation *and* length) of the long axes of elongated skeleton grain cross-sections in thin-sections under the microscope. The results can then be shown in polar co-ordinates by plotting either the relative frequency (in %) or the sums of the lengths of the long axes versus the orientation. This technique is most suitable when some information about the possible preferred orientation (e.g. orientation direction of terrain slope, current direction of a river or creek, etc.) is already available. The orientation of the required thin-section(s) can then be related beforehand in the most advantageous manner to the known or suspected regional structure. The method *can* be used, however, without such previous information.

Results of the application of this technique are demonstrated for an oriented red-brown earth sample from a slope near Panorama, S. A. in

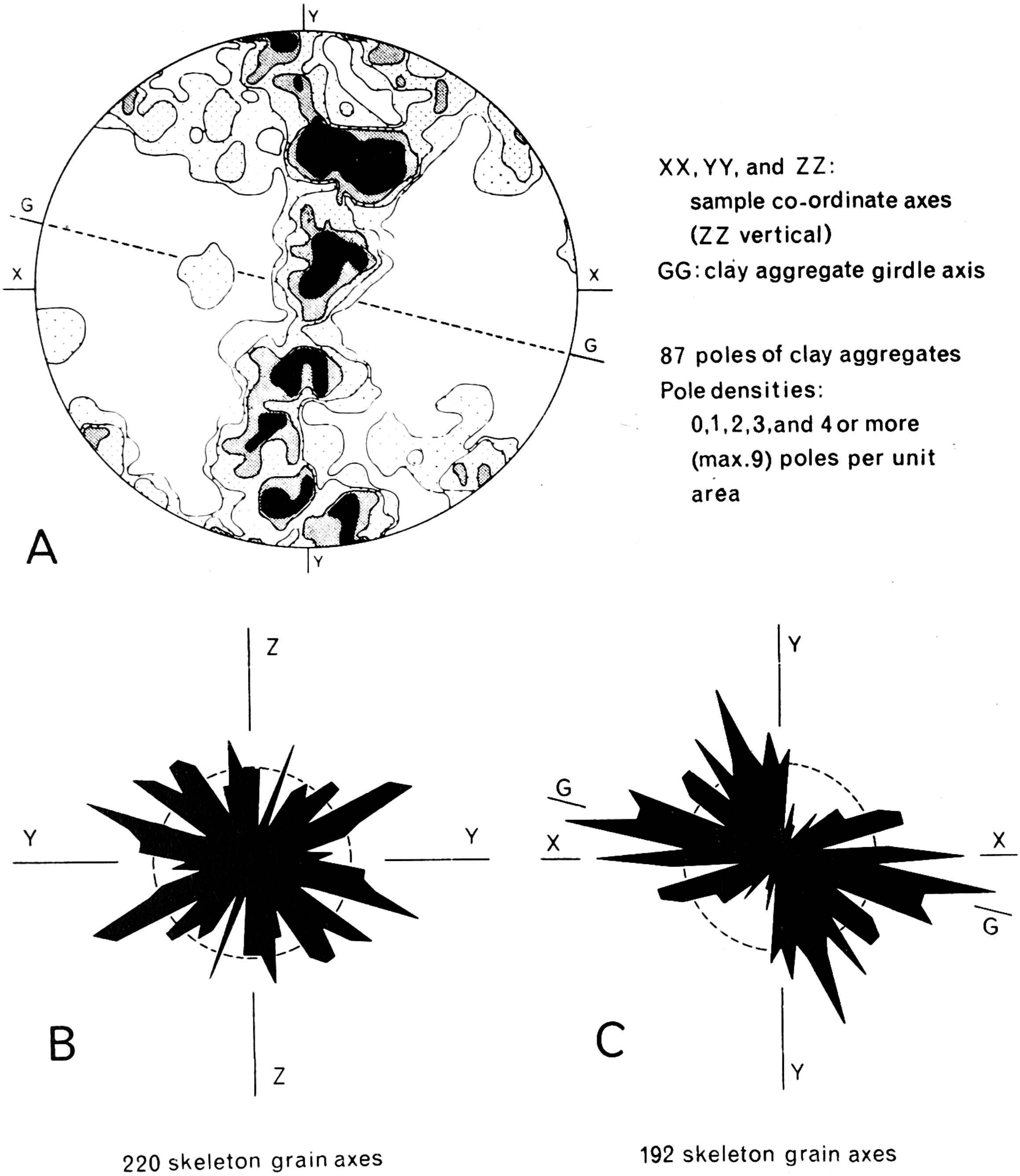

Fig. 1. Preferred orientation patterns in red-brown earth, Panorama, South Australia. A. Orientation of platy clay mineral domains in equal-area projection; horizontal projection plane. GG = clay domain girdle axis, approx. parallel to strike of terrain slope. Pole densities 0, 1, 2, 3, and 4 and more (maximum 9) per unit area. Unit area: $1.15^{0}/_{0}$ of total area (after Lafeber [16], modified). B. Orientation of elongated skeleton grains in polar co-ordinates. *Vertical* cross-section, approx. perpendicular to strike of terrain slope. Broken circle: uniform distribution of long axes = $2.77^{0}/_{0}$. C. Orientation of elongated skeleton grains in polar co-ordinates. *Horizontal* cross-section. Broken circle: uniform distribution of long axes = $2.77^{0}/_{0}$.

Fig. 1. The sample co-ordinate axes [14] are: XX = horizontal, YY = = horizontal, and ZZ = vertical. The horizontal line GG corresponds approximately to the strike of the terrain slope. One vertical thin-section has been prepared parallel to the YZ coordinate plane and approximately perpendicular to the strike of the terrain slope. The orientations of the long axes of elongated skeleton grain cross-sections have been determined (within 5°), and the relative frequency plotted vs. the orientation in polar co-ordinates (Fig. 1B). The broken circle represents a uniform distribution of frequencies over all directions, i.e. 2.77%. It will be seen that there is no distinct preference for any particular direction in this diagram, i.e. the distribution appears to be random.

A second thin-section has been prepared in a horizontal direction parallel to the XY co-ordinate plane and containing GG. In the corresponding diagram (Fig. 1C) it will be observed that there is a certain preference for the long axes of skeleton grain cross-sections to orient themselves approximately parallel to GG, i.e. the direction of the strike of the terrain slope. Also, the whole diagram is elongated in that direction.

