Mesofabric, Microfabric, and Submicrofabric of Ice-Thrust Bedrock, Highvale Mine, Wabamun Lake Area, Alberta

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Abstract

The fabric of the ice-thrust argillaceous bedrock from a shear zone was studied in hand specimens, under a polarizing microscope and a scanning electron microscope. The fabric included principal displacement shears, Riedel shears, conjugate sets of particle alignments, cutans, lithorelics, and aggregations which had dense cores of randomly oriented groups of clay platelets wrapped by an external layer of oriented clay particles in a turbostatic arrangement. In addition the bedrock has been disturbed by permafrost, cycles of loading and unloading and weathering causing the magnitude of deformation to vary within the ice-thrust shear zone.

The fabric of the ice-thrust shear zone is similar to shear zones formed by tectonic activity and by laboratory shear tests, suggesting that all these shear zones were formed under conditions of similar kinematic restraint.

Purpose of Investigation and Location of the Study Area

Recent slope instability along the highwall of the Highvale coal mine in ice-thrust terrain (Fenton *et al.* 1983; Andriashek *et al.* 1979), caused concern for mining operations near the crest of the slope. The Highvale coal mine is south of Lake Wabamun, about 70 km west of Edmonton (Fig. 1) in the interglacial North Saskatchewan Valley (Stalker, 1961). As a contribution to safe and economic design of the highwall, a program was set up to study the fabric and the geotechnical properties of the ice-thrust bedrock in Pit 3 of the mine.

This paper describes the fabric study; the geotechnical properties and slope movements are presented in detail elsewhere (Tsui *et al.* 1988a, b).

While ice-thrust features are widespread on the Prairies (Moran *et al.* 1980; Kupsch 1962), and glacially-disturbed and weakened sediments are associated with many landslides (Morgenstern 1977; Sauer 1978; Christiansen and Whitaker 1976), the fabric and the related geotechnical properties of ice-deformed bedrock has not been studied in detail (Sauer 1978). Appreciation of the fabric of the sediments would help to interpret the engineering behavior of the soils in the laboratory and in the field. The fabric of a clayey soil also may reveal evidence of deformation by permafrost, weathering, shear deformation, and past overburden pressure (Marsland *et al.* 1983; Barden 1972a; Barden and Sides 1971b; Morgenstern and Tchalenko 1967a), so this study may throw light on the fabric and shear properties of the clay before ice thrusting and on the ground conditions when ice thrusting took place. Understanding the distribution (within a shear zone) of the fabric and strength properties which influence engineering properties would also help the selection of field sampling techniques and in-situ and laboratory testing methods (Rowe 1972; Marsland and Butler 1967).

Field Investigation and Sampling

The mine, in the Lower Tertiary Paskapoo Formation, which comprises bentonitic sandstone, coal, and thin shales, is underlain by the Upper Cretaceous Battle Formation which consists of bentonitic sandstone, shales, coal and bentonite. The surficial geology has been studied by Andriashek *et al.* (1979) and Fenton *et al.* (1983). A till veneer on the bedrock is about 4 m thick.

Interpretation of Alberta Government airphotos AS135, 20, 21, 22 shows isolated gentle hills and slope movements in the mine near the north-facing valley wall of a meltwater channel. Excavations in these hills show gentle to close folds, thrust faults and shear zones up to 3.8 m thick. These deformed structures in the hills located in a glaciated region which has no recent regional tectonic activity indicate the deformations are ice-thrust features.

Field studies show that the ice-thrust shear zone in Pit 3 is the main cause of slope failure in the mine. This zone is composed of two horizontal layers, a crumbly and fissured bentonitic mudstone layer up to 3.4 m thick which was overlain by a gently deformed bentonitic sandstone layer, and a folded, faulted bentonite layer up to 130 - 200 mm thick overlain and underlain by two thin coal beds about 150 to 250 mm thick. Both of these layers contain a few continuous and horizontal, sheared and polished surfaces. The macrofabric of the ice-thrust shear zones in Pit 3 has been studied in detail (Tsui *et al.*, 1986).

The top of the shear zone is distinct and is at the contact of the bentonitic mudstone with the overlying bentonitic sandstone. The base of the shear zone is defined as the boundary between the thin coal bed that underlies the bentonite and the carbonaceous shale that overlies the horizontal and undeformed main coal seams.

Test pits in the shear zone along the highwall yielded block samples 0.3 m x 0.3 m x 0.15 m in size from close to the continuous and flat-lying shears in the bentonitic mudstone layer and the bentonite layer.

This paper describes the meso-, micro-, and submicrofabric observed in these block samples.

Fabric Study

The mesofabric is large enough to be observed without the aid of a microscope yet small enough to be observed in its entirety. The microfabric is the features of the soil texture that require a petrographic microscope to identify them. The submicrofabric is the units and arrangements that can only be seen under an electron microscope.

The shrinkage disturbance of the bentonitic mudstone samples during sample preparation is considered to be insignificant because the natural moisture content of the bentonitic mudstone is lower than its shrinkage limit. However, the bentonite has a natural moisture content well above its shrinkage limit and shrinkage disturbance of the microscopic features is thought to be significant during sample preparation and thin sectioning (Tsui 1987). As a result, no thin sections and SEM samples were made from the bentonite and microfabric and submicrofabric studies were performed only on the bentonitic mudstone.

The polarized light microscope study is qualitative and follows similar work performed on clays and shale by Mitchell (1956) and Morgenstern and Tchalenko (1967a). Because the orientation of the fold axes and slickensided features found in the deformed structure observed in Highvale mine indicate that the sediments were deformed by an ice lobe coming from the north, samples for thin sectioning were cut in vertical north-south planes. Four slices were cut from the bentonitic mudstone with a steel wire to a thickness of about 10 mm, a length of 50 mm and a height of 80 mm. They were logged, photographed and thin sectioned. A standard polarized microscope with a 35 mm camera for photomicrographs was used in this study.

The bentonitic mudstone samples used for the scanning electromicroscope (SEM) study were prepared by the methods suggested by Gillott (1969), Barden and Sides (1971a), and Tovey and Wong (1977). The Cambridge Stereoscan 250 equipped with the Kevex 7000 Energy Dispersive Analyzer for mineral identification was used in this study. Twelve samples were examined under the SEM. The fractured faces of these samples were chosen such that they were either parallel or normal to the plane of the principal displacement shear. About 20 sites on each face were studied under magnifications of 1,000x to 20,000x. The results of the fabric study are described below.

Observations of the Mesofabric

Fold structure was not seen in the bentonitic mudstone; however, small-scale folds and monoclinal structures were found in the bentonite and the thin coal layers which overlie and underlie it. These layers are undulatory with fold axes approximately perpendicular to the direction of recent ice movement in the area.

The bentonitic mudstone within the ice-thrust shear zone contains a few continuous and horizontal polished surfaces. These shear surfaces are known as principal displacement shears and develop in a shear zone after movements of about 100 mm have occurred (Skempton and Petley 1967). One hand specimen coincided with the rupture surface of the slides in the area. This sample indicated that the portion above the shear was a light to dark grey, very fine-grained, moist and plastic layer. The bottom portion was a dark brown to dark greyish brown, stiff, fissured, relatively dry layer with many angular lumps and peds up to 7 mm long and fissures up to 1 mm wide. Thin sections from these hand specimens show that adjacent to the principal displacement shear, there is a mixture of light grey to brown nodules up to 3 mm in length, and vertical to inclined fractures diverging upward and downward from the shear surface.