Combining the results of both diagrams, it is suggested that the majority of platy skeleton grains (i.e. those displaying elongated cross-sections in thin-section) tend to orient themselves parallel to the horizontal line GG that represents the strike of the terrain slope. Or, in other words, the preferred orientation of the platy skeleton grains can be considered as a reflection of a *downslope rolling movement*. It will be shown later that this suggestion is fully supported by the three-dimensional orientation pattern of the platy clay minerals in this particular soil.

The same technique has been used on undisturbed samples of a recent beach sand from Portsea, Vic. Three sets of thin-sections have been prepared, namely one set vertical and parallel to the coastline, one set vertical and perpendicular to the coastline, and the third set horizontal (Fig. 2). The conclusion drawn from the diagrams is that the flattened grains and shell fragments in this sand tend to orient themselves in a plane surface P, parallel to the coastline, and dipping about 20° inland. It is interesting to note that in triaxial loading experiments on this sand the failure surfaces or failure zones are very distinctly and closely related to the orientation of this plane surface P.

A somewhat different, basically three-dimensional technique has been described by Willoughby [35]. In this technique one or more series of parallel polished surfaces [33] at known distances from each other are used to determine the dimensional orientation of elongated and/or platy skeleton grains in soils. The observed data can be plotted in equal-area projection in the conventional manner. It is not necessary in this case to have any previous information about regional structural features.

Using the particular technique, Willoughby has determined the orientation pattern (Fig. 3) of small, planar rock fragments in the deeper parts of a black soil profile on a sloping site near Glen Osmond, S. A. From the diagram it will be seen that there is a distinct preference for orientation around the pole of the terrain slope, suggesting a *downslope sliding movement* of the platy rock fragments.

PREFERRED ORIENTATION OF PLATY CLAY MINERALS IN NATURAL SOILS

The determination of the three-dimensional orientation of the platy clay minerals in natural soils appears to be of major importance in pedological as well as in engineering soil fabric analysis. Consequently, a number of attempts has been made in the past to find an acceptable solution for this problem.

The development of the interest in fabric studies in soil mechanics

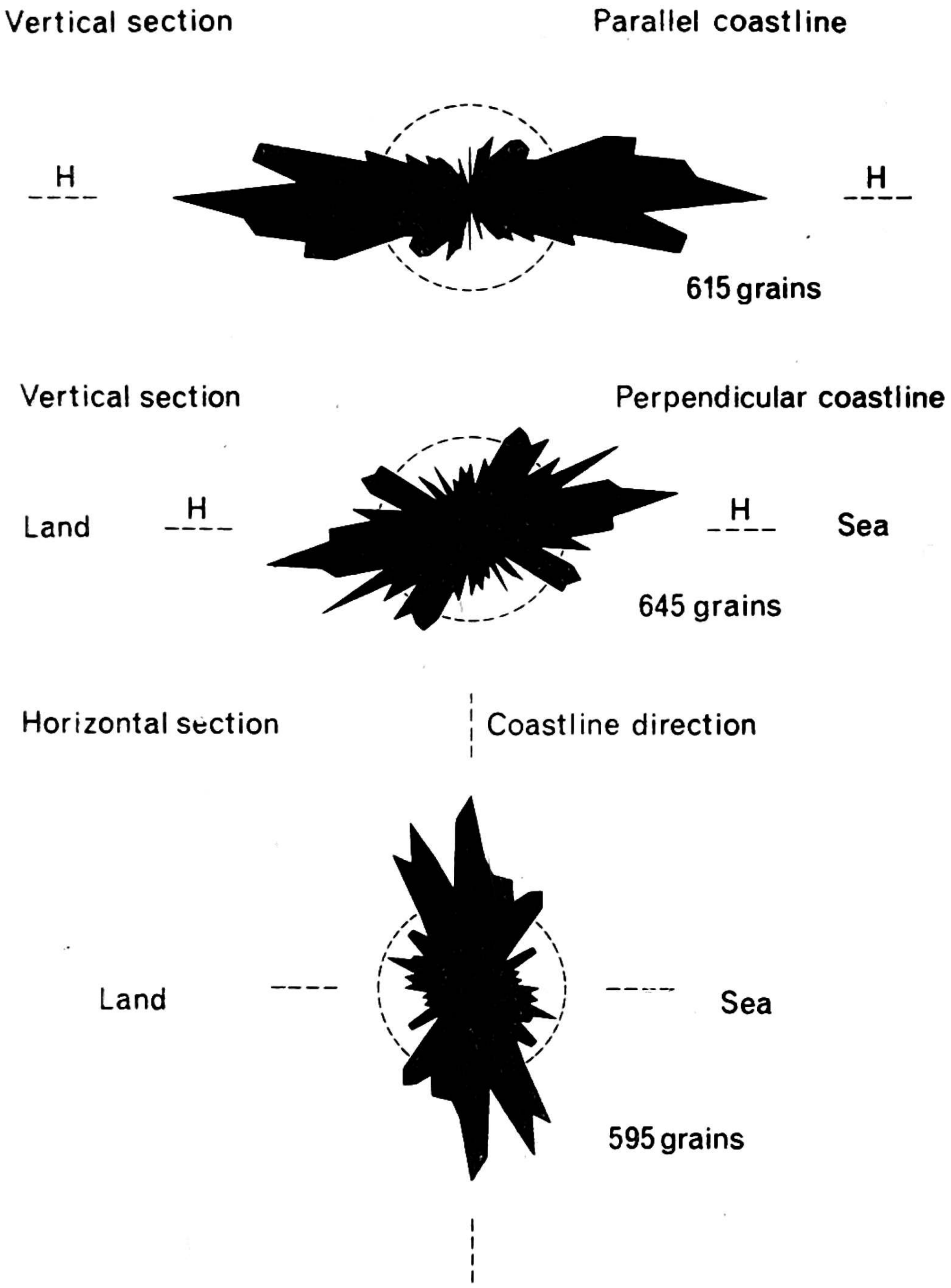

Fig. 2. Preferred orientation of elongated skeleton grains (sand grains and shell fragments) in recent beach sand, Ocean Beach, Portsea, Victoria. Polar co-ordinates. Broken circles: uniform distribution of long axes = 2.77%.

since the initial speculative studies of Terzaghi [31] and Casagrande [4] has partly coincided with an appreciable increase in knowledge of the crystallographic, mineralogical and physico-chemical characteristics of the clay minerals. Simultaneously with this work, methods for the application of X-ray methods particularly on clay minerals were developed. The unfortunate result, however, has been that in soil mechanics from then on the term soil fabric has practically come to mean clay fabric. This is clearly demonstrated in a number of studies (e.g. [3, 34], and many others).

The tendency, demonstrated in these and other studies, to concentrate on the clay fabric has been reinforced by theoretical considerations and studies such as those of Lambe [19], and particularly by Rosenqvist's [29] work on Norwegian quick clays. It must be remembered, however, that these are very exceptional soils in a number of ways. Consequently the results obtained from their study cannot simply be extrapolated without appreciable risk to other, quite different soils.

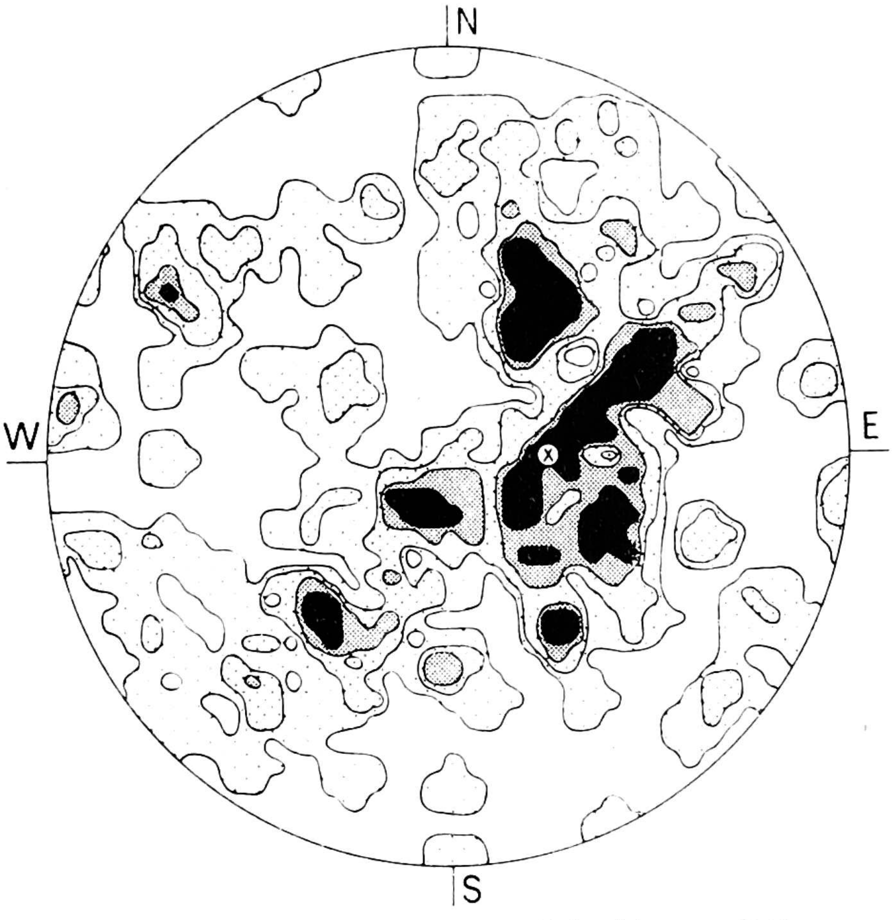

Fig. 3. Preferred orientation of platy skeleton grains in black earth, Glen Osmond, South Australia. Equal-area projection, horizontal projection plane. Pole densities 0, 1, 2, 3, and 4 or more (maximum 11) per unit area. Unit area: 0.50% of total area (after Willoughby [35], modified).

Furthermore, the outcome of, and often the techniques used in most of these and several other similar studies, appear to have been strongly influenced, even until very recently [22, 23, 27] by the preconceived idea that clay orientation in soils should necessarily mean a (statistical) parallel orientation of all or nearly all clay mineral platelets in these soils. The possibility of the occurrence of other preferred orientation patterns in natural soils has been completely or largely ignored, although their occurrence in metal and rock fabrics has been known for many years. As another result of this preconceived idea no serious attempts seem to have been made, until very recently, to adopt or improve the existing, inadequate optical and X-ray methods for the determination of other, more complex three-dimensional orientation patterns of clay minerals and other soil constituents. The present inadequacy of optical methods particularly has tended to place an exaggerated and partly unwarranted emphasis on the reliability and simplicity of X-ray techniques. A very serious disadvantage, however, of the application of X-ray diffraction methods (even as refined as that of Taylor and Norrish [30]) in soil fabric analysis, is that preferred orientation of pores and cracks, and preferred *dimensional* orientation of skeleton grains are inaccessible to these methods. The kinematically important correlations between clay orientation, the orientation of pores and grains, and displacements or strains, therefore, *cannot* be established in a *direct* manner by means of X-ray methods. It will be shown, however, that appropriate optical methods can accomplish this in a satisfactory manner.

About ten years ago Martinez [20] proposed a photometric method for the measurement of the degree of *lattice* orientation of quartz individuals in quartzites. The same method was simultaneously, but apparently independently, discussed for clay minerals by Wu [36]. More recently, Morgenstern and Tchalenko [22, 23] have attempted to revive interest in the method by applying it to artificially prepared kaolinite samples with a simple, i.e. planar orientation pattern. The technique has a number of inherent disadvantages, however, that make the possibility of its application for the present purpose rather doubtful [17].

(a) The application of the method should be restricted to mono-mineralic materials with the simplest possible orientation patterns [20, 36]. Presently, it has only been applied to minerals (quartz, kaolinite) that, in a thin-section of standard thickness (0.03 mm), show a white interference colour. Other minerals, however, such as illite or montmorillonite, will show in a thin-section of the same thickness yellow, brown, or even reddish or bluish interference colours, while quartz grains *in the same thin-section simultaneously* show the usual bright white interference colours. Fundamentally, a photometric method cannot distinguish between or separate the various effects. Similar complications will occur in soils stained e.g. by Fe compounds.

(b) Any photometric technique integrates light intensity over a certain area, and, when light intensity is plotted against direction in the thin-section, it will result in rather complicated graphs. These may be very difficult to interpret in more complex cases, as a thin-section is only a two-dimensional sample of a usually intricate three-dimensional fabric arrangement pattern (see also Martinez [21]).

(c) The method tends to obscure the presence of minor quantities of the mineral studied with a preferred orientation significantly different from that of the bulk of the material. Such minorities, however, may well influence or even control certain initial phases of the deformation under load [18].