The hand specimens from the bentonite layer indicate that the principal displacement shears are generally overlain and underlain by a black, brownish grey to dark grey, moist, plastic, and dense clay 5 to 35 mm thick. Angular coal fragments up to 8 mm long have their sides oriented parallel to these shears. However, the grains become randomly oriented about 5 mm below the shear. Away from the shear plane, the material is light brown, light greyish white, dry, stiff, and crumbly clay.

In general, the sediments between the principal slip surfaces are dry, porous, and with many fissures and lumps. These fissures are probably the minor shears, (displacement shears, Riedel- and thrust-shears) described by Skempton and Petley (1967). Movements along individual minor shears are a few millimetres because they are often polished but are seldom striated. They are similar to the sheared features observed in tectonic shear zones by Fookes (1965) and Skempton (1966).

The Microfabric of the Bentonitic Mudstone

The mineralogical composition and the general microfabric observed in the thin sections is shown in Figure 2. The terminology used to describe the texture of the microfabric follows Brewer (1964), Skempton (1966) and Yong and Sheeran (1973).

The sediments consist of four main components: peds (aggregates or crumbs), nodules which include skeleton grains and organic inclusions, fractures, and clay matrix. The peds and nodules were angular to rounded and ranged up to 2.7 mm in diameter. A matrix composed mainly of microscopic to submicroscopic clay particles surrounded the nodules and peds. In the upper portion of the thin section, clay matrix dominated and the fewer rounded nodules were randomly oriented and not in contact (Fig. 3). In contrast, the lower portion of the thin section was composed chiefly of angular and subangular peds. The peds were usually in contact with each other. In the middle of the thin section, a layer 7 to 15 mm thick of nodules and clay matrix contained the principal displacement shear.

The principal displacement shear is a horizontal discontinuity with smooth surfaces bounded by a thin layer of clay particles oriented parallel to the surfaces and about 12 to 300 μm thick. Sheared nodules were found along it. Inclined fissures and lineations diverge upward and downward from this shear plane. Other shears with similar structural features were found in the upper portion of the thin sections. There, the layers of clay particles that were parallel to these planes were thinner and had a thickness of 15 - 60 μm (Fig. 4).

The Riedel and thrust shears diverged from the principal displacement shear at inclinations of 16° - 30° and about 130° from the horizontal. These sheared discontinuities usually have a length of 0.3 to 1.65 mm and a width of 4 to 80 μm. Other lineations in the clay matrix found in the upper portion of the thin sections were more discontinuous than the Riedel and thrust shears and these lineations often intersected each other. The discontinuous nature and general orientation of these conjugate sets of lineations differ from the configuration of the Riedel and thrust shears, and their abundance in the clay matrix, that lacks distinct shear discontinuities (Fig. 3), resembles the right bimasepic fabric and clino-bimasepic fabric in soil formed due to shrinkage and swelling (Brewer 1964).

Cutan is a modification of the fabric at natural surfaces in soil materials due to concentration of particular constituents or in-situ modification of the clay matrix (Brewer 1964). It is termed argillan when the constituents are composed of clay particles. Embedded grain argillans, which are layers of preferred oriented clay particles with a thickness of 4 - 7 μm lying parallel and/or around the boundaries of nodules, were common in the upper portion of the thin sections (Fig. 4) and near the major principal displacement shear. Argillans were also found bordering fractures and shear planes.

The fractures found in the upper portion of the thin sections were relatively short and narrow and generally had a length of 0.6 - 1.65 mm and a width of 0.015 - 0.3 mm. However, the fractures in the lower portion of the thin section had a length of 0.08 mm to greater than 5.4 mm and a width of 0.03 to 0.3 mm. The fractures found in the lower portion of the thin sections delineated the sides of the peds and were probably formed by the connection of numerous short planes which resemble crazing planes formed due to irregular drying (Brewer 1964). Horizontal and slightly inclined fractures at and adjacent to the principal displacement shear at the middle of the thin sections were continuous with smooth fracture surfaces about 0.20 mm wide. These fractures were formed by the opening of the displacement shears and/or the coalescence of shear lenses.

About 4 mm below the principal displacement shear, an organic lamination about 6.4 μm thick was deformed into anticlinal and synclinal structures. Riedel and thrust shears which seem to act as micro-thrusts, had segmented the fold structure into many pieces.

The submicrofabric of the bentonitic mudstone

The general submicrofabric observed in the ice-thrust bedrock is indicated in Figure 5. The terminology used to describe the submicroscopic sediment units mainly follows Collins and McGown (1974).

The elementary particle arrangements of the clay are densely compacted, random to preferred oriented, partly discernible groups of clay platelets (Figs. 6(a) and 6(b)). However, these groups of clay platelets may be in an open arrangement locally (Fig. 6(c). Particle interaction was not seen although at the shear discontinuities, individual clay platelets were found interacting with groups of clay particles. In general, interactions between small groups of clay platelets were the dominant elementary particle arrangements in the sample. The group of clay platelets may have a length of 3 - 6 μm though single platelets up to 10 - 20 μm long were noted.

Generally, the highly compacted and oriented groups of clay platelets were similar to the turbostratic arrangements proposed by Aylmore and Quirk (1960). The compacted and randomly oriented groups of clay platelets that consisted of face-face clay plates, could result from the collapse and compaction of the edge-edge, edge-face floccuated and aggregated arrangement, the bookhouse arrangement, and the stepped cluster arrangement suggested by Van Olphen (1963), Sloane and Kell (1966) and Smalley and Cabrera (1969).

Particle assemblages are defined as units of particle organization with definable physical boundaries and a specific mechanical function (Collins and McGown 1974). Three types of particle assemblages were observed: aggregations, connectors, and bunches and matrices.

Except at the principal displacement shear, densely compacted, oval, to irregular aggregations were found in all samples (Figs. 6(d) and 6(e)). The aggregations comprised a dense internal core made up of randomly oriented groups of compacted clay platelets, and an external shell, resembling an onion skin, of dense layers of clay platelets in a turbostratic arrangement parallel to the surfaces of the aggregations (Figs. 6(b) and 6(e)). This external shell or onion skin varies from a few to tens of clay platelets thick.

At the contacts of the cores and the onion skins of most of the aggregations, the clay platelet groups of these two units touch but without linkage or fusion (Fig. 6(f)). The close but disconnected contact between the randomly oriented clay groups in the cores and the turbostatic arrangement in the skins suggests that they were different submicro features before aggregation. These aggregations interact with other microfabric features at the contact of their onion skins (Fig. 6(d)). Minor shears at these contacts are shown by particle alignments along the discontinuities that extended through the onion skins (Figs. 6(e) and 7(a)).

Connectors are elongated clay and fine silt assemblages that form between silt and sand grains (Collins and McGown 1974). No connectors were found between the silt size aggregations of the ice-thrust sediments but connectors made by a partly discernible particle system link groups of clay platelets in a few of the cores of aggregations with an open structural arrangement (Fig. 6(c)).

Aggregations were often densely compacted and their skins tended to fuse. This formed a system of interweaving bunches of oriented groups of clay platelets wrapped around aggregations (Fig. 6(d)). Except at the principal displacement shear, where aggregations were absent (Fig. 7(b)), the bunches were the main particle matrix that bound the aggregations together.