A fundamentally different procedure has been developed [16] that avoids the above mentioned deficiencies altogether, and allows the direct measurement of the three-dimensional orientation of platy clay mineral domains or even platelets (as long as they are adequately visible under the microscope at a magnification of about 200 times). The technique consists of measuring (in a thin-section with known orientation) the apparent birefringence, or, actually the retardation, with a standard Berek compensator. At the same time the particular clay domain is given various tilts by means of a universal stage mounted on the microscope. The purpose is to find one or two (90° apart) critical positions, i.e. tilts, for the particular clay domain, where the apparent birefringence shows either a maximum or a minimum value. In the position where the domain shows a maximum of the apparent birefringence, the basal plane (001) is parallel to the microscope axis. In the position where a minimum occurs, the basal plane (001) is perpendicular to the microscope axis. The method is equally applicable to all platy clay minerals as well as to the common rock-forming micas. It is independent of the value of the actual maximum birefringence of the mineral being examined. In other words, even if more than one species of clay mineral occurs in a particular thin-section, the procedure is still fully applicable to the different species without any corrections at all. The technique is also independent of the actual thickness of the thin-section and even if the thickness of a thin-section should vary, no corrections are required. Obviously, the results of the measurements can be plotted and contoured in the conventional equal-area projection [18].

The results of a clay mineral orientation analysis using the particular technique on the same specimen of a red-brown earth from Panorama, S. A. as discussed in the previous section, is demonstrated in Fig. 1A. It will be seen that the particular soil displays a very distinct preferred orientation of the platy clay mineral domains or aggregates. They appear to be statistically parallel to the line GG (a so-called girdle orientation pattern) parallel to the strike of the terrain slope. In other words, their orientation can be considered as a clear expression of a downslope rolling movement, identical and actually coinciding with the suggestion made earlier for the platy skeleton grains in the same soil. The striking relationship between the preferred orientation of both skeleton grains and platy clay minerals and the geometrical characteristics of the natural terrain slope should be emphasised.

PREFERRED ORIENTATION OF LINEAR AND PLANAR PORES IN NATURAL SOILS

In contrast to the exhaustive studies of joints and joint patterns occurring in many rock masses, remarkably little attention has been given, until recently, to the very common occurrence of cracks (or planar pores) and crack patterns in many natural soils. Virtually all attempts made in this direction were based on qualitative descriptions, mainly in relation to what is generally known in pedology as soil structure. This is even more remarkable since the classical tectonic model experiments of Cloos [5], and Riedel [28] were clearly indicative of systematic relationships between stress distribution pattern and planar pore pattern in moist, or even wet clay materials.

Recently, Fookes [6] and Fookes and Wilson [7] have made orientation studies on planar pore (= fissure, or crack) arrangement patterns of stiff Siwalik clays in Pakistan, using conventional geological field techniques. They found that in these materials the macroscopical planar pore patterns are frequently closely related geometrically to such features as faults and minor slips. Some of the failure surfaces in these clays were found to be largely governed by the geometry of the discontinuity pattern of the parent rock material.

At the same time Lafeber [14] has developed a method to determine the three-dimensional orientation of planar pores in natural soils by means of a series of parallel cross-sections at known mutual distances through a Carbowax-impregnated, oriented specimen of soil. This development has been followed by a similar technique [35] for the determination of the spatial orientation of simple and compound linear features in soils.

A number of natural soils has been examined using these techniques, and it has been found that the spatial orientation of the planar pore patterns shows in general distinct anisotropic characteristics [14, 15, 18]. Obviously, the genesis of many of these natural planar pore arrangements will be very complex, as they are governed by the depositional, pedological and stress-strain histories of the particular soils, and frequently also will exhibit features inherited from the parent rock.

Some results of the application of this technique are shown in Fig. 4 for an oriented krasnozem specimen from Silvan, Vic. The sample has been taken on a very gentle slope, at a depth of 85-100 cm. The slope strikes approximately NE-SW, and dips about 5° to the NW. It will be seen that the diagram demonstrates a very distinct anisotropy in the natural planar pore pattern. Obviously, the maxima in the diagram are spatially closely related to the geometry of the natural terrain slope, representing a predominance of subvertical planar pores approximately perpendicular to the strike of the terrain slope.

Willoughby [35] has applied the particular techniques also in a pilot study on a possible geometrical relationship between plant (= grass) roots and soil planar pores in the upper 10 cm of a black earth profile near Jondaryan, Qld. The sampling site is in a treeless, flat area, and has clearly not been disturbed for many years. Willoughby's diagram for the planar pore pattern of this soil shows, in the usual manner, a small number of (six) maxima of planar pore poles (i.e. the normals to the actual planar pores). These maxima have been replaced for the sake of clarity, by the corresponding great circles or cyclographic projections [26] through the centres of the maxima. In Fig. 5 these great circles are shown together with the maxima of the root orientation. It will be seen that there is a very close geometrical relationship between the most common root orientation and the predominant planar pores.