Intra-elemental pores were absent; however, intergroup pores were found in a few aggregations (Fig. 6(c)). Intra-assemblage irregular pore spaces found within aggregations, often between onion skins and cores were more common than the intergroup pores (Fig. 6(f)). Inter-assemblage pores, elongated spaces between aggregations, were connected and formed trans-assemblage fractures that extended across several aggregations (Fig. 7(c)). However, the submicrofabric is often so compact that only dense bunches and shears were found between aggregations.

A submicroscopic shear zone of aligned clay platelets 10 - 20 μm thick was found immediately below the principal displacement shear (Fig. 7(b)). Away from this submicroscopic shear zone, the matrices of the samples varied from porous to compact, and clay platelets that coalesced into aggregations were common. Minor shears at the contacts of the onion skins of the aggregations may have been deformed into undulatory discontinuities attached by aligned clay platelets (Fig. 7(a)). The displacements along these minor shears were small and only a few clay platelets were inclined along these discontinuities. This indicates that there was insufficient movement along the minor shears reorient the clay particles. Figure 7(d) shows platelets normal to a minor shear are fractured and have angular edges in contact with the minor shear located 5 mm below the principal displacement shear.

Aggregations were absent in the immediate vicinity of the principal displacement shear but about 10 - 20 μm away aggregations and minor shears were common. This shows that the displacement was strong enough to break the dense aggregations and create aligned shear matrices. However, the deformation rapidly diminished and became unevenly distributed tens of microns away from the principal shear.

The trans-assemblage pores (Fig. 7(c)) seem to be comparable to the close-packed aggregations and large cracks within the peds of a clayey soil after freeze/thaw/dry/wet cycles (Smart and Tovey 1981, Fig. 12.2). However, the discontinuities formed by freeze-thaw action cannot be differentiated from those fractures and minor shears caused by ice thrusting. Both processes probably occurred in the study area.

Genesis of the mesoscopic fabric

Submicroscopic fractures and minor shears, (Figs. 6(e) and 7(a)) form local planes of weakness, and are probably the reason for the bedrock breaking into lumps under finger pressure. Similar fabric has been found in other heavily overconsolidated clays (Barden 1972a, 1972b). The dense silt size aggregations between these submicroscopic discontinuities resist breaking the sediments down into individual particles for grain size analysis. Grain size classification tests (Tsui 1987) classify the bentonitic mudstone as a silt although the SEM studies indicate that most of the material is clay. Similar observations have been made by Barden and Sides (1971b) and Chandler (1969).

This non-marine heavily overconsolidated sedimentary rock has been subjected to overburden pressures up to about 16 MPa (Nurkowski 1984) and now showed poor to absent fissility and tended to disintegrate. Petrographic studies indicate that random clay flakes dominate in non-fissile claystone while in shale with moderate fissility, the particles are parallel but comprise domains with other oriented particles (O'Brien 1970; Odom 1967). Fissility in the samples studied is absent because the clay platelets are oriented, not in horizontal layers, but in interweaving bunches of compacted, preferentially oriented groups of clay platelets between aggregations

(Fig. 6(d)).

Compression texture and kink band structure, found in clay soils subjected to direct shear (Morgenstern and Tchalenko 1967b; Tchalenko 1968b, 1970), were not seen in the ice-thrust bedrock in the Highvale mine (Fig. 4). The shearing along the principal displacement shear during ice thrusting was strong enough to break down the microfabric at this shear plane and create an aligned shear matrix but the deformation diminished rapidly away from the principal shear (Figs 6(d) and 7(a)), and could not break down the compacted aggregations and orient the clay platelets into a kink band structure.

The meso- and microfabric elements, such as Riedel shears and principal displacement shears, observed in the ice-thrust shear zone are similar to those within shear zones of landslides and earthquakes, and laboratory direct shear tests (Morgenstern and Tchalenko 1967a, 1967b; Tchalenko 1968b, 1970; Skempton and Petley 1967; Skempton 1966; Tchalenko and Ambraseys 1970). All these shear zones were formed under similar modes of kinematic restraint during shearing. Similarly, in glaciotectonism, kinematic restraints imposed on the subglacial strata by the overlying glacier and the surrounding strata cause shear to concentrate at a weak horizon within the sediments.

The distribution and amount of lithorelicts and peds in the samples studied (Fig. 2) suggest that the principal displacement shear was overlain by a weathered layer and underlain by a relatively less weathered layer. During ice thrusting, shear displacement was concentrated along the contact between these layers. This resulted in shearing and breakdown of the peds and nodules adjacent to the contact, and migration and mixing of the material from the layers. A highly deformed layer was created that comprised sheared peds and lithorelicts and contained a principal displacement shear.

Genesis of the Microfabric and Submicrofabric of the Ice-Thrust Sediments

Brecciation and nodules resembling lithorelicts in the ice-thrust shear zone indicate that, in addition to glaciotectonism, the ice-thrust materials in that area have undergone other kinds of deformation. For example, brecciation could be formed by the decay of permafrost (Chandler 1972) or glaciotectonics (Geikie 1889). Four processes other than glacial thrusting that may develop some of the fabrics observed in the ice-thrust sediments are suggested below.

1. Melting ground ice might cause internal crumbling in argillaceous sediments resulting in a microfabric of shattered peds or lithorelicts in a matrix of brecciated, remoulded, and structureless soft clay (Chandler 1972, Fig. 15; Marsland et al. 1983, Fig. 24). The rounded nodules in the clay matrix (Fig. 3) and broken ped structure within the shear zone studied resemble brecciation due to permafrost.

2. Unloading might cause microscopic shears in stiff overconsolidated clay (Bjerrum 1967). Unloading occurred due to the erosion of Tertiary sediments before Pleistocene time (Nurkowski 1984). Loading and unloading ocurred again during glaciation of the study area. Minor shears developed in the underlying strata due to these loading and unloading cycles, although those near the principal displacement shears were probably due to shearing by ice thrusting.

3. Surface weathering is shown by an erosional surface near the top of the shear zone (Tsui 1987). The bentonitic mudstone had been under subaerial

erosion before glaciotectonism when it had been disturbed by seasonal and annual water content changes and freeze-thaw cycles. Microstructure, similar to the nodules and conjugate sets of micro-lineations found within the bentonitic mudstone, has been found in London clay which has undergone surface weathering (Tchalenko 1968a, Fig. 4). Brewer (1964) also commented that weathering would cause deformation in a clay matrix and form a striated orientation pattern; while rotation and translocation of nodules under pressure may shear the adjacent clay matrix and cause embedded grain cutans to develop. These cutans are a common feature in the ice-thrust sediments studied (Fig. 3). Furthermore, trans-assemblage pores and fractures found in the samples indicate freeze-thaw occurred (Fig. 7(c)).

4. The nature of the fractures observed suggest that some may be due to shrinkage upon drying. However, the amount of fracturing in the bentonitic mudstone caused by sample preparation is considered to be small because its natural moisture content was below the shrinkage limit (Tsui 1987).

To summarize, before glaciation, surface weathering and removal of the overburden developed the microfabric, minor shears and cutans in the bentonitic mudstone. During glaciotectonism, ice thrusting deformed the sediments and loading and unloading by the continental glaciers further deformed the underlying strata. Permafrost also disturbed the bedrock during and probably before glaciotectonism.

Evolution of the Microfabric and Submicrofabric of the Ice-Thrust Sediments

A model for natural clays consists of stiff aggregates of closely spaced particles connected by links or bridges of particle network (Pusch 1973a).

Under high shear stress or stresses exceeding the preconsolidation pressure, these links may collapse into connected groups of oriented particle aggregates in stable positions (Pusch 1973a, Fig. 3). SEM studies of post-glacial, normally to lightly overconsolidated clays support this view of the primary microfabric of clayey soils as aggregations chained by narrow elongated assemblages of fine silt to clay particles (Collins and McGown 1974, Fig. 10e; Pusch 1973b; Barden and Sides 1971b). SEM studies on heavily overconsolidated, stiff, fissured clay show that the large silt size particles are wrapped with a closely-packed dispersed turbostratic clay structure with a tendency for horizontal orientation (Barden 1972a, Figs. 12 - 15; Barden 1972b). Barden (1972a) concluded that the microfabric of the stiff fissured clays originated from an flocculated structure that collapsed into a turbostratic arrangement. In contrast, the ice-thrust heavily overconsolidated sediments studied, also show a compact structure without connectors or large pore spaces between aggregations (Figs. 6(d) and 6(e)). The connection and fusion of the onion skins of these aggregations has produced a braided stream of oriented clay particles around the dense cores of aggregations (Fig. 6(d)), resembling the turbulent microstructure proposed by Sergeyev *et al.* (1980, Fig. 7) to form by compacting clay sediments containing honeycomb and matrix microstructures.

Comparison of the submicrofabric in the mine samples with microstructure in soils mentioned above suggests the original microfabrics of the ice-thrust sediments were probably silt size aggregations of flocculated groups of clay platelets linked by elongate chains of clay platelets. Under high overburden pressure, these chains collapsed into groups of oriented particles (domains) (Pusch, 1973a, Fig. 3c). Since the primary aggregations are dense and stiff, compression caused the groups of clay platelets in the aggregations to compact but the lack of space prevented the groups of particles reorienting normal to the major principal stress. However, the chains between these aggregations are fragile and are located in a space that allows rotation to the preferred orientation. Prolonged compression caused the domains to come into close contact with the aggregations and create a dense matrix. Weathering which caused uneven breakdown of the silt size aggregates of clay particles and particle intergrowth that bound individual clay platelets into 'patches' (Fig. 6(a)). Subsequently, ice thrusting sheared the sediments, and further compressed the groups of clay particles into aggregations. The authors believe that, as in the evolution of tectonic and laboratory shear zones (Skempton 1966; Tchalenko 1968b, 1970; Morgenstern and Tchalenko 1967b; Tchalenko and Ambraseys 1970), the ice-thrust shear zone was initially deformed in simple shear and many local discontinuities such as Riedel shears were produced. However, due to the kinematic restraints imposed upon the shear zone by the overlying glacier and the surrounding rock masses, the deformation of the sediments evolved from simple to direct shear. In subsequent deformation in the central portion of the shear zone, the Riedel shears were interconnected by thrust or P shears. At large strains, the deformation of the shear zone was concentrated along a few horizons a few millimetres thick thus creating the principal displacement shears. The rest of the shear zone was undisturbed. The final products are compacted secondary aggregations of a dense core of randomly oriented groups of clay platelets surrounded by an onion skin of groups of oriented particles with a turbostratic arrangement, fissures, minor shears, micro-folds and principal displacement shears bounded with strongly oriented clay particles (Figs. 5, 6(d) and 6(e)). The open, flocculated structure in local areas of the sediments (Fig. 6(c)) is the original microfabric of the material that survived the post-depositional processes probably due to arching effects (Barden 1973).

Figure 8 illustrates the evolution of the microfabric and submicrofabric of the sediments due to overburden pressure, weathering, and ice thrusting.

Conclusion

The observed fabric includes principal displacement shears, Riedel shears, conjugate sets of particle alignments, cutans, lithorelicts, aggregations with dense cores of randomly oriented groups of clay platelets wrapped by an external layer of oriented clay particles in a turbostratic arrangement, minor shears and suspected freeze-thaw features. The fabric in an ice-thrust shear zone in the Highvale mine suggests that, in addition to glaciotectonism, the ice-thrust sediments have been disturbed by permafrost, cycles of loading and unloading, and surface weathering. The distribution of the fabric suggests that the magnitude of deformation varies in the ice-thrust shear zone.

During ice thrusting, the kinematic restraints of the overlying ice sheet and the surrounding rock masses produce flat-lying shear zones with fabric similar to shear zones formed by tectonic activities and laboratory shear tests in clayey sediments.

The fabrics of ice-thrust bedrock discussed in this paper, are based on the examination of 15 - 20 hand specimens, 4 thin sections (40 x 22 mm^2 per section), and 12 SEM samples from block samples collected at a horizon at a specfic site in Highvale mine. The sample is small compared to the large volumes of rock affected by glaciotectonism in the study area. More studies should be performed on different horizons in the ice-thrust shear zone at other sites to verify the observations of this present study.

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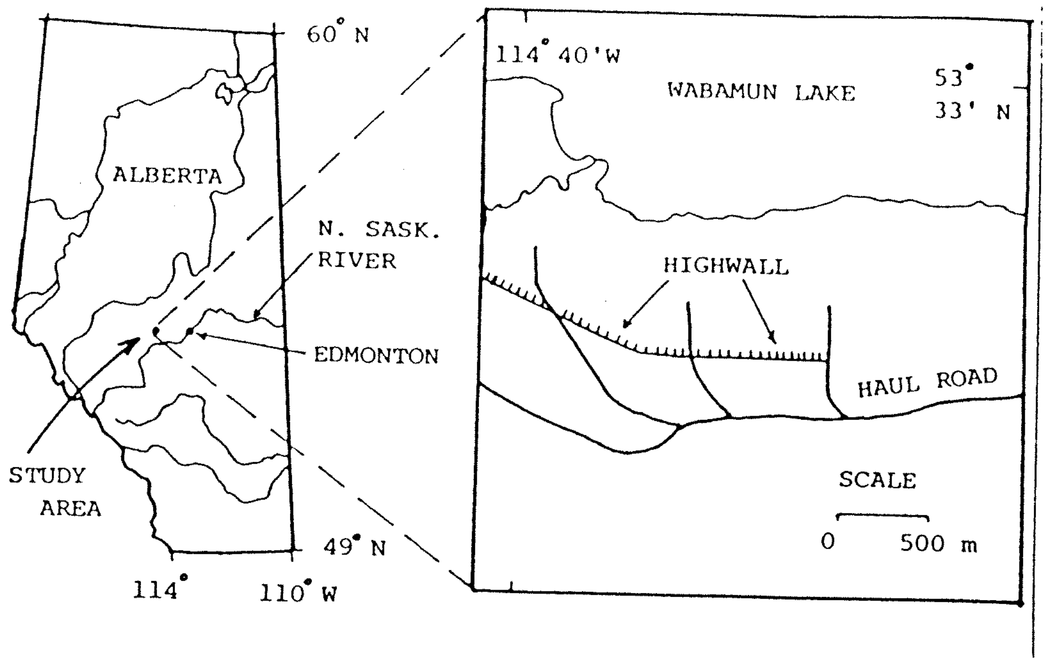
LIST OF FIGURES

d) Formation of aggregations composed of onion skins, compacted cores and minor shears