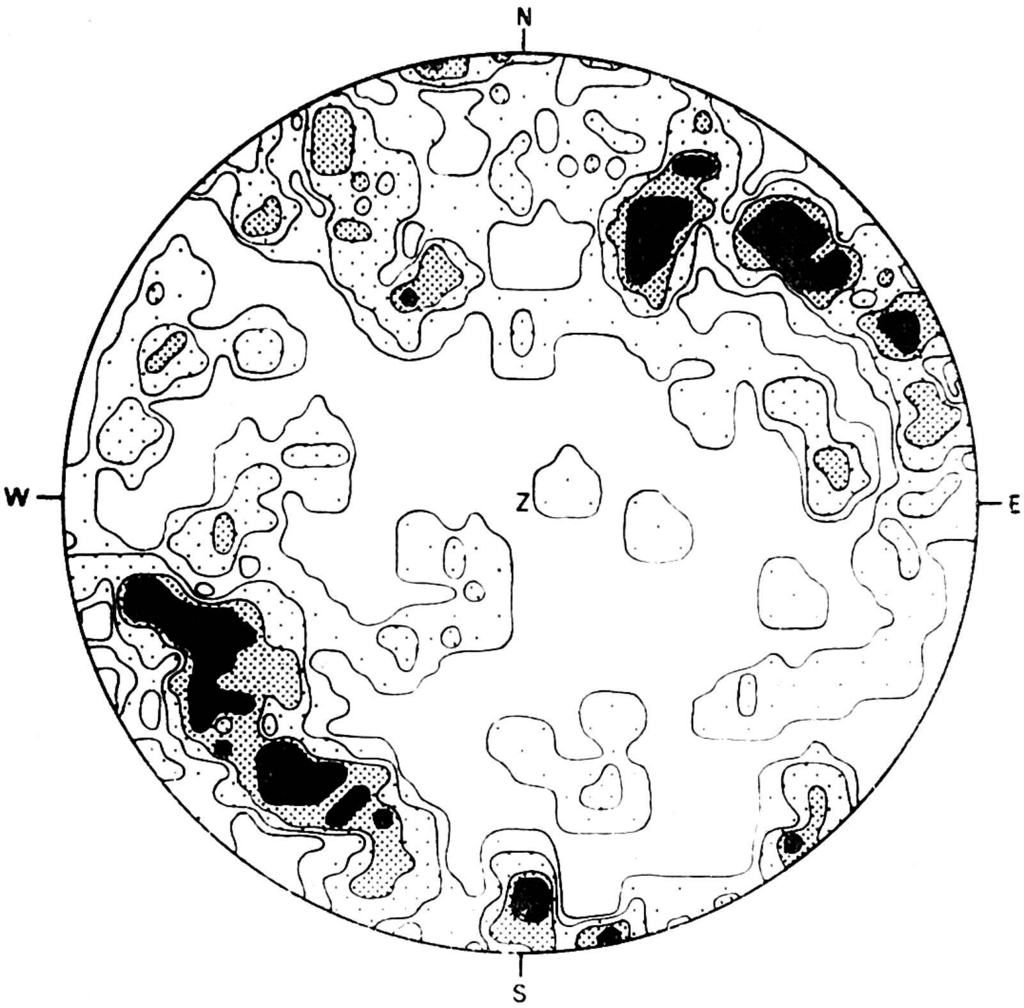

Fig. 4. Preferred orientation of planar pores in krasnozem, Silvan, Victoria. Equal-area projection, horizontal projection plane. Pole densities 0, 1, 2, 3, and 4 or more (max. 8) per unit area. Unit area: 0.56% of total area.

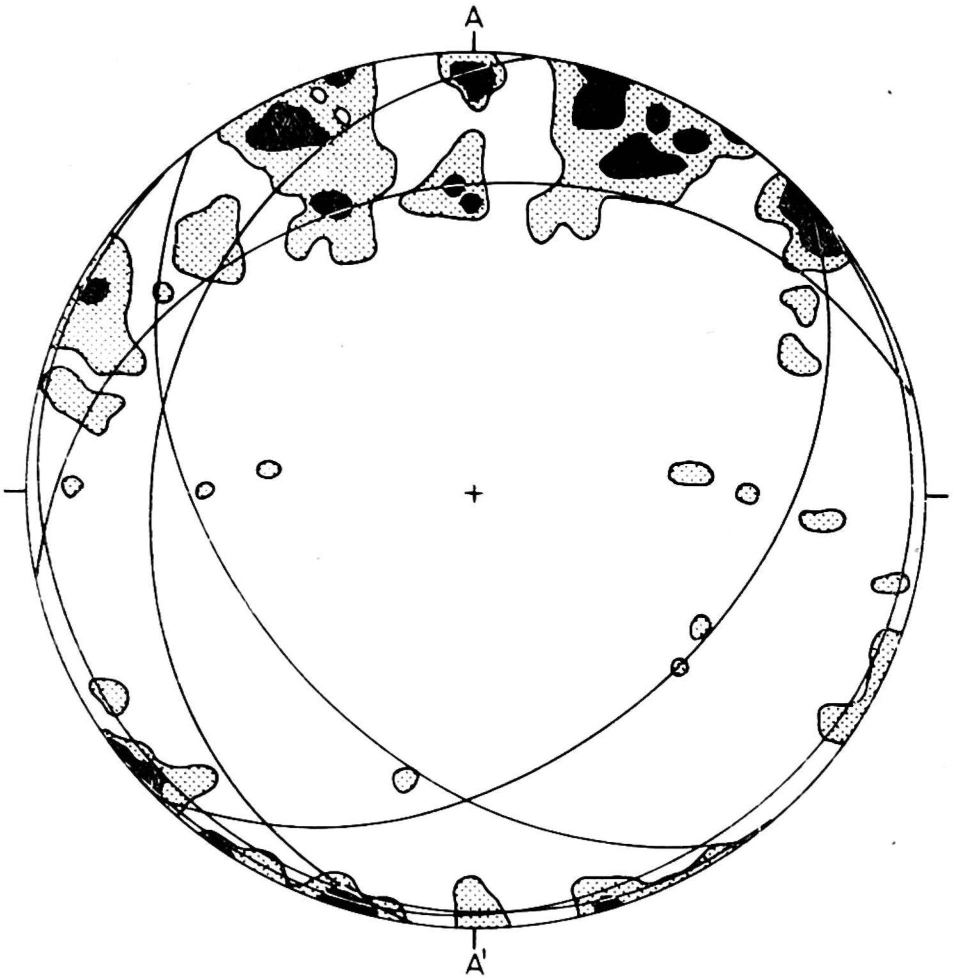

Fig. 5. Preferred orientation of plant roots and planar pores in black earth, Jondaryan, Queensland. Equal-area projection, horizontal projection plane. Planar pore orientation maxima represented by their cyclographic projections (= thin curves), plant root orientation maxima are shown by conventional contours (after Willoughby [35]).

PREFERRED ORIENTATION AND THE MECHANICAL BEHAVIOUR OF SOILS

It has at this stage been pointed out and demonstrated that preferred dimensional orientation of one or more of the major soil components, seems to be a common feature in natural soils. This need not be surprising as the same phenomenon is very common in a great number of rocks.

In effect, such preferred dimensional orientation of one or more components means *geometrical anisotropy*. As the mechanical properties of the major soil components are orders of magnitude apart [11], such geometrical anisotropy will inevitably lead to a corresponding *physical anisotropy*.

From the point of view of engineering soil fabric analysis, the following factors have now to be considered:

(a) the geometrical and physical anisotropy of the soil in its natural condition,

(b) the anisotropy characteristics of the *external load configuration* due to a particular engineering construction or to a certain experimental arrangement, and

(c) the anisotropy of the *internal stress distribution* in a particular soil or soil sample, as a result of the interaction between external load and natural soil fabric.

The first factor has been briefly discussed in the previous sections. A few simple examples of the significance of the second factor will be given in the present section. Apart from the results of certain theoretical considerations, so little is really known about the last factor that it will not be discussed presently.