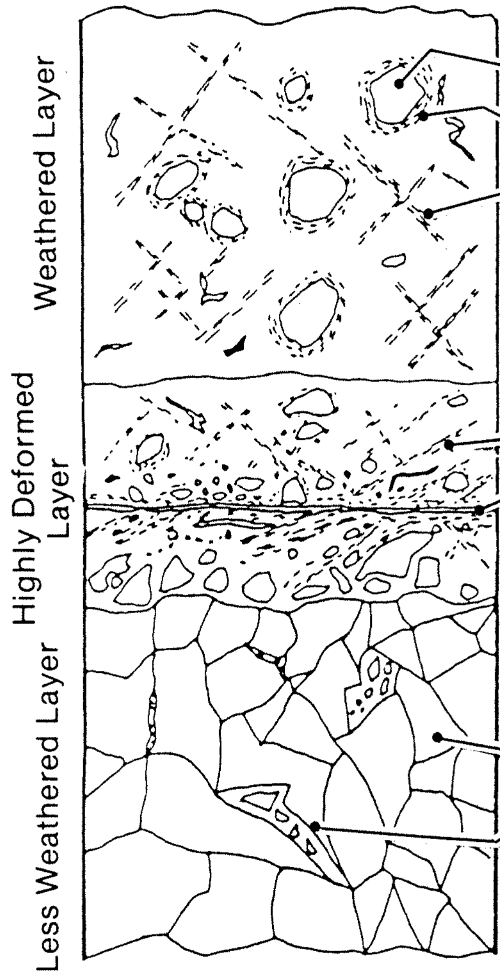
e) Glacistectonic deformation, the formation of the principal displacement shear and the shear matrix is shown in Figure 5.

(a, b follow Collins and McGown (1974) and Pusch (1973a); c, d, e are suggested by the authors)



Tsui, Cruden, & Thomson: Mesofabric, Microfabric & Submicrofabric of ice-thrust Sediments, Highvale Mine.

Fig. 1



- Light grey to grey
- Scattered and randomly oriented nodules resembling lithorelicts,
- Argillans around nodules engulfed by clay matrix
- Conjugate sets of lineaments in clay matrix
- Narrow fractures and small voids.

Montmorillonite content	:	60 - 65% (average = 62%)
Illite content	:	10 - 30% (average = 18%)
Kaolinite content	:	5 - 25% (average = 18%)
Chlorite content	:	absent to 5%

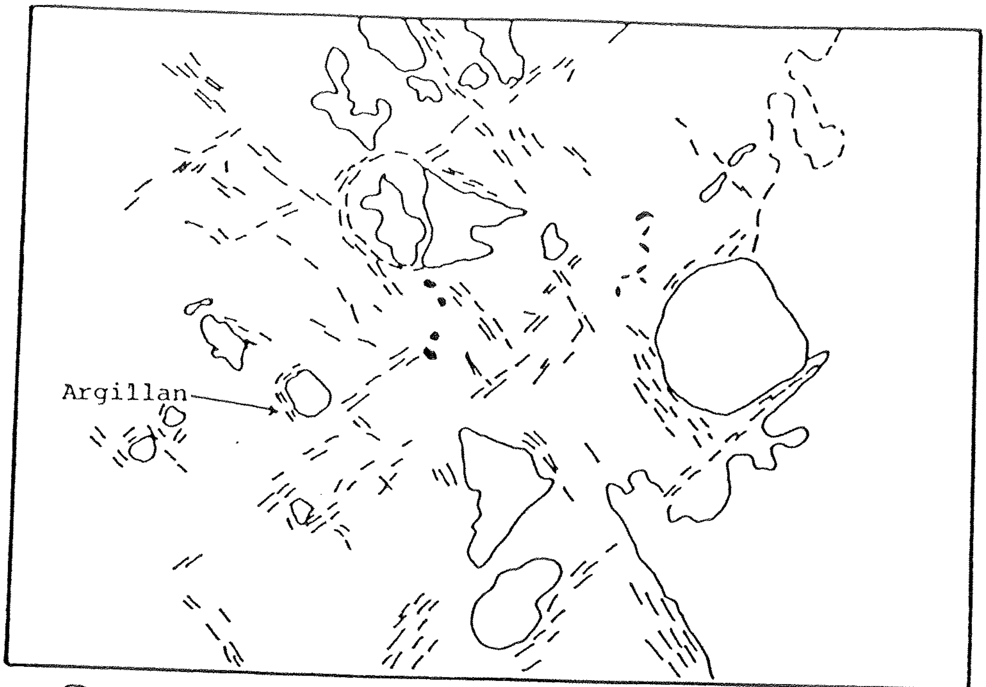
- Light grey, brown to dark brown
- Many inclined lineaments (Riedel and thrust shears)
- Principal Displacement Shear, clay particles oriented parallel to the shears
- Fractures with smooth surfaces, presence of fold structure

Montmorillonite content	:	65 - 85% (average = 73%)
Illite content	:	5 - 24% (average = 15%)
Kaolinite content	:	5 - 15% (average = 12%)
Chlorite content	:	absent to trace amount

- Brown to dark brown
- Angular to subangular peds
- Fractures are wide and with irregular surfaces

Montmorillonite content	:	35 - 68% (average = 48%)
Illite content	:	11 - 45% (average = 30%)
Kaolinite content	:	15 - 21% (average = 19%)
Chlorite content	:	about 5%

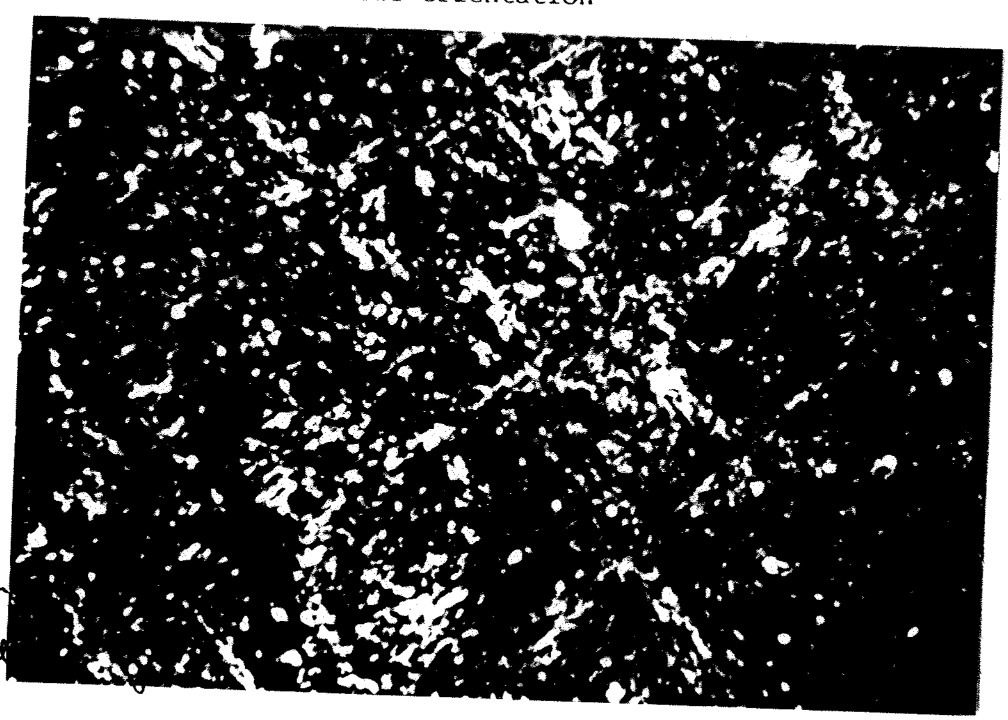
Figure 2



= Nodule (Defined, Approximate)

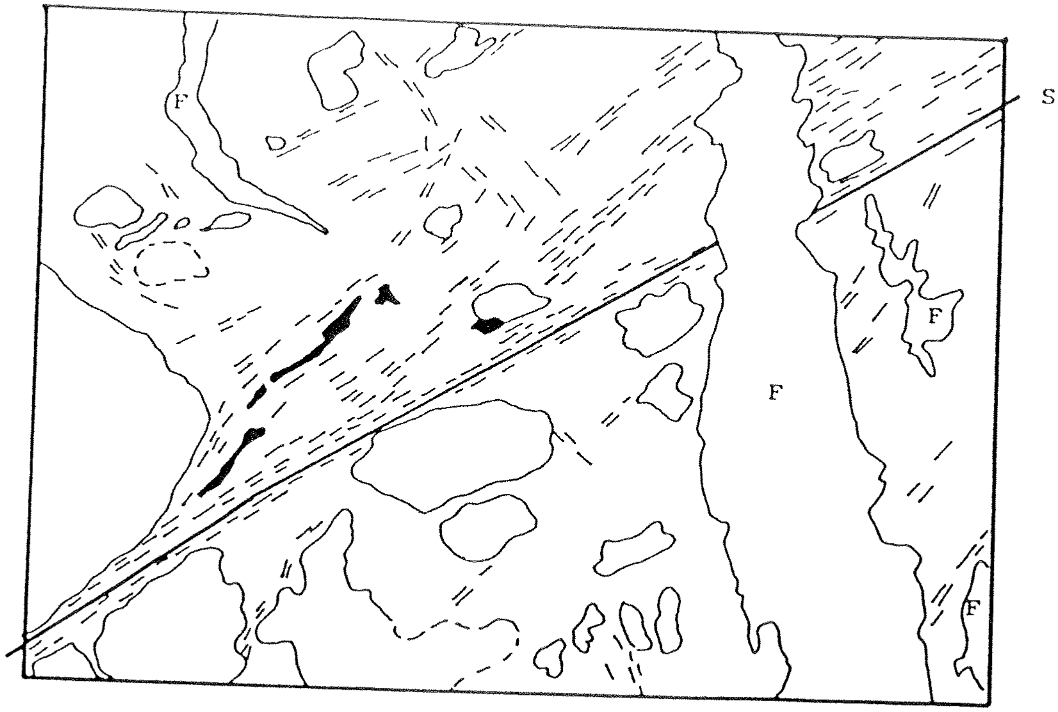
= Organic Inclusion

= Particle Orientation



Tsui, Cruden
Submicrofab

Fig. 3



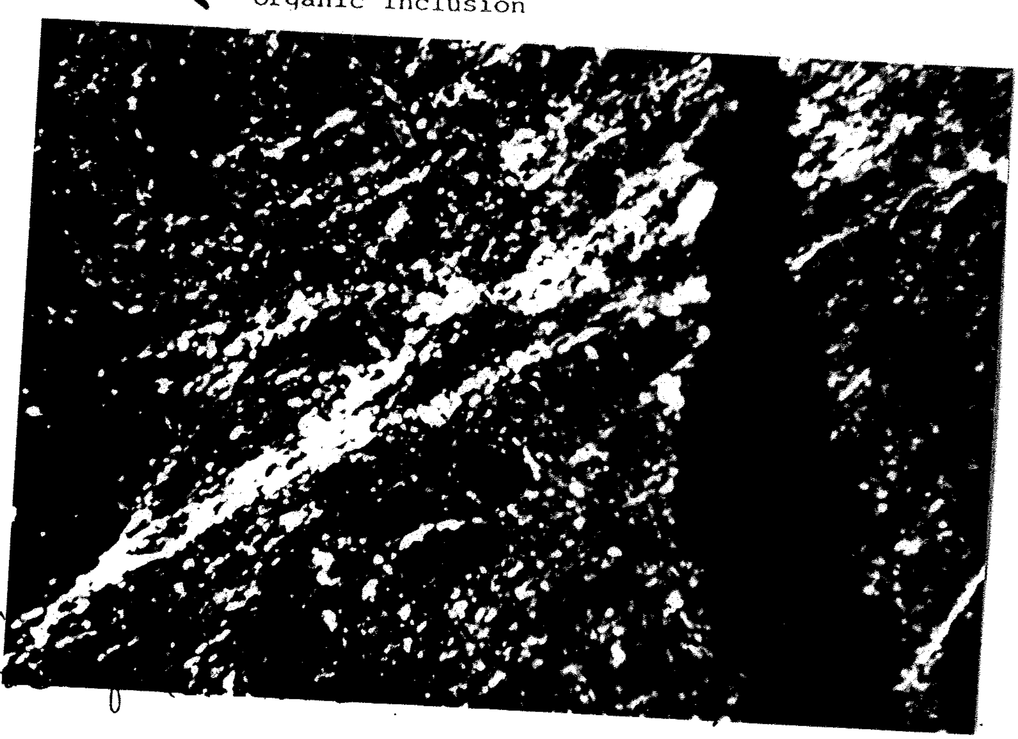
S ——— S' = Displacement Shear

F = Fracture.

= Nodule (Defined, Approximate)