The first example will consist of a comparison between two oriented samples of the uppermost layer (0-3.5 cm) of a dark-grey, heavy, montmorillonitic clay from the neighbourhood of Tullamarine, Vic. [8]. The locations where the two samples have been taken are at a distance of 4 to 5 m from each other. The one sample has been taken in an unmade, unsealed (double) wheeltrack, regularly used by heavy oil-tanker vehicles, travelling in both directions. The other sample has been collected well outside of the wheeltrack and in soil not disturbed by any vehicular traffic. Figure 6A shows the planar pore orientation pattern of the sample *outside* of the wheeltrack, and it will be observed that there is an area with high density of poles around the centre of the diagram. In other words, there appears to be a predominance of subhorizontal, planar pores in the unaffected soil outside of the wheeltrack. Figure 6B, on the other hand, shows *two* areas with a high concentration of poles, corresponding with two sets of planar pores. Each of these encloses an angle of about 30-40° with the

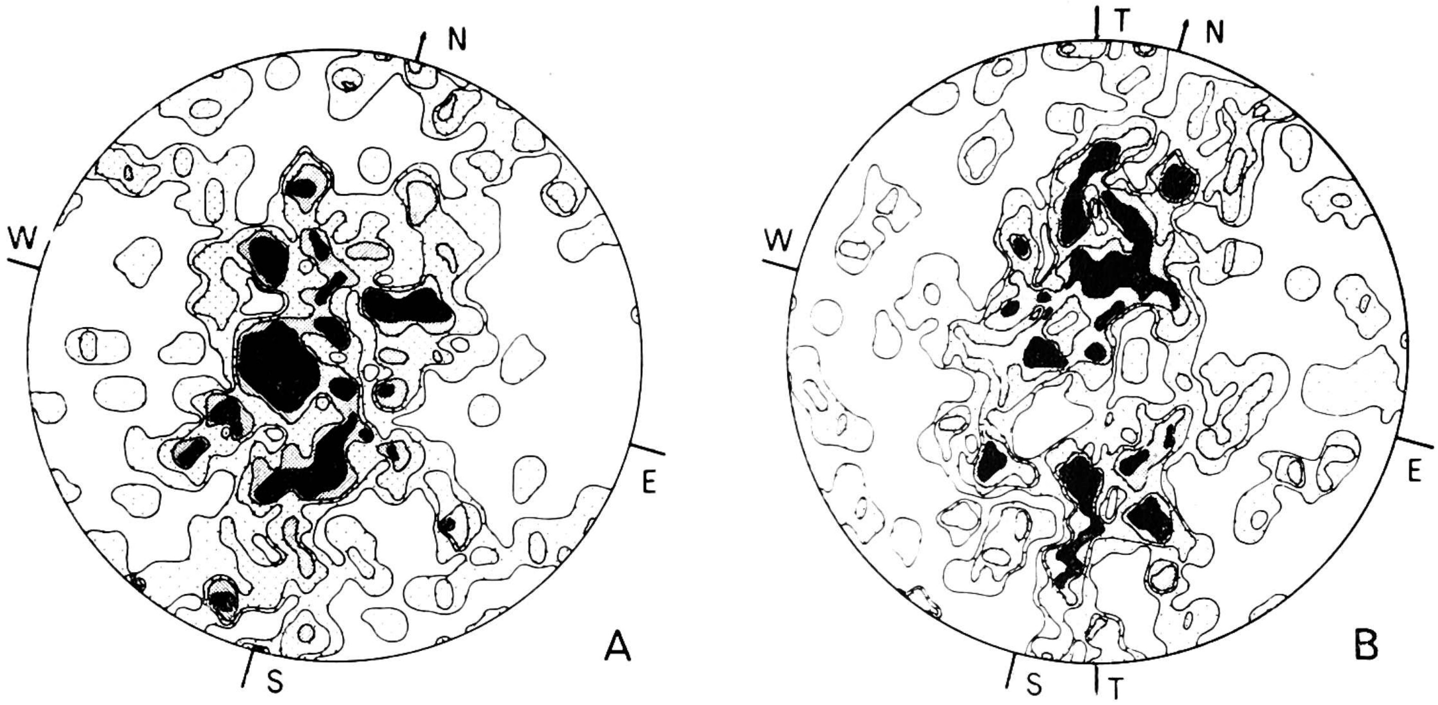

Fig. 6. Preferred orientation of planar pores in montmorillonitic clay, Tullamarine, Victoria. Equal-area projection, horizontal projection plane [8]. A. Specimen outside of wheeltrack. Pole densities 0, 1, 2, 3 and 4 or more (maximum 11) per unit area. Unit area: 0.41% of total area. B. Specimen in wheeltrack. TT = traffic direction. Pole densities 0, 1, 2, 3 and 4 or more (maximum 7) per unit area. Unit area: 0.41% of total area.

horizontal plane. The dip direction of the two sets are obviously opposite to each other. The most striking feature, however, is the way in which the two maxima align themselves in the traffic direction TT, apparently reflecting the *orthorhombic symmetry* of the traffic loading.

In this example the original soil fabric displayed a certain geometrical anisotropy. Superposition of a distinctly anisotropic stress configuration, such as the particular traffic loading, on this natural anisotropic arrangement results in this particular instance in a planar pore pattern that clearly reflects the symmetry (i.e. a vertical symmetry plane) of the external stress pattern. In the following example the opposite phenomenon will be demonstrated, namely the predominant influence of the original, natural fabric of the soil on the final result of loading and deformation.

In this instance, an experimental loading procedure (the so-called 'triaxial' compression test) has been applied. The experimental arrangement consists of a cylindrical soil specimen (7.5 cm diameter and 15 cm height), enclosed in a tightly fitting, watertight, rubber membrane, and placed between two circular plates of either ceramic material or metal, in a wide cylinder or cell in which an all-round fluid pressure can be produced and maintained. Simultaneously, the soil specimen can be loaded vertically through the top endplate. Obviously, this experimental arrangement is in fact different from a true triaxial arrangement in so far that it is characterized by a vertical n-fold symmetry axis in combination with a horizontal symmetry plane. On the basis of these elementary symmetry considerations, the 'triaxial' compression test on natural soils would be expected to result in the development of one or more conical failure surfaces, provided soil could be accepted as mechanically isotropic. The axes of these conical failure surfaces would have to coincide with the axis of the cylindrical test specimen. Very frequently, however, this does not seem to take place at all in natural soil specimens under actual loading conditions. Sometimes, one or two inclined, approximately plane, or only slightly curved, intersecting failure surfaces are developed. In other instances, completely different failure patterns have been obtained. The first case is very well demonstrated in Fig. 7, a stereopair of a model showing the failure surfaces of a 'triaxially' loaded undisturbed krasnozem soil from Silvan, Vic. The model consists of a series of appropriately spaced transparent tracings of the failure surfaces as they appear in subsequent cross-sections through the Carbowax-impregnated soil specimen [14]. It will be observed clearly that there is no indication of a conical failure surface, but instead, two nearly plane, intersecting failure surfaces.