= Particle Orientation

= Organic Inclusion



Tsui, Cruden

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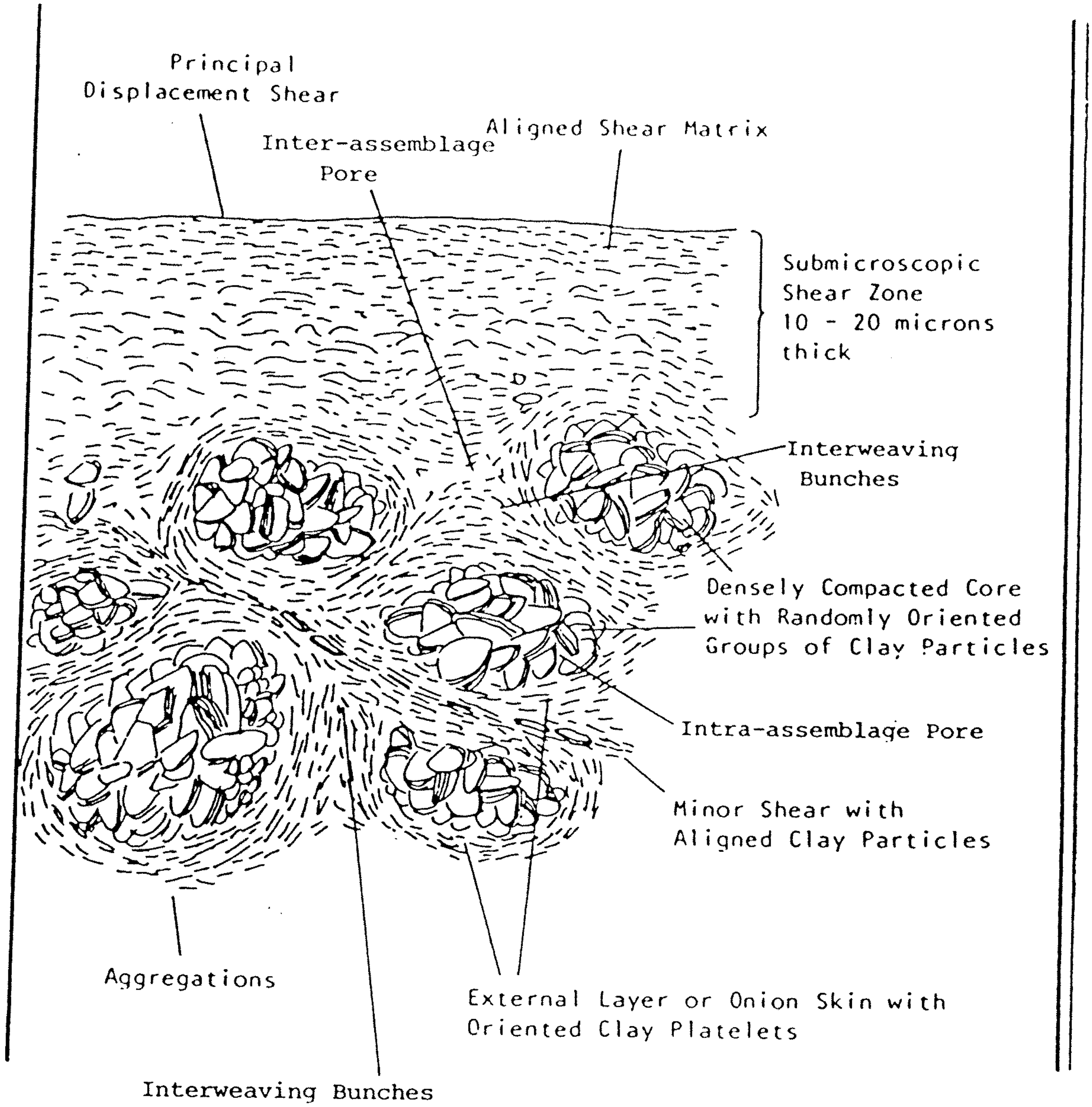
Fig. A. 4



Tsui, Cruden & Thomson. Mesofabric, microfabric & Submicrofabric of Ice-Thrust sediments. Highvale Mine.

Fig. ~~8~~ 5.

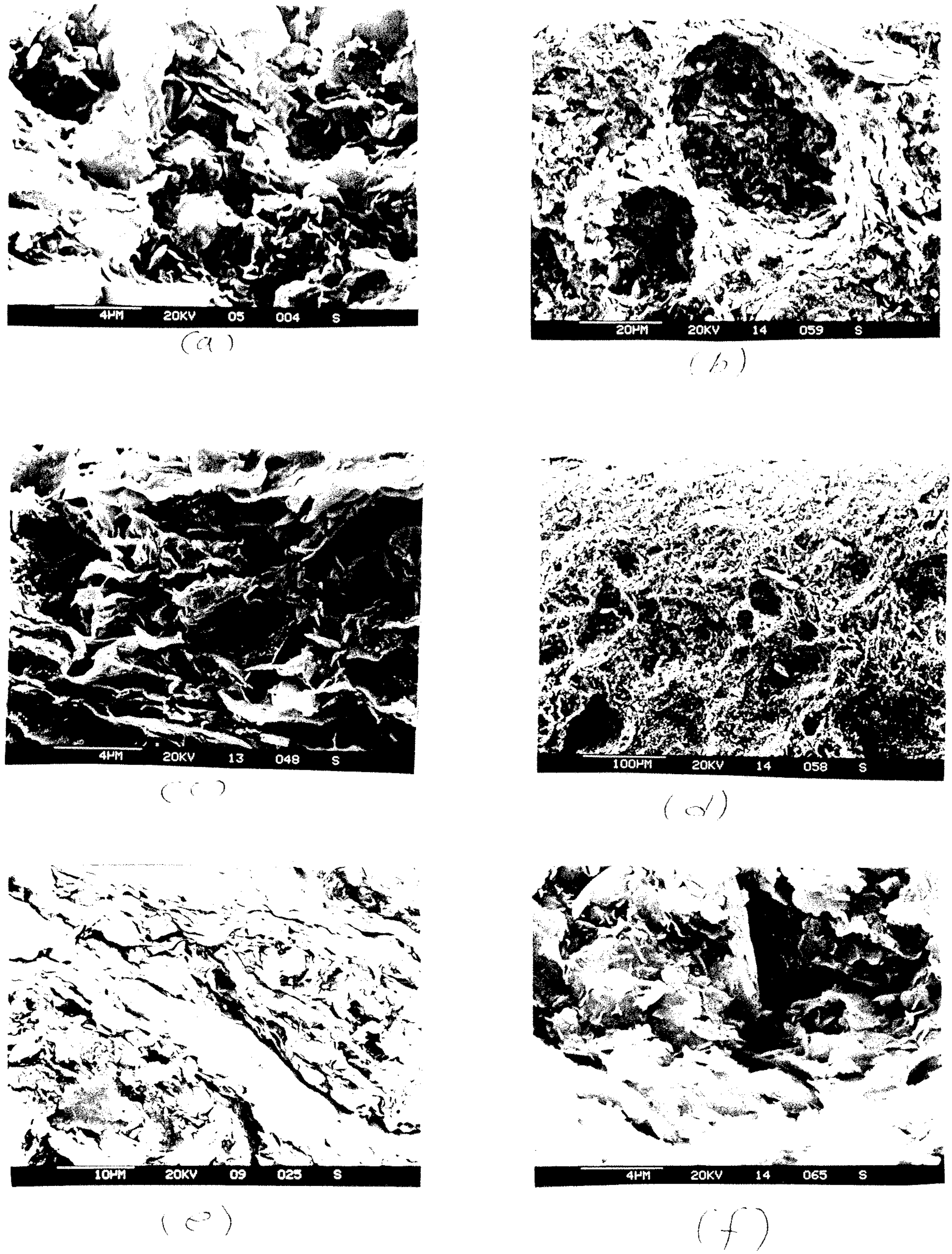

4µM 20KV 05 004 S
(a)
20µM 20KV 14 059 S
(b)
4µM 20KV 13 048 S
(c)
100µM 20KV 14 058 S
(d)
10µM 20KV 09 025 S
(e)
4µM 20KV 14 065 S
(f)