More recently, Lafeber and Willoughby [18] examined and tested a limited number of oriented, undisturbed yellow podzolic soil samples from Syndal, Vic. In the particular soil the preferred orientation patterns of the platy clay minerals as well as that of the planar pores have been determined, using the previously discussed techniques. At the same time,

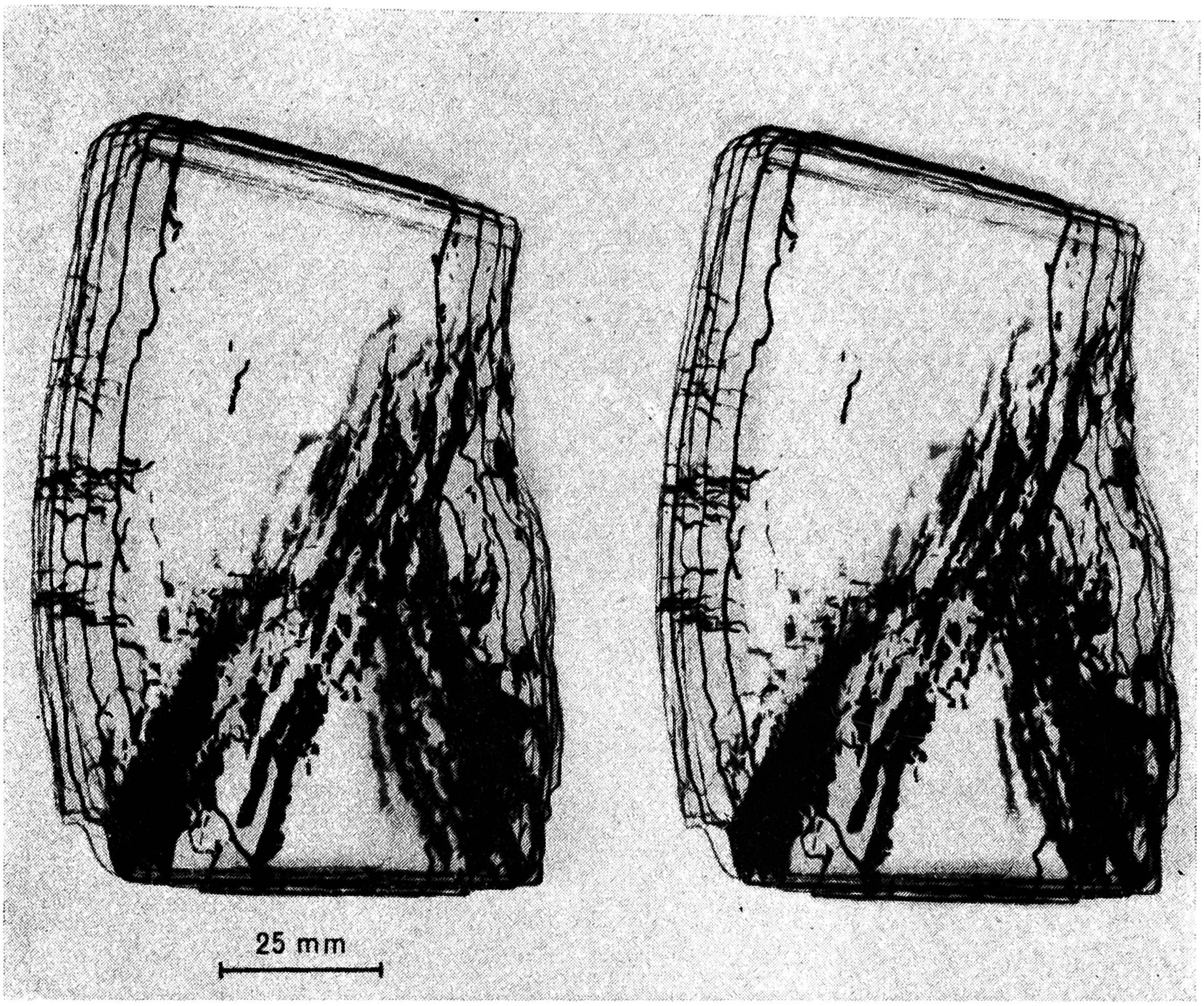

Fig. 7. Stereopair of photographs of a transparent model showing the failure surfaces of a 'triaxially' loaded and failed specimen of krasnozem, Silvan, Victoria. The dimensions of the original cylinder are 75 mm by 150 mm.

the planar pore orientation pattern (in effect the failure pattern) has been determined on two oriented specimens after 'triaxial' loading and failure:

(a) a cylindrical specimen with its longitudinal axis corresponding to the vertical in the field;

(b) a cylindrical specimen with its longitudinal axis corresponding to a horizontal NS-line in the field.

The results of the examination are demonstrated in Fig. 8A and B. In both figures the stippled areas represent the pole density maxima of the planar pore and of the clay aggregate orientation in the undisturbed, natural soil. (These areas will be called the *pre-loading maxima*). Also, in both Fig. 8A and B, the pole density maxima of the planar pores in the failed specimens have been plotted as areas surrounded by heavy lines. (These will be called *failure maxima*). In addition, the area in which the poles of all planes enclosing an angle between 25 and 40° with the longitudinal axis of the cylindrical specimen will plot, is shown in both figures:

(a) in Fig. 8A (for the vertical specimen) this area is delineated by the two thin concentric circles,

(b) in Fig. 8B (for the horizontal specimen) the areas are delineated by the two pairs of thin curves.

It will be seen now that for the vertical cylinder most of the failure maxima fall within the annular area between the two concentric circles, but are clearly restricted to that part of the area where pre-loading maxima occur. For the horizontal cylinder, the majority of the failure maxima are located around pre-loading maxima in the belt bounded by the upper pair of thin curves, and partly around the central pre-loading maxima of the diagram. The latter may indicate a certain amount of axial fracturing in the specimen.

Evidently, in both instances the failure pattern seems to be largely predetermined by certain fabric characteristics, i.e. in the particular case the preferred orientation of the planar pores and that of the platy clay minerals, of the original, undisturbed soil.

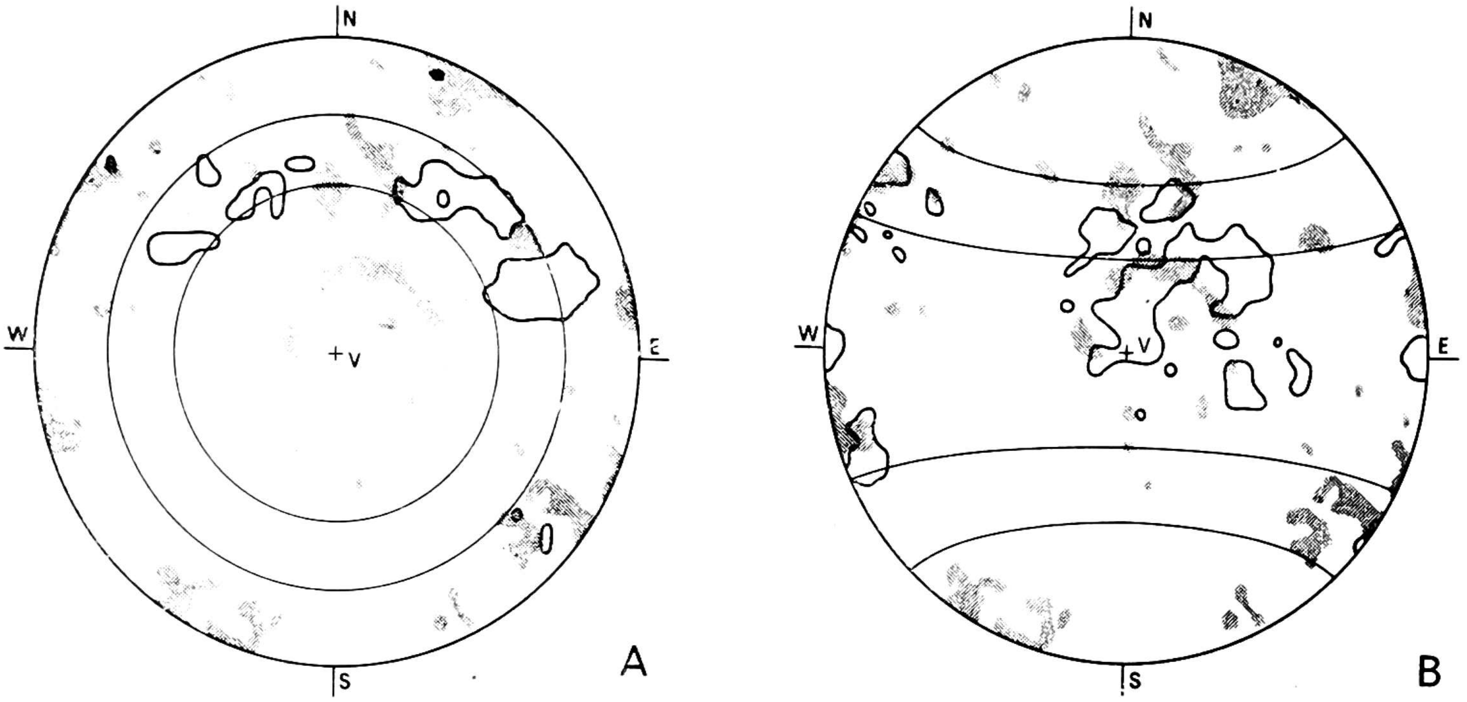

Fig. 8. Orientation of planar pores in 'triaxially' failed yellow podzolic soil, Syndal, Victoria. Equal-area projection, horizontal projection plane. Areas bounded by heavy lines: pole density maxima of planar pores in failed specimens; stippled areas: pole density maxima of clay domains and planar pores in the undisturbed soil. A. *Vertical* cylindrical specimen. Planes enclosing an angle between 25° and 45° with the longitudinal axis V of the cylindrical specimen will plot in the area between the thin concentric circles. B. *Horizontal* cylindrical specimen. Planes enclosing an angle between 25° and 45° with the longitudinal axis NS of the cylindrical specimen will plot in the zones between the two sets of thin curves [18].

CONCLUSIONS

Geometrical anisotropy patterns, involving one or more of the major soil components (skeleton grains, clay minerals, and pores) have been recognized in a number of arbitrarily chosen natural Australian soils, using micromorphometric techniques developed by the author and his coworkers. Graphical description of these three-dimensional arrangements by means of the conventional fabric or structural diagrams has been chosen for reasons of convenience. There would be no fundamental objections, however, against the application of (presumably more complex) analytical techniques instead.

The action of anisotropic external stress configurations on such soils results in corresponding anisotropic strain patterns, apparently in such manner that only those symmetry elements that are common to both the soil fabric and the external stress pattern will occur in the ultimate strain pattern.

The techniques applied here are primarily suited for the detection and description of directional or vectorial properties characteristic for both soils and stress and strain fields. As an appreciable number of processes of pedological interest are also, at least partially controlled by vector properties, it is considered that these techniques may be of value in the study of a number of pedological and paleopedological problems as well.

SUMMARY

A number of recently developed micromorphometric techniques for the determination of the three-dimensional preferred orientation patterns of non-equidimensional skeleton grains, clay minerals, and pores in undisturbed, natural soil samples is briefly described and discussed. The applicability of these techniques is demonstrated for a limited number of arbitrarily chosen Australian soils.

The results show that all these soils are characterized by some form of geometrical anisotropy. As the major soil components are physically (particularly mechanically) quite different materials, these geometrical anisotropies will be accompanied by corresponding physical anisotropies. Consequently, these soils will show a distinct anisotropic strain behaviour when under load. In combination with anisotropic external stress fields they will show a strain behaviour demonstrating only those symmetry elements that are common to both soil fabric and external stress pattern. Examples of this mutual interaction between soil fabric and external load pattern are presented.

The particular techniques are primarily meant for the detection and description of vectorial properties. As many pedological processes are also influenced by vector fields, it is considered that the present techniques may be of similar value in certain types of pedological or paleopedological problems.

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