Fig 6

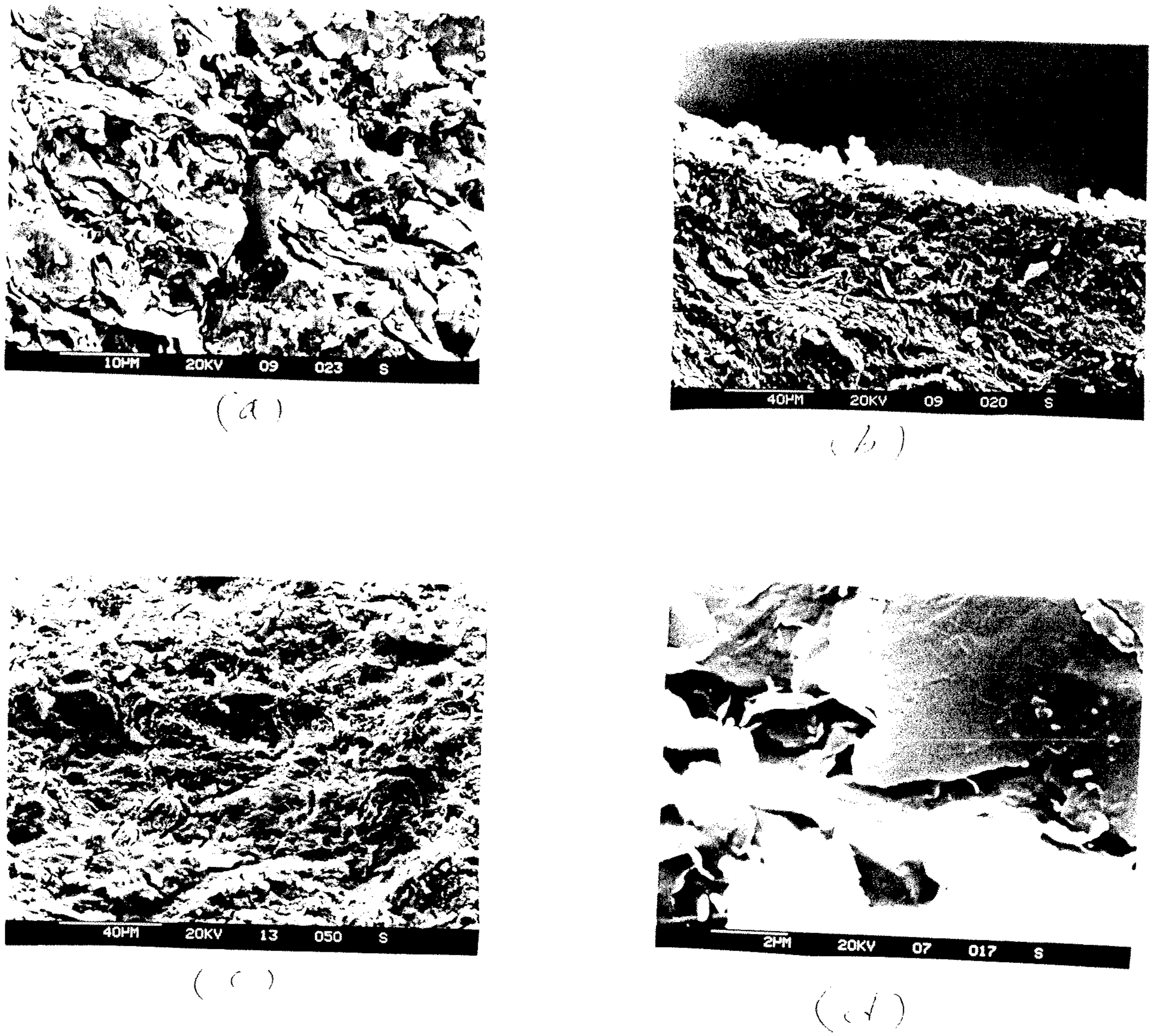
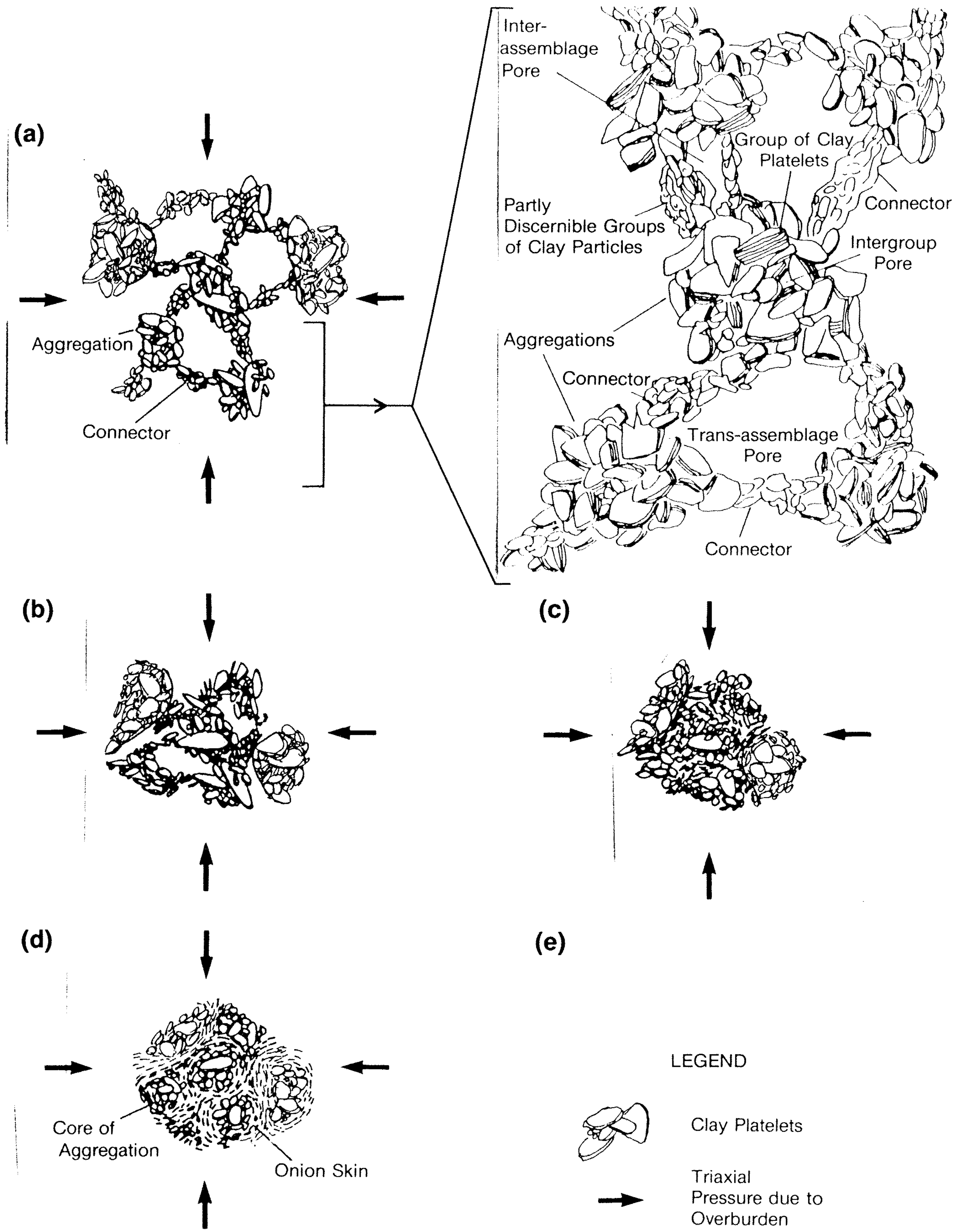

10HM 20KV 09 023 S
(a)
40HM 20KV 09 020 S
(b)
40HM 20KV 13 050 S
(c)
2HM 20KV 07 017 S
(d)

Figure 7



(a)
Aggregation
Connector
Inter-assemblage Pore
Group of Clay Platelets
Connector
Partly Discernible Groups of Clay Particles
Intergroup Pore
Aggregations
Connector
Trans-assemblage Pore
Connector
(b)
(c)
(d)
Core of Aggregation
Onion Skin
(e)
LEGEND
Clay Platelets
Triaxial Pressure due to Overburden

Figure 